



# A Review of the Hydrodynamic Drivers Influencing Coastal Erosion and Hazard Assessments in South Africa

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## ABSTRACT

Coastal areas hold immense value, but development and climate change pose threats. Extreme climate events accelerate erosion, inundate wetlands, and contaminate resources. Coastal erosion, worsened by sea-level rise and storms, requires innovative management. This review focuses on hydrodynamic drivers like sea-level rise, tidal currents, and wave energy in coastal erosion assessments. South Africa's coast faces vulnerability due to sea-level rise and high-energy waves. The review aims to identify key hydrodynamic factors for comprehensive assessments, informing better modeling and management. It evaluates existing approaches, highlights gaps, and offers recommendations for future research.

**KEYWORDS:** COASTAL EROSION, HYDRODYNAMIC DRIVERS, SEA-LEVEL RISE

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## INTRODUCTION

Coastal areas hold substantial economic, social, cultural, and spiritual value for various stakeholders and related communities (Neumann et al., 2017, Pervaiz & Hummel, 2023). It is therefore not surprising that the maintenance of the integrity of coastal areas has become an important consideration in efforts to achieve sustainable coastal development, and that government authorities, academia, and stakeholders have expressed growing concern about the impacts of development on the coastal environment. In addition to the general issues stemming from anthropogenic pressures on coastal resources and the management thereof, the issue of climate change has increasingly demanded attention and consideration. In particular, the consequences of increased extreme coastal climate events including amongst others “acceleration of coastline erosion, inundation of wetlands and estuaries, contamination of freshwater resources, and threats to socio-economic activities as well as infrastructure” (Hereher, 2015: 342) require urgent action.

Coastal erosion as a hazard is increasingly triggering disastrous outcomes for both human life and the natural environment (Yincan et al, 2017). The rate of coastal erosion and its increased infrastructural cost are expected to increase due to effects associated with climate change for instance of sea-level rise and increased storminess (Smith et al., 2013, Pervaiz & Hummel, 2021). Increasing coastal erosion has demanded innovative and integrated approaches to coastal assessment and management, especially considering the vast area of coast, a growing coastal population, increasing development pressure, increasing storm intensities and frequencies, and limited resources available for mitigation and adaptation measures. Essentially, coastal vulnerability to erosion has been described to be contingent upon physical factors such as geology, the rate of sea-level rise, past shoreline evolution, coastal slope, mean tidal range (Thieler & Hammar-Klose, 2000) coastal geomorphology, - hydrodynamics, climate, and anthropogenic actions (Łabuz, 2015).

Although all the above-mentioned physical factors are vital in coastal erosion assessment considerations, this review is specifically concerned with the hydrodynamic drivers that influence coastal erosion assessments such as sea-level rise, tidal levels, and range, tidal current velocities, as well as wave energy and transformation amongst others. The impact of coastal hydrodynamics is becoming increasingly significant as it evolves with - and responds to the effects of climate change (Stansby, 2013, Ahmad & Eisma, 2023). Coastal erosion is a serious concern along the South African coast due to being exposed to the effects of sea-level rise as a result of climate change and high energy waves (Theron et al., 2010).

The above-mentioned significance necessitates further research of hydrodynamic drivers of coastal erosion along the South African coast. To this end, this review concisely investigates hydrodynamic drivers in coastal erosion hazard assessments. It aims to identify the hydrodynamic drivers that need to be considered when conducting comprehensive coastal erosion assessments along the South African Coasts. The outcome of this review can be used to inform best practice methods for considering and modeling hydrodynamic drivers in coastal erosion hazard assessments. Ultimately, facilitating the development of better management and assessment of coastal erosion hazards, as well as advancing greater resilience in

the face of changing climate.

The study will firstly provide a brief overview of various coastal erosion assessment approaches and models used. Secondly, the extent to which hydrodynamic considerations informed these assessment approaches/models/frameworks will be reviewed. Thirdly, South African coastal hazard assessment approaches will be reviewed. Consequently, the study will identify and assess their limitations, gaps, and needs in terms of hydrodynamic considerations. Finally, recommendations for future research on the subject are offered.

