Running Title: Hydrodynamic Drivers Influencing Coastal Erosion

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

1   Coastal areas hold substantial economic, social, cultural, and spiritual value for various stakeholders
2   and related communities (Neumann et al., 2017, Pervaiz & Hummel, 2023). It is therefore not surprising
3   that the maintenance of the integrity of coastal areas has become an important consideration in efforts to
4   achieve sustainable coastal development, and that government authorities, academia, and stakeholders
5   have expressed growing concern about the impacts of development on the coastal environment. In
6   addition to the general issues stemming from anthropogenic pressures on coastal resources and the
7   management thereof, the issue of climate change has increasingly demanded attention and consideration.
8   In particular, the consequences of increased extreme coastal climate events including amongst others
9   "acceleration of coastline erosion, inundation of wetlands and estuaries, contamination of freshwater
10 resources, and threats to socio-economic activities as well as infrastructure" (Hereher, 2015: 342) require
11 urgent action.
12 Coastal erosion as a hazard is increasingly triggering disastrous outcomes for both human life and the
13 natural environment (Yincan et al, 2017). The rate of coastal erosion and its increased infrastructural cost
14 are expected to increase due to effects associated with climate change for instance of sea-level rise and
15 increased storminess (Smith et al., 2013, Pervaiz & Hummel, 2021). Increasing coastal erosion has
16 demanded innovative and integrated approaches to coastal assessment and management, especially
17 considering the vast area of coast, a growing coastal population, increasing development pressure,
18 increasing storm intensities and frequencies, and limited resources available for mitigation and adaptation
19 measures. Essentially, coastal vulnerability to erosion has been described to be contingent upon physical
20 factors such as geology, the rate of sea-level rise, past shoreline evolution, coastal slope, mean tidal range
21 (Thieler & Hammar-Klose, 2000) coastal geomorphology, - hydrodynamics, climate, and anthropogenic
22 actions (Łabuz, 2015).
23 Although all the above-mentioned physical factors are vital in coastal erosion assessment
24 considerations, this review is specifically concerned with the hydrodynamic drivers that influence coastal
25 erosion assessments such as sea-level rise, tidal levels, and range, tidal current velocities, as well as wave
26 energy and transformation amongst others. The impact of coastal hydrodynamics is becoming increasingly
27 significant as it evolves with - and responds to the effects of climate change (Stansby, 2013, Ahmad &
28 Eisma, 2023). Coastal erosion is a serious concern along the South African coast due to being exposed to
29 the effects of sea-level rise as a result of climate change and high energy waves (Theron et al., 2010).
30 The above-mentioned significance necessitates further research of hydrodynamic drivers of coastal
31 erosion along the South African coast. To this end, this review concisely investigates hydrodynamic drivers
32 in coastal erosion hazard assessments. It aims to identify the hydrodynamic drivers that need to be
33 considered when conducting comprehensive coastal erosion assessments along the South African Coasts.
34 The outcome of this review can be used to inform best practice methods for considering and modeling
35 hydrodynamic drivers in coastal erosion hazard assessments. Ultimately, facilitating the development of
36 better management and assessment of coastal erosion hazards, as well as advancing greater resilience in

37   the face of changing climate.