## OVERVIEW OF COASTAL EROSION ASSESSMENTS

The inward movement of the shoreline towards the land caused by permanent deficit transportation of coastal sediment away from an area by waves, currents, wind, and/or human activities is termed as 'coastal erosion' (British Geological Survey, 2012). Coastal erosion assessments quantify the movement and changing the position of the coast. The quantification of coastal erosion in terms of shoreline position change is fundamentally important to relief and development agencies, coastal scientists, engineers, and managers (Douglas & Crowell, 2000). More particularly so when they are engaged with sustainable coastal management and engineering design to mitigate, manage, and prevent permanent coastal and seawater encroachment, beach erosion, disasters, and hazards (Prasad & Kumar, 2014).

The effects of coastal erosion have furthermore received a lot of attention from climate change impact literature. This is not surprising as coastal erosion as a climate change linked hazard is increasingly triggering disastrous outcomes for both human life and the natural environment (Yincan et al, 2017). Although coastal erosion has always contributed to the forming of the existing coastlines (Van Rijn, 2011), the rate of coastal erosion and its increased infrastructural cost are expected to intensify due to effects associated with climate change (Smith et al., 2013) as well as due to the rise in exposure expected with global coastal population growth. Increasing coastal erosion is demanding innovative, predictive, and integrated approaches to coastal assessment and management, especially considering the vast area of coast, a growing coastal population, increasing development pressure, increasing storm intensities and frequencies, and limited resources available for mitigation and adaptation measures.

Towards addressing the above-mentioned demand for improved coastal erosion hazard assessments various contributing factors to coastal erosion have been progressively included and investigated. Assessments and research have been practically concerned with the constant changes in geological, geomorphological, hydrodynamic, biological, climatic, and anthropogenic factors that lead to coastal erosion hazards and impacts that stem from such changes (Łabuz, 2015). The way these factors have been assessed and modeled have likewise been increasingly researched and various methods have been developed.

A variety of analytical assessment methods have been proposed and developed to detect coastal erosion induced shoreline change. The range of erosion assessment methods can largely be divided into two approaches, namely deterministic and probabilistic. The deterministic process was introduced by Pelnard-Considere in 1956 through his equation for determining future coastline position evolvement (Reeve & Fleming, 1997). It was predominantly used in assessing coastal erosion and related processes, which is especially evident in assessments done by Shand, et al. (2015) and Mariani, et al. (2012) on segments of Australian and New Zealand coastlines, as well as various studies regarding dune erosion on the Dutch coastline, such as assessments done by van Gent, et al. (2008) and Vellinga (1986). This method produces the expected erosion hazard setback by dividing and accordingly assessing independent

components before combining them, the method often includes aspects or measurement error allowance (Shand, et al., 2015). It is largely based on the mean erosion rates caused by a single, dominant failure mechanism (Dong & Guzzetti, 2005) and accordingly follows a one-line model (Reeve & Fleming, 1997). Deterministic techniques subsequently have the advantage of allowing for clear interpretation and manageable data updates but fall short in some crucial areas of coastal erosion predictions induced by a combination of both natural - and anthropogenic factors (Shand, et al., 2015).

The use of average values by the deterministic approach, however, not only excludes the consideration of rare, large-magnitude events but also that of the considerable variety of factors that could contribute to more localized coastal erosion events (Dong & Guzzetti, 2005). Furthermore, the deterministic approach for evaluating coastal erosion largely does not include the intensive consideration of uncertainty (Wainwright, et al., 2015; Shand, 2015). Due to the availing uncertainty present in current coastal processes and the associated climate change, it is crucial that this uncertainty should form part of coastal planning and decision making (Wainwright, et al., 2015).