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

OVERVIEW OF COASTAL EROSION ASSESSMENTS

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

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

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

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

78   components before combining them, the method often includes aspects or measurement error allowance
79   (Shand, et al., 2015). It is largely based on the mean erosion rates caused by a single, dominant failure
80   mechanism (Dong & Guzzetti, 2005) and accordingly follows a one-line model (Reeve & Fleming, 1997).
81   Deterministic techniques subsequently have the advantage of allowing for clear interpretation and
82   manageable data updates but fall short in some crucial areas of coastal erosion predictions induced by a
83   combination of both natural - and anthropogenic factors (Shand, et al., 2015).
84   The use of average values by the deterministic approach, however, not only excludes the consideration
85   of rare, large-magnitude events but also that of the considerable variety of factors that could contribute
86   to more localized coastal erosion events (Dong & Guzzetti, 2005). Furthermore, the deterministic approach
87   for evaluating coastal erosion largely does not include the intensive consideration of uncertainty
88   (Wainwright, et al., 2015; Shand, 2015). Due to the availing uncertainty present in current coastal processes
89   and the associated climate change, it is crucial that this uncertainty should form part of coastal planning
90   and decision making (Wainwright, et al., 2015).
91   As Douglas & Crowell (2000) support, the approximations of erosion rates are calculated in various
92   ways, including the endpoint rate (EPR) and linear regression rate (LRR) methods, but should always
93   account for the variety of uncertainties present in, for example, measurements and historical model
94   analyses through an added quantity of erosion. This is where the use of the EPR and LRR techniques fall
95   short in a deterministic approach. The EPR model assumes that the observed historical regression rates
96   will continue in the future and accordingly utilizes this data to predict future regression rates, as in the
97   study by Mukhopadhyay, et al. (2012) on shoreline regression and erosion on the Puri Coast in the Bay of
98   Bengal, India. The LRR model, implemented in Adarsa & Bhattacharya's (2013) coastal erosion vulnerability
99   assessment around the Midnapur-Balasore Coast in India, among others, uses available data to find a line
100   which contains the comprehensive minimum of the squared distance to the shoreline (Hedge & Akshava,
101   2015; Mukhopadhyay, et al., 2012). Accordingly, these techniques mostly require no knowledge of
102   sediment transport, wave interference, or disaster events because it assumes that the cumulative effect of
103   the foregrounded processes is indicated in the shoreline position history (Mukhopadhyay, et al., 2012).
104   Considering the above-mentioned shortfall and the increased rate of climate change Wainwright, et al.
105   (2015) rightly emphasizes that a range of approximations of different probabilities of coastal erosion
106   factors should be considered for a more transparent method of conveying possible future scenarios to be
107   put in place. This is in line with what the probabilistic techniques look like.
108   Barnes (2017) notes that, in the case of Australia, coastal movement processes and hazard studies are
109   currently largely based on and moving towards data analysis as well as numerical and parametric modeling
110   through probabilistic methods. The probabilistic method, developed by van der Graaff (1986) has become
111   much more prominent than the traditional process of deterministic methods with regards to coastal
112   erosion assessments in recent decades (Shand, et al., 2015). This includes Hall, et al.'s (2002) model which
113   considers both the rate of erosion as well as the size thereof. Additionally, it observes both the likelihood
114   and consequence of hazard occurrence (with the inclusion of areas likely affected, such as existing
115   development, as well as those potentially affected, such as new or potential development) which moves
116   away from single value prediction and limited understandings (Shand, et al., 2015). The probabilistic
117   method also utilizes stochastic simulation, as done by both den Heijer, et al., (2012) in the case of dune
118   failure along the Dutch coast and Dong & Guzzetti (2005) regarding soft-cliff erosion in England, which
119   accounts for a distribution of values for each parameter to include the anticipated variations and
120   uncertainties that are not considered in the single value-producing deterministic methods (Shand, et al.,
121   2015; Reeve & Fleming, 1997). The Monte-Carlo technique is accordingly implemented, which is based