As Douglas & Crowell (2000) support, the approximations of erosion rates are calculated in various ways, including the endpoint rate (EPR) and linear regression rate (LRR) methods, but should always account for the variety of uncertainties present in, for example, measurements and historical model analyses through an added quantity of erosion. This is where the use of the EPR and LRR techniques fall short in a deterministic approach. The EPR model assumes that the observed historical regression rates will continue in the future and accordingly utilizes this data to predict future regression rates, as in the study by Mukhopadhyay, et al. (2012) on shoreline regression and erosion on the Puri Coast in the Bay of Bengal, India. The LRR model, implemented in Adarsa & Bhattacharya's (2013) coastal erosion vulnerability assessment around the Midnapur-Balasore Coast in India, among others, uses available data to find a line which contains the comprehensive minimum of the squared distance to the shoreline (Hedge & Akshava, 2015; Mukhopadhyay, et al., 2012). Accordingly, these techniques mostly require no knowledge of sediment transport, wave interference, or disaster events because it assumes that the cumulative effect of the foregrounded processes is indicated in the shoreline position history (Mukhopadhyay, et al., 2012). Considering the above-mentioned shortfall and the increased rate of climate change Wainwright, et al. (2015) rightly emphasizes that a range of approximations of different probabilities of coastal erosion factors should be considered for a more transparent method of conveying possible future scenarios to be put in place. This is in line with what the probabilistic techniques look like.

Barnes (2017) notes that, in the case of Australia, coastal movement processes and hazard studies are currently largely based on and moving towards data analysis as well as numerical and parametric modeling through probabilistic methods. The probabilistic method, developed by van der Graaff (1986) has become much more prominent than the traditional process of deterministic methods with regards to coastal erosion assessments in recent decades (Shand, et al., 2015). This includes Hall, et al.'s (2002) model which considers both the rate of erosion as well as the size thereof. Additionally, it observes both the likelihood and consequence of hazard occurrence (with the inclusion of areas likely affected, such as existing development, as well as those potentially affected, such as new or potential development) which moves away from single value prediction and limited understandings (Shand, et al., 2015). The probabilistic method also utilizes stochastic simulation, as done by both den Heijer, et al., (2012) in the case of dune failure along the Dutch coast and Dong & Guzzetti (2005) regarding soft-cliff erosion in England, which accounts for a distribution of values for each parameter to include the anticipated variations and uncertainties that are not considered in the single value-producing deterministic methods (Shand, et al., 2015; Reeve & Fleming, 1997). The Monte-Carlo technique is accordingly implemented, which is based

on a deterministic process model, to combine these parameters which produce a probabilistic prediction of coastal erosion processes (Shand, et al., 2015; Reeve & Fleming, 1997). Accordingly, it uses both stochastic (probabilistic) variables and deterministic (fixed value) variables to provide valuable recognition of the actual coastal erosion probabilities (den Heijer, et al., 2012; Shand, et al., 2015).

The variety of erosion modeling methods largely follow two analytical approaches, one being numerical modeling and the other being spatial analysis. As with the beach and dune erosion assessment through a probabilistic framework in the Menorca Island, Western Mediterranean by Enriquez, et al. (2019) numerical modeling utilizes atmospheric and oceanographic hindcast data to better understand and assimilate spatially defined oceanic processes for forecasting purposes (Bonetti et al., 2013). Numerical modeling is especially helpful when and where data about the impact and response of the coastal processes are lacking. This process can be divided into two primary models namely empirical (data-driven) and process-based numerical models (Hansen, 2016). While empirical models involve developing a mathematical model that recreates a set of observations to then be used predictively, the process-based numerical models consider the various pertinent physical processes (including wave propagation, wind, wave breaking, currents, and sea-level variations) which contribute to coastal erosion (Hansen, 2016). These respective models are often used, as in the case of Callaghan, et al. (2008), in combination to create a more considered model. It is important to note, however, that the application of these currently available numerical models are restricted in considering climate change as they generally simulate processes existing at a single spatial-temporal scale (Enriquez, et al., 2019; Le Cozannet, et al., 2014; Ranasinghe, et al., 2012).