122   on a deterministic process model, to combine these parameters which produce a probabilistic prediction
123   of coastal erosion processes (Shand, et al., 2015; Reeve & Fleming, 1997). Accordingly, it uses both
124   stochastic (probabilistic) variables and deterministic (fixed value) variables to provide valuable recognition
125   of the actual coastal erosion probabilities (den Heijer, et al., 2012; Shand, et al., 2015).
126   The variety of erosion modeling methods largely follow two analytical approaches, one being numerical
127   modeling and the other being spatial analysis. As with the beach and dune erosion assessment through a
128   probabilistic framework in the Menorca Island, Western Mediterranean by Enriquez, et al. (2019) numerical
129   modeling utilizes atmospheric and oceanographic hindcast data to better understand and assimilate
130   spatially defined oceanic processes for forecasting purposes (Bonetti et al., 2013). Numerical modeling is
131   especially helpful when and where data about the impact and response of the coastal processes are
132   lacking. This process can be divided into two primary models namely empirical (data-driven) and process-
133   based numerical models (Hansen, 2016). While empirical models involve developing a mathematical
134   model that recreates a set of observations to then be used predictively, the process-based numerical
135   models consider the various pertinent physical processes (including wave propagation, wind, wave
136   breaking, currents, and sea-level variations) which contribute to coastal erosion (Hansen, 2016). These
137   respective models are often used, as in the case of Callaghan, et al. (2008), in combination to create a
138   more considered model. It is important to note, however, that the application of these currently available
139   numerical models are restricted in considering climate change as they generally simulate processes
140   existing at a single spatial-temporal scale (Enriquez, et al., 2019; Le Cozannet, et al., 2014; Ranasinghe, et
141   al., 2012).
142   Whereas numeric modeling focuses on examining the physical coastal dynamic processes, the spatial
143   analysis' approach is focused on the analysis and representation of vulnerability to the hazard (Bastos, et
144   al., 2016). Spatial analysis approaches, based on Geographical Information Systems, is an integrated
145   approach wherein remote sensed imagery and data of variables that affect coastal erosion are jointly
146   analyzed. Spatial analysis has significantly advanced the understanding and monitoring of various coastal
147   dynamic processes and features. Its integrated approach has allowed for analysis of - and investigation
148   into the interrelationship between various coastal elements and processes. Numerous spatial analysis
149   methods for assessing coastal erosion and shoreline changes have been developed and applied. The
150   straightforward inundation of static topography, the Bruun rule, as used within a probabilistic framework
151   by Ranasinghe, et al. (2012) to assess the coastal erosion of Narrabeen Beach in Sydney, Australia, that
152   extrapolates shoreline displacement rates from historic aerial imagery, and simple automated detection
153   mathematical models based empirical observations, such as the End Point Rate (EPR) model
154   (Mukhopadhyay et al., 2012) are examples of only a few of them.
155   As asserted by Bonetti, et al. (2013) it is valuable to note that the combination of both numerical
156   modeling and spatial analysis techniques in coastal erosion assessments have potential in providing more
157   valid evaluations than they would independently. For the development of both deterministic and
158   probabilistic models, however, it is essential to acquire high-resolution series of coastal retreats and to
159   obtain the frequency-size statistics of the retreats from the data (Dong, 2005)
160   The latest modus operandi of spatial analysis generally consists of a ranked-based coastal vulnerability
161   to erosion index assessments. These indexes are focused on identifying segments of the coast that are
162   more vulnerable to coastal erosion (Alexandrakis et al., 2010). These indexes are constructed, and their
163   segments are calculated by ranking and combining various, geographic, oceanographic, and natural
164   process variables and data that affect erosion within coastal systems and presenting them on a map.
165   Variables include, amongst others, coastal geomorphology, coastal slope, rate of sea-level rise, mean

166 significant wave height, mean tidal range, and sediment budget (Gornitz, 1991; Hereher, 2015; Özyurt &
167 Ergin, 2010; Thieler & Hammar-Klose, 1991; Tragaki et al., 2018)Although their methodology highlights
168 those regions in which the various effects of sea-level rise may be the greatest, the method yields
169 numerical data that cannot be directly equated with particular physical effects (Thieler & Hammar-Klose,
170 2000). Another shortcoming of the model is that it does not consider the impacts of human manipulation
171 of the coastal environment on the physical processes of the impacts of sea-level rise (Özyurt & Ergin,
172 2010). Accordingly, the coastal erosion hazard assessment in coastal vulnerability indexes is generally not
173 encompassing of all the erosion parameters and subsequently, a coastal vulnerability index should not
174 currently be read as a coastal erosion hazard assessment.

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

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

191 **THE ROLE OF HYDRODYNAMIC DRIVERS IN COASTAL EROSION ASSESSMENTS**

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

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

210   most influential driver of coastal erosion (Almar, et al., 2015). This is especially relevant as the Bight of Benin
211   is specifically vulnerable to economic, ecological, and societal losses in the case of coastal erosion as this
212   area concentrates about 80% of the regional economic activity in this sub-African region and houses over
213   70% of the four countries bordering it (Almar, et al., 2015). With all of the above in mind, it can once more
214   be confidently asserted that a coastal erosion assessment requires a thorough understanding of the
215   hydrodynamic drivers involved in coastal erosion processes. Accordingly, an investigation was done into
216   existing coastal erosion hazard, risk and vulnerability assessments, and indexes. A variety of studies were
217   chosen based on the availability of considered parameters and different approaches and techniques to
218   provide a broad overview of what has been done with regards to assessing the risks, hazards, and
219   vulnerability involved in coastal erosion.

221   Through this investigation, it is evident that although a general consideration of the hydrodynamic
222   drivers exists in the relevant studies, they predominantly fail to acknowledge all of the hydrodynamic
223   drivers involved in coastal erosion processes. This is evident, for example, in the case study for the
224   Colombian Caribbean and Pacific coast (Stronkhorst, et al., 2018) where the authors acknowledge the
225   limited attention given to hydrodynamic factors and the possible inaccurate coastal erosion estimations
226   this could have had on the study. This is supported by Doran, et al. (2013) in their coastal erosion
227   assessment on the U.S. mid-Atlantic coast where they strongly assert that studies that do not fully engage
228   with wave climate drivers will underestimate the coastal erosion processes.
229   Furthermore, as also pronounced by Mortlock, et al. (2017) and Hemer, et al. (2010), even when
230   studies consider hydrodynamic drivers more thoroughly, there is only secondary, or no, consideration of
231   wave direction and its influence on coastal erosion, while it might be one of the most important factors in
232   the changing wave climate. This is evident in the previously mentioned study by Doran, et al. (2013)
233   wherein spite of their awareness of the importance of an exhaustive wave climate investigation in coastal
234   erosion assessments, they do not consider wave direction. In case studies done by Zacharioudaki & Reeve
235   (2011) and Mortlock, et al. (2017) on the south-central coast of England and the coast of Sydney, Australia
236   respectively, for example, it was found that shoreline changes were mainly results of wave direction
237   changes due to climate change impacts. This presents the problem Casas-Prat (2015) and Mortlock, et al.
238   (2017) were also concerned about, that we are far from thoroughly understanding and recognizing the
239   several effects that climate change, and its consequent changes in atmospheric patterns, will have on the
240   wave climate, specifically regarding wave direction. Mortlock, et al. (2017) attributes this problem to the
241   universal emphasis on the sea-level rise over wave climate change in the consideration of climate change
242   effects on coastal erosion.
243   Besides wave direction, other hydrodynamic drivers that might need greater consideration are those
244   involved in the effects of increased storm frequency. As one of the effects of climate change, storm
245   frequency is experiencing an increase (Bonetti, et al., 2013; Stansby, 2013; Komar, et al., 2002). Accordingly,
246   the frequency of hydrodynamic drivers such as storm waves and surges, among others, which are
247   significant coastal erosion drivers also increase, leading to more frequent erosion events (Merlotto, et al.,
248   2016; Cai, et al., 2009). While coastal erosion assessments such as in the study by Merlotto, et al. (2016) in
249   Necochea Municipality, Buenos Aires Province, Argentina (see Table 1), consider the frequency of storm
250   waves, it does not indicate the inclusion of increased frequency. According to Cai, et al. (2009) storm surges
251   and its increased frequency, have been the greatest cause of loss of life, property, and economy in Chinese
252   regions such as the Zhejiang and Fujian provinces. As Corbella & Stretch (2012a) also assert, it is
253   accordingly necessary for coastal erosion risk and hazard assessments to incorporate the increase in the

254   frequency of storm waves and surges.

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

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

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

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

282   Wave direction seems to receive more valuable consideration in the abovementioned South African
283   studies of Table 2. A total of half of the mentioned studies included wave direction in their modeling,
284   which might provide more considered coastal erosion assessments and vulnerability indexes. A study by
285   Corbella & Stretch (2014) on the directional wave spectra on the east coast of South Africa, however,
286   proposes an even more comprehensive inclusion of the directional studies of waves. They believe that the
287   detailed information on the wave climate of directional wave spectra could contribute greatly to coastal
288   vulnerability assessments and mere summary wave statistics such as wave height, period and direction,
289   are inadequate in their depiction of complex wave climates (Corbella & Stretch, 2014). Corbella & Stretch
290   (2014) include, among others, the seasonal distribution of directional wave spectra, instead of merely
291   covering the average wave direction.