Whereas numeric modeling focuses on examining the physical coastal dynamic processes, the spatial analysis' approach is focused on the analysis and representation of vulnerability to the hazard (Bastos, et al., 2016). Spatial analysis approaches, based on Geographical Information Systems, is an integrated approach wherein remote sensed imagery and data of variables that affect coastal erosion are jointly analyzed. Spatial analysis has significantly advanced the understanding and monitoring of various coastal dynamic processes and features. Its integrated approach has allowed for analysis of - and investigation into the interrelationship between various coastal elements and processes. Numerous spatial analysis methods for assessing coastal erosion and shoreline changes have been developed and applied. The straightforward inundation of static topography, the Bruun rule, as used within a probabilistic framework by Ranasinghe, et al. (2012) to assess the coastal erosion of Narrabeen Beach in Sydney, Australia, that extrapolates shoreline displacement rates from historic aerial imagery, and simple automated detection mathematical models based empirical observations, such as the End Point Rate (EPR) model (Mukhopadhyay et al., 2012) are examples of only a few of them.

As asserted by Bonetti, et al. (2013) it is valuable to note that the combination of both numerical modeling and spatial analysis techniques in coastal erosion assessments have potential in providing more valid evaluations than they would independently. For the development of both deterministic and probabilistic models, however, it is essential to acquire high-resolution series of coastal retreats and to obtain the frequency-size statistics of the retreats from the data (Dong, 2005)

The latest modus operandi of spatial analysis generally consists of a ranked-based coastal vulnerability to erosion index assessments. These indexes are focused on identifying segments of the coast that are more vulnerable to coastal erosion (Alexandrakis et al., 2010). These indexes are constructed, and their segments are calculated by ranking and combining various, geographic, oceanographic, and natural process variables and data that affect erosion within coastal systems and presenting them on a map. Variables include, amongst others, coastal geomorphology, coastal slope, rate of sea-level rise, mean

significant wave height, mean tidal range, and sediment budget (Gornitz, 1991; Hereher, 2015; Özyurt & Ergin, 2010; Thieler & Hammar-Klose, 1991; Tragaki et al., 2018) Although their methodology highlights those regions in which the various effects of sea-level rise may be the greatest, the method yields numerical data that cannot be directly equated with particular physical effects (Thieler & Hammar-Klose, 2000). Another shortcoming of the model is that it does not consider the impacts of human manipulation of the coastal environment on the physical processes of the impacts of sea-level rise (Özyurt & Ergin, 2010). Accordingly, the coastal erosion hazard assessment in coastal vulnerability indexes is generally not encompassing of all the erosion parameters and subsequently, a coastal vulnerability index should not currently be read as a coastal erosion hazard assessment.

In considering all of the above assessment methods and techniques, a few gaps are present in the development of a fully encompassing coastal erosion hazard assessment. The consideration of sediment supply, for instance, needs more in-depth consideration. While the minority of assessments such as Corbella & Stretch (2012) consider sediment supply, although very briefly and of surface-level value, others such as den Heijer, et al. (2012) and Enriquez, et al. (2019) don't consider sediment supply in their studies. With regards to sediment, the seasonal variations of its movement might also need deeper consideration, as is evident in the lack of thorough investigation thereof in studies such as those of Mujabar & Chandrasekar (2013) and Mukhopadhyay, et al. (2012).

Enriquez, et al. (2019) notes that with the investigation of continuous, long term shoreline movement, sea-level rise is considered as the main hydrodynamic driver, neglecting various other factors, including wave movement and variations. Towards enhancing effective assessment and prediction, hydrodynamic drivers should be increasingly researched, assessed, and modeled. This review will accordingly continue to further investigate the presence and pertinence of hydrodynamic drivers in coastal erosion hazard assessments.

## THE ROLE OF HYDRODYNAMIC DRIVERS IN COASTAL EROSION ASSESSMENTS

Considerable progress has been made in the field of coastal erosion processes, yet the hydrodynamic drivers require deeper investigation and understanding (van Rijn, 2013). As Ranga Rao, et al. (2015) assert, studies on the behavior of coastal hydrodynamic drivers is crucial to coastal management, especially in terms of shoreline protection and disaster mitigation measures. Furthermore, the need for an understanding of coastal hydrodynamic drivers is increasing due to climate change and sea-level rise (Almar, et al., 2015; Chowdhury, et al., 2019; Cranfield Murtlock, 2015; Stansby, 2013). Accordingly, for this study, the role of hydrodynamic drivers in coastal erosion assessment is investigated.