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

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

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

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

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

327   In the consideration of possible influences on hydrodynamic drivers due to climate change, Habets
328 (2015: 16) asserts that "all exchanges of momentum, energy, heat, mass, and radiation fluxes are relevant
329 in the projection of gravity wave-driven processes at the interface between air and sea". Noting this,
330 Habets (2015) identifies cold front systems, cut-off low systems, and tropical cyclones as the three major
331 atmospheric weather systems that create most of the big wave events in his study on coastal erosion near
332 Durban, in the east of South Africa. In terms of the effects of climate change, however, there is an expected
333 change in these systems. Malherbe et al. (2013), in their study on projected changes in tropical cyclone
334 climatology due to anthropogenically induced climate change, for example, have projected that not only
335 are tropical cyclones in the Southwest Indian Ocean expected to decrease but that there is also an
336 expected northward shift thereof over the southern African subcontinent. Accordingly, there is an
337 expectation that South Africa will become less affected by tropical cyclones and experience a decrease in
338 coastal erosion due to this particular system. The inclusion of projected changes in a cold front, cut-off
339 low, and tropical cyclone systems are thus crucial to understanding the possibilities of future coastal
340 erosion and should be included in coastal erosion assessments.

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

342   South Africa is expected to increase in all seasons. Based on this, they note that if a mere modest 10%
343   increase in wind speed were to occur, this would mean an increase of 12% in wind stress and accordingly
344   26% increase in wave height, making various shorelines even more susceptible to erosion (Theron &
345   Rossouw, 2008). Based on this information, a valuable addition could lie within the inclusion of an
346   uncertainty measurement in future wave height increase as a parameter to account for the likely effects
347   of climate change on hydrodynamic factors.

348   As Habets (2015) also notes, accurate satellite and wave buoy data sets are not available for an
349   extended historical period in South Africa, accordingly inhibiting the comprehensive projections in coastal
350   erosion assessments. The studies mentioned in table 2 were accordingly all affected by this absence. This
351   further motivates the need for extensive research to be done in the South African context to gain greater
352   insights into possible mitigation and management of coastal erosion along South African shorelines. Harris
353   (2008) further recommends more local scale assessments of coastal erosion events be performed to broaden
354   the understanding of appropriate response strategies.

CONCLUSION

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

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

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

383   in any of the included studies, as Hemer et. al. (2010) notes the expected direction change being clockwise.
384   The inclusion of this expected wave direction change could be beneficial to coastal erosion assessment on
385   South African coasts. Storm frequency increase as a variable is still lacking in these South African studies,
386   except for Corbella & Stretch (2012c) who introduce the valuable proposal to account for increased storm
387   frequency and accordingly storm waves and surges through adding an average recurrence variable with
388   an added time-dependent factor. A gap in including swash zone dynamics still exists in the South African
389   case, even though one study did include swash zone accretion specifically. An interesting observation from
390   the South African case is the lack of including sea-level rise as a physical variable in more than half of the
391   studies, which accordingly calls for more consideration of this anthropogenic climate change factor.
392   Another important factor that should be considered more thoroughly in South African cases of coastal
393   erosion assessments is the expected decrease of big wave inducing events such as tropical cyclones, as
394   noted by Habets (2015) and Malherbe et. al. (2015), due to climate change. Theron & Rossouw (2008) note
395   the expected increase in average wind velocity, which, with modest projections, is expected to cause a
396   26% increase effect on wave heights on South African coastlines. Accordingly, the inclusion of a
397   measurement of uncertainty in wave height increase as a parameter is also needed to provide for a
398   comprehensive view of the effects of hydrodynamic drivers on coastal erosion on the South African scale.
399   All of these factors, including the absence of accurate satellite and wave buoy data sets for extended
400   historical periods, as Habets (2015) also asserts, motivates the need for extensive research on coastal
401   erosion assessments, which include comprehensive considerations of hydrodynamic drivers, to be
402   performed on the South African scale.

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403   Figures and graphics at a sufficiently high resolution (minimum 1000 pixels width/height, or a
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AUTHOR CONTRIBUTION

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Example for three authors:

A.B.C.: Conceptualization; Investigation; Writing – original draft; Writing – review & editing;

D.E.F.G.: Methodology; Software; Formal Analysis; Investigation; Writing – review & editing;

H.I.: Supervision; Resources; Project Administration; Funding Acquisition; Writing – review & editing.

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650   water coral ecosystems. Science, 312, 543- 547.

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656   *Table 1 Overview of global coastal erosion hazard, risk and vulnerability assessments*

Study	Purpose of the Study	Parameters Considered	Hydrodynamic Drivers Considered
Regional Assessment of Long-term Trends of Coastal Erosion in Northeastern Brazil (Landim Dominguez & Pinto Bittencourt, 1996)	Long Term Coastal Erosion Trend Evaluation	Geology (formations, terraces, beach rocks, lagoonal deposits, dune deposits, and coral reefs) and hydrodynamics	Sea level rise, wave climate (seasonal directions & height), and tidal range
An Integrated Risk Assessment of Coastal Erosion based on Fuzzy Set Theory	Coastal Erosion Risk Assessment	Geology (erodibility in coastal substrates) and hydrodynamics	Sea level rise, wave height, storm surge, tidal range

along Fujian Coast, Southeast China (Luo, et al., 2013)			
Regional Coastal Erosion Assessment based on Global Open Access Data: a case study for Colombia (Stronkhorst, et al., 2018)	Coastal Erosion Assessment	Geological layout, sediment balance, vegetation, storms, and hydrodynamics	Wave climate (height) and tidal range.
Coastal Erosion Risk Assessment, Shoreline Retreat Rates, and Causes of Coastal Erosion Along with the State of Sao Paulo Coast, Brazil (Souza, 2001)	Coastal Erosion Risk Assessment	Geomorphology, sediment balance, and hydrodynamics	Sea level rise, wave regime (increased storminess), current circulation, and tidal range
Erosion Hazard Vulnerability of US Coastal Counties (Boruff, et al., 2005)	Coastal social and erosion hazard vulnerability index	Geomorphology (erodibility), sediment balance, coastal slope, social vulnerability variables, and hydrodynamics	Sea level rise, wave height, and tidal range.
Coastal erosion hazard and vulnerability assessment for southern coastal Tamil	Coastal vulnerability index	Geology, geomorphology, shore configuration, beach width, gradient and composition,	Sea level rise, wave height, and tidal range

Nadu of India by using remote sensing and GIS (Mujabar & Chandrasekar, 2013)		drainage/estuaries, sediment balance, and hydrodynamics	
A Holistic Approach to Beach Erosion Vulnerability Assessment (Alexandrakis & Poulos, 2014)	Coastal vulnerability index	Geomorphology, beach morphology, wind climate, sedimentology, and hydrodynamics	Sea level rise, mean sea level, wave climate (wave breaking height & angle, significant wave height, wave period, and closure depth), and tidal range
National Assessment of Hurricane-Induced Coastal Erosion Hazards: Mid-Atlantic Coast (Doran, et al., 2013)	Coastal erosion hazard assessment.	Beach morphology (dune crest and toe, shoreline position and beach slope) and hydrodynamics.	Wave setup and swash, wave height and period, and tide and storm surge.
Hazard, vulnerability, and coastal erosion risk assessment in Necochea Municipality, Buenos Aires Province, Argentina (Merlotto, et al., 2016)	Coastal erosion hazard, risk, and vulnerability assessment	Coastal geomorphology, sediment supply, erosion/accretion rate, and hydrodynamics	Storm waves (height, frequency, duration).

657   *Table 2 Overview of South African based coastal erosion hazard, risk, and vulnerability assessments*

Study	Purpose of the Study	Parameters Considered	Hydrodynamic Drivers Considered
The Influence of Wave Action on Coastal Erosion along Monwabisi Beach, Cape Town (Fourie, et al., 2015)	Coastal Erosion Assessment	Coastal retreat rate, geological substrate, and hydrodynamics	Wave climate (significant wave height, maximum wave height, extreme wave heights, wave seasonality, wave direction, and storm waves)
An Assessment of Coastal Vulnerability for the South African Coast (Musekiwa, et al., 2015)	Coastal Vulnerability Index	Beach geomorphology, geology, elevation to chart datum, beach width, distance to 20m isobaths, anthropogenic activities, and hydrodynamics	SLR, wave climate (maximum wave height, mean wave height), and tidal range
Predicting Coastal Erosion Trends using Non-stationary Statistics and	Coastal Erosion Hazard Prediction Model	Storm duration, storm frequency increase, dune height above mean	SLR, wave climate (maximum wave height, wave height, wave duration, wave