Coastal hydrodynamics involve the fluid motion of water in the nearshore region which, under the influence of different external forces, exhibit as tides and tidal currents, coastal currents, internal and surface waves, storm surges, and tsunamis among others (Horikawa, 1988). In other words, as van Rijn (2013) summarises, the principal hydrodynamic processes in the coastal zone are wind-induced and tide-induced waves and tide-, wind-, density- and wave-induced currents (van Rijn, 2013). These hydrodynamic processes are, especially with its exacerbated effects due to climate change, in many cases the main drivers of coastal erosion which leave coastal populations and coastal ecosystems vulnerable to economic and ecological loss and societal problems (Chowdhury, et al., 2019; Luo, et al., 2013; Ramsay, 2011; van Rijn, 2013; Zacharioudaki & Reeve, 2011). This is evident in the case of the Bight of Benin, West Africa where the wave climate is the



most influential driver of coastal erosion (Almar, et al., 2015). This is especially relevant as the Bight of Benin is specifically vulnerable to economic, ecological, and societal losses in the case of coastal erosion as this area concentrates about 80% of the regional economic activity in this sub-African region and houses over 70% of the four countries bordering it (Almar, et al., 2015). With all of the above in mind, it can once more be confidently asserted that a coastal erosion assessment requires a thorough understanding of the hydrodynamic drivers involved in coastal erosion processes. Accordingly, an investigation was done into existing coastal erosion hazard, risk and vulnerability assessments, and indexes. A variety of studies were chosen based on the availability of considered parameters and different approaches and techniques to provide a broad overview of what has been done with regards to assessing the risks, hazards, and vulnerability involved in coastal erosion.

Through this investigation, it is evident that although a general consideration of the hydrodynamic drivers exists in the relevant studies, they predominantly fail to acknowledge all of the hydrodynamic drivers involved in coastal erosion processes. This is evident, for example, in the case study for the Colombian Caribbean and Pacific coast (Stronkhorst, et al., 2018) where the authors acknowledge the limited attention given to hydrodynamic factors and the possible inaccurate coastal erosion estimations this could have had on the study. This is supported by Doran, et al. (2013) in their coastal erosion assessment on the U.S. mid-Atlantic coast where they strongly assert that studies that do not fully engage with wave climate drivers will underestimate the coastal erosion processes.

Furthermore, as also pronounced by Mortlock, et al. (2017) and Hemer, et al. (2010), even when studies consider hydrodynamic drivers more thoroughly, there is only secondary, or no, consideration of wave direction and its influence on coastal erosion, while it might be one of the most important factors in the changing wave climate. This is evident in the previously mentioned study by Doran, et al. (2013) wherein spite of their awareness of the importance of an exhaustive wave climate investigation in coastal erosion assessments, they do not consider wave direction. In case studies done by Zacharioudaki & Reeve (2011) and Mortlock, et al. (2017) on the south-central coast of England and the coast of Sydney, Australia respectively, for example, it was found that shoreline changes were mainly results of wave direction changes due to climate change impacts. This presents the problem Casas-Prat (2015) and Mortlock, et al. (2017) were also concerned about, that we are far from thoroughly understanding and recognizing the several effects that climate change, and its consequent changes in atmospheric patterns, will have on the wave climate, specifically regarding wave direction. Mortlock, et al. (2017) attributes this problem to the universal emphasis on the sea-level rise over wave climate change in the consideration of climate change effects on coastal erosion.

Besides wave direction, other hydrodynamic drivers that might need greater consideration are those involved in the effects of increased storm frequency. As one of the effects of climate change, storm frequency is experiencing an increase (Bonetti, et al., 2013; Stansby, 2013; Komar, et al., 2002). Accordingly, the frequency of hydrodynamic drivers such as storm waves and surges, among others, which are significant coastal erosion drivers also increase, leading to more frequent erosion events (Merlotto, et al., 2016; Cai, et al., 2009). While coastal erosion assessments such as in the study by Merlotto, et al. (2016) in Necochea Municipality, Buenos Aires Province, Argentina (see Table 1), consider the frequency of storm waves, it does not indicate the inclusion of increased frequency. According to Cai, et al. (2009) storm surges and its increased frequency, have been the greatest cause of loss of life, property, and economy in Chinese regions such as the Zhejiang and Fujian provinces. As Corbella & Stretch (2012a) also assert, it is accordingly necessary for coastal erosion risk and hazard assessments to incorporate the increase in the

frequency of storm waves and surges.