		sea level, cross-shore distance offshore, hydrodynamics	peak, wave period, and wave angle in storm events), and water level.
Process-based Models (Corbella & Stretch, 2012a)			
Preliminary Coastal Vulnerability Assessment for KwaZulu-Natal, South Africa (Palmer, et al., 2011)	Coastal Vulnerability Index	Beach width, dune width, distance to 20m isobaths, the distance of vegetation behind the back beach, percentage rocky outcrop	
Decadal Trends in Beach Morphology on the East Coast of South Africa and Likely Causative Factors (Corbella & Stretch, 2012b)	Coastal Erosion Assessment	Beach gain, beach loss, wind trends, storm frequency, duration and calm period, and hydrodynamics	SLR, wave climate (maximum wave height, maximum significant wave height, average significant wave height, maximum peak period, average peak period, peak energy frequency, average direction), and tidal range
Quantification of Risks to Coastal Areas and Development: Wave	Coastal Vulnerability & Risk Assessment	Geomorphology, geology, coastal slope, erosion/accretion	SLR, wave climate (wave height), and tidal range

Run-up and Erosion (Theron, et al., 2010)		rate, ground cover, wave exposure, foredune buffer volume/ height, and hydrodynamics	
Mapping the Sandy Beach Evolution around Seaports at the Scale of the African Continent (de Boer, et al., 2019)	Coastal Impact Map	Coastline orientation, sediment sources & sinks, natural sheltering setting, coastal protection (cross-shore & longshore structures), breakwater length, port construction date, and hydrodynamics	Wave climate (mean wave direction)
Geophysical Monitoring of Coastal Erosion and Cliff Retreat of Monwabisi Beach, False Bay, South Africa (MacHutchon, 2015)	Coastal Erosion Assessment	Nearshore & coastal morphology, wind patterns, and hydrodynamics	Wave climate (mean significant wave height, mean peak wave period, wave angle, and wave run-up), tidal range, and nearshore, and surface currents.

Contrasting Styles of Swell-driven Coastal Erosion: Examples from KwaZulu-Natal, South Africa (Smith, et al., 2010)	Coastal Erosion Assessment	Geomorphology, nearshore bars, erosion, coastline recovery, wind speed variation, wind direction variation, storm type, and hydrodynamics	Wave climate (significant shallow wave height, maximum swell height, highest significant offshore swell, swell morphodynamics, swell direction), tidal height & state, water level dynamics, currents, and storm surge
The Use of Landsat and Aerial Photography for the Assessment of Coastal Erosion and Erosion Susceptibility in False Bay, South Africa (Callaghan, et al., 2015)	Coastal Erosion Assessment	Shoreline evolution and landcover change	
Geohazards in Coastal Areas (Wigley, 2011)	Physical Vulnerability Index	Geomorphology, shoreline erosion, and accretion rates, coastal slope, and hydrodynamics	Rate of relative SLR, mean tidal range, mean wave height

Swashed away? Storm impacts on sandy beach macrofaunal communities (Harris, et al., 2011)	Coastal Erosion Assessment	Beach intertidal width, beach intertidal elevation, mean sand grain size, sediment fall velocity, dean's parameter, beach index, beach state index, beach deposit index, sorting, skewness, kurtosis, and hydrodynamics	Wave breaker height, wave period, swash period, mean tide range, and relative tide range

MAIN EXAMPLES OF REFERENCING LITERATURE

JOURNALS: PRINT AND ONLINE.

ONE AUTHOR

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Reference List Example:

SCHNEIDER, E. K. 2015. Trajectory analysis of the mechanism for westward propagation of Rossby waves. *Journal of the Atmospheric Sciences*, 72, 2178-2182. doi:10.1175/JAS-D-14-0242.1

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WHO (World Health Organization) 1993. *WHO editorial style manual*. Geneva: World Health Organization.

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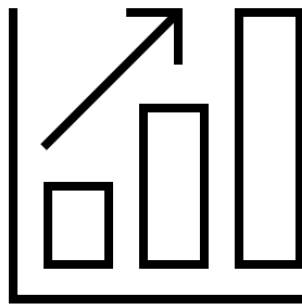678   B   C

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