Despite the importance of hydrodynamic processes in the swash zone relating to coastal erosion, the consideration thereof has been quite limited thus far (Bakhtyar, et al., 2009; Butt & Russel, 2000). Although considerably more research has been conducted about this area of the foreshore in the past two decades (Chardon-Maldonado, et al., 2015), it seems that its consideration in coastal erosion assessments continues to be rare as seen in table 1. These studies seem to present no specific reference to the differing dynamics of the swash zone, including its variable reverse direction flows and fluid processes which contain large sediment loads (Chardon-Maldonado, et al., 2015). In Table 1 above, Doran, et al. (2013) do consider swash wave action along the Mid-Atlantic Coast in the United States, but the consideration is limited to its occurrence in storm-induced coastal erosion events. Accordingly, as Puleo, et al. (2014) also assert, it is necessary to analyze the hydrodynamics over multiple areas in the coastal zone, including the swash zone, to provide for a better understanding of coastal erosion processes.

The current section accordingly identifies three parameters that are absent from the general global coastal erosion assessments, as in Table 1. These include the consideration of wave direction change, increased storm frequency, and movements within the swash area. The understanding and identification of these gaps present in coastal erosion assessments globally create a platform for the evaluation of coastal erosion assessments in South Africa. This will be explored in the following section.

Gaps in coastal hazard assessments in South Africa with regards to hydrodynamic considerations. Roughly 40% of South Africa's population lives within 100km of the coast (Wigley, 2011), indicating, similarly to the global context, the importance of coherent coastal erosion assessments to facilitate efficient management of coastal areas in South Africa. Furthermore, there is added incentive for thoroughly considered coastal erosion assessments as 80% of South African coasts are sandy shore, high energy beaches, which are accordingly increasingly susceptible to erosion (Jones, 2018).

It has been asserted that, in the case of South Africa, the most prominent drivers of coastal erosion are hydrodynamic nature such as waves, tides, and future sea-level rise (Theron, et al., 2010). Accordingly, the thorough consideration of these hydrodynamic factors, as with the case globally, is needed to provide a fully engaged coastal erosion hazard assessment. This section aims to evaluate the coastal erosion and related assessments implemented on the South African coastline.

Wave direction seems to receive more valuable consideration in the abovementioned South African studies of Table 2. A total of half of the mentioned studies included wave direction in their modeling, which might provide more considered coastal erosion assessments and vulnerability indexes. A study by Corbella & Stretch (2014) on the directional wave spectra on the east coast of South Africa, however, proposes an even more comprehensive inclusion of the directional studies of waves. They believe that the detailed information on the wave climate of directional wave spectra could contribute greatly to coastal vulnerability assessments and mere summary wave statistics such as wave height, period and direction, are inadequate in their depiction of complex wave climates (Corbella & Stretch, 2014). Corbella & Stretch (2014) include, among others, the seasonal distribution of directional wave spectra, instead of merely covering the average wave direction.

Beyond the current wave direction inclusion, provision should also be made for an expected wave direction change, which will accordingly cause a shift in which areas might be susceptible to coastal erosion. According to Hemer et al. (2010), this change in the general area of South African coasts would likely follow a clockwise rotation. This expected change could be included in coastal erosion assessments to provide more in-depth understandings of what the future of coastal erosion might entail.

While various of the abovementioned studies acknowledge that climate change will mean an



increased frequency of storms which will accordingly cause significant coastal erosion (de Boer, et al., 2019; Harris, et al., 2011; Palmer, et al., 2011; Smith, et al., 2010; Theron, et al., 2010; Wigley, 2011), most fail to include this as a physical variable. Corbella & Stretch (2012a), however, propose that the increased frequency of storms should be accounted for based on its average recurrence interval, with an added time-dependent factor. Another valuable contribution by Corbella & Stretch (2012c) is the suggestion of the further investigation and inclusion of wave height return periods to have a more well-rounded understanding of the wave climate specifically.

As with the case globally, a gap still exists in the consideration of swash zone dynamics. While (Harris, et al., 2011) and (MacHutchon, 2015) do consider the swash zone, it is still limited. Harris, et al. (2011) includes the swash period as a parameter in their study on the storm impacts of sandy beaches in Sardinia Bay, South Africa, but this swash refers to the wave run-up or swash beyond the swash zone, rather than the specific dynamics within the swash zone. MacHutchon (2015), in his geophysical monitoring of coastal erosion at Monwabisi Beach, South Africa, successfully considers the particular accretion evident in the swash zone of the beach. This consideration could be taken further, in coastal erosion hazard, risk, and vulnerability assessments, to incorporate specific accretion/erosion within the swash zone, as well as the hydrodynamic particularities within the swash zone.

It is also significant to note that more than half of the abovementioned (table 2) South African studies do not consider sea-level rise as a parameter in their various studies, even though the majority acknowledge it as a substantial driver of coastal erosion. This is contrary to the global case, as previously mentioned, where Enriquez, et al. (2019) asserts that sea-level rise is mostly considered as the predominant hydrodynamic driver in coastal erosion assessments, accordingly neglecting other crucial hydrodynamic drivers of coastal erosion. Although the reason for its exclusion, as with Callaghan, et al. (2015), de Boer, et al. (2019), Fourie, et al. (2015), and MacHutchon's (2015) coastal erosion assessments, might be due to the methodological nature of using Landsat and aerial imagery, as well as a deterministic approach, there is still a need for its incorporation to provide comprehensive assessments and understandings of coastal erosion processes. This is where the inclusion of probabilistic approaches in inherently deterministic methods might be valuable in the South African case to understand the measurements of uncertainty inherent in the effects of climate change on hydrodynamic drivers of coastal erosion, including sea-level rise.

In the consideration of possible influences on hydrodynamic drivers due to climate change, Habets (2015: 16) asserts that "all exchanges of momentum, energy, heat, mass, and radiation fluxes are relevant in the projection of gravity wave-driven processes at the interface between air and sea". Noting this, Habets (2015) identifies cold front systems, cut-off low systems, and tropical cyclones as the three major atmospheric weather systems that create most of the big wave events in his study on coastal erosion near Durban, in the east of South Africa. In terms of the effects of climate change, however, there is an expected change in these systems. Malherbe et al. (2013), in their study on projected changes in tropical cyclone climatology due to anthropogenically induced climate change, for example, have projected that not only are tropical cyclones in the Southwest Indian Ocean expected to decrease but that there is also an expected northward shift thereof over the southern African subcontinent. Accordingly, there is an expectation that South Africa will become less affected by tropical cyclones and experience a decrease in coastal erosion due to this particular system. The inclusion of projected changes in a cold front, cut-off low, and tropical cyclone systems are thus crucial to understanding the possibilities of future coastal erosion and should be included in coastal erosion assessments.

Theron & Rossouw (2008) note that, with the effects of climate change, the average wind velocity in

South Africa is expected to increase in all seasons. Based on this, they note that if a mere modest 10% increase in wind speed were to occur, this would mean an increase of 12% in wind stress and accordingly 26% increase in wave height, making various shorelines even more susceptible to erosion (Theron & Rossouw, 2008). Based on this information, a valuable addition could lie within the inclusion of an uncertainty measurement in future wave height increase as a parameter to account for the likely effects of climate change on hydrodynamic factors.

As Habets (2015) also notes, accurate satellite and wave buoy data sets are not available for an extended historical period in South Africa, accordingly inhibiting the comprehensive projections in coastal erosion assessments. The studies mentioned in table 2 were accordingly all affected by this absence. This further motivates the need for extensive research to be done in the South African context to gain greater insights into possible mitigation and management of coastal erosion along South African shorelines. Harris (2008) further recommends more local scale assessments of coastal erosion events be performed to broaden the understanding of appropriate response strategies.

## CONCLUSION

In the overview of various coastal erosion assessment approaches and models used, it was apparent that a range of different probabilities of coastal erosion factors should be considered to provide for a more transparent outcome. As seen throughout the rest of the review, this has remained true in the need for more comprehensive and inclusive ranges of hydrodynamic factors influencing coastal erosion. Additionally, it is clear that a combination of approaches and techniques are further needed, such as a combination of deterministic and probabilistic approaches, as well as an incorporation of both spatial analysis and numeric modeling techniques, as Bonetti, et al. (2013) also supports.

Through the review of the extent to which hydrodynamic considerations inform coastal erosion hazard, risk, and vulnerability assessments, and indexes it becomes clear that more thorough understandings of hydrodynamic drivers are needed, especially considering expected climate change and sea-level rise that are expected to influence this further (Almar, et al., 2015; Chowdhury, et al., 2019; Cranfield Murtlock, 2015; Stansby, 2013). This section made it evident that currently available studies mostly fail to acknowledge all coastal hydrodynamic drivers of coastal erosion. Furthermore, it was noted that when studies do carefully attend to hydrodynamic drivers, gaps still exist that could provide for a thorough investigation. Three main shortcomings were identified in terms of hydrodynamic driver consideration, namely wave direction, storm frequency (and accordingly storm surge and wave) increase, and swash zone related parameters. As seen in this section, even when studies include an exhaustive consideration of the wave climate, the prevailing shortcoming is the hydrodynamic driver of wave direction. Furthermore, even when studies do include wave direction as a parameter, the issue of wave direction change as a parameter also becomes apparent with expected climate change. While some studies do consider the frequency of storms' surges and waves, none in this section included an expected increase thereof. As Puleo, et.al. (2014) also assert, it is necessary for inclusion of the dynamics of all coastal zones that influence coastal erosion to provide for a comprehensive study. Accordingly, the inclusion of different hydrodynamics present in the swash zone was identified as a gap in coastal erosion assessments globally.

It is interesting to note that, regarding the South African case studies, there is currently more valuable consideration of wave direction, than we have seen in the case globally in this study. The previously mentioned issue in the global review of coastal erosion assessments regarding the inclusion of wave direction change is also touched on in the South African case, although not included as a physical variable

in any of the included studies, as Hemer et. al. (2010) notes the expected direction change being clockwise. The inclusion of this expected wave direction change could be beneficial to coastal erosion assessment on South African coasts. Storm frequency increase as a variable is still lacking in these South African studies, except for Corbella & Stretch (2012c) who introduce the valuable proposal to account for increased storm frequency and accordingly storm waves and surges through adding an average recurrence variable with an added time-dependent factor. A gap in including swash zone dynamics still exists in the South African case, even though one study did include swash zone accretion specifically. An interesting observation from the South African case is the lack of including sea-level rise as a physical variable in more than half of the studies, which accordingly calls for more consideration of this anthropogenic climate change factor. Another important factor that should be considered more thoroughly in South African cases of coastal erosion assessments is the expected decrease of big wave inducing events such as tropical cyclones, as noted by Habets (2015) and Malherbe et. al. (2015), due to climate change. Theron & Rossouw (2008) note the expected increase in average wind velocity, which, with modest projections, is expected to cause a 26% increase effect on wave heights on South African coastlines. Accordingly, the inclusion of a measurement of uncertainty in wave height increase as a parameter is also needed to provide for a comprehensive view of the effects of hydrodynamic drivers on coastal erosion on the South African scale.

All of these factors, including the absence of accurate satellite and wave buoy data sets for extended historical periods, as Habets (2015) also asserts, motivates the need for extensive research on coastal erosion assessments, which include comprehensive considerations of hydrodynamic drivers, to be performed on the South African scale.

## PREPARING FIGURES AND TABLES

Figures and graphics at a sufficiently high resolution (minimum 1000 pixels width/height, or a resolution of 300 dpi or higher) can be uploaded in a proper field in the submission platform. Make sure figures have sufficient pixel definition before submission. Common formats are accepted; however, TIFF, JPEG and EPS are preferred.

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## ACKNOWLEDGMENTS

Acknowledgments must be brief, straight to the point. Funding agencies and other funding sources must be disclosed, with their respective grant number(s) if necessary. Keep the original names and acronyms of the native language of institutions and sponsors.