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Nature-based solutions for coastal resilience in South Africa

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ABSTRACT

Coastlines globally are sensitive to the effects of sea-level rise, increased coastal storminess and changes in coastal sediment supply and sediment dynamics in the Anthropocene. Coastlines are also influenced by land use change, urbanization and development of built infrastructure. These changes can affect the dynamics of coastal landforms, weaken coastal resilience and make coasts more sensitive to climate hazards. This study critically examines the properties of coastlines that contribute to coastal biophysical resilience in South Africa, highlighting their relativerates of change and dynamic behaviour in response to physical and human forcing factors. Coastal landforms can be considered as 'green infrastructure' that can buffer the effects of climate change as well as providing ecosystem and environmental services in their own right. Viewing coastal landforms as green infrastructure provides a 'nature-based solution' to mitigate against climate change impacts that can work with – not against – the natural geomorphic, sedimentary and ecological processes of coastlines. Coastal landforms can also contribute to socioecological resilience, where they provide environmental and ecosystem services. The green infrastructure approach to coastal resilience has not been well developed in South Africa but is more effective in supporting coastal sustainable development.

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1. Introduction

Coastlines lie at the interface of terrestrial and marine environments and, as such, are sensitive to hazards such as sea-level rise and extreme storms (Kesavan & Swaminathan, 2006; Kron, 2013; Luijendijk et al., 2018; Mather & Stretch, 2012; Ramesh et al., 2015). Understanding the impacts that these and other hazards can have on coastlines is important for hazard impact mitigation, management, and sustainable development. Hazard impacts on coasts have been extensively studied worldwide at different spatial and temporal scales, and using many different dataset types, from numerical models of future climate or wave regimes, to geological evidence for the imprints of past hazards, and to behavioural analysis of affected coastal populations (e.g. Gaillard et al., 2009; Kazemi et al., 2017; Pile et al., 2018). The resilience of coastlines to withstand hazards is related to the nature of the climate events themselves (their magnitude, frequency, duration); the properties of the affected coastline (sandy vs rocky coasts, nearshore

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bathymetry and coastal hinterland topography, vegetation); the nature of human activity and infrastructure in the affected region (population exposed, socioeconomic factors, urban development, port/harbour facilities, geoengineering such as sea walls); and any mitigating actions that may reduce hazard impacts to the natural or to the built or human environments (Glavovic et al., 2015; Ruckelshaus et al., 2020). In South Africa, several studies on coastal hazards and their impacts have been undertaken, but these have tended to focus on urban areas (e.g. Colenbrander & Bavinck, 2017; Colenbrander et al., 2015; Mather & Stretch, 2012). There has been less attention paid to open rocky and sandy coastlines, and in understanding their morphodynamics and responses to climate forcing (Botha et al., 2018; La Cock et al., 1992; Mitchell et al., 2005; Musekiwa et al., 2015). This is important as these rocky, sandy and urbanized coastlines, with different landforms and dynamics, respond differently to climate forcing and may have different abilities to withstand climate forcing (i.e. their resilience). In a recent analysis, Williams et al. (2022) evaluated the 'intactness' of global coastlines based on the anthropogenic footprint present within the coastal hinterland, using data points spaced 1 km apart. For South Africa (number of data points = 2606), the authors calculated that 97.5% of the coastline was exposed to high human pressure arising mainly from demographic factors (based on GPD, GINI coefficient, regulatory quality), compared to 47.9% globally. This may highlight the potential sensitivity – and thus low resilience – of the South African coastline to climate change impacts and coastal hazards.

The concept of coastline resilience provides a useful and integrated framework to consider the effects of climate forcing as it describes the net *outcomes* of forcing on a coastline rather than the detailed factors or properties that give rise to those outcomes (Nichols et al., 2019; Flood & Schechtman, 2014; Masselink & Lazarus, 2019). *Resilience* is useful because it considers the nature of the feedbacks that exist between the human environment (geoengineering, socioeconomic and cultural factors) and the physical environment, through the ways in which coastal landforms are used, valued and managed (Knight, 2022a). Measuring coastal resilience, however, is not easy because it requires (1) establishing the state of the system that exists before a forcing event(s) takes place; (2) understanding the nature of the forcing event(s) itself, including its magnitude, characteristics and spatial and temporal extent; and (3) evaluating its impacts on the physical and human environments, and any changes in the workings of physical and human systems that have taken place afterwards, bearing in mind that the spatial and temporal extent of any impacts may not be the same as the original forcing (Brown et al., 2016; Schultz & Smith, 2016). These sequential steps and this kind of *post hoc* analysis is in reality difficult to achieve. This is because it requires monitoring of coastal and hinterland sediment systems and geomorphic changes over long (10^2–10^4 year) timescales, which is often unachievable, and it assumes a simple forcing – response relationship along a coastline that does not change. An alternative approach to evaluating coastal resilience is by monitoring and measuring coastal morphodynamic responses to forcing by wind, waves and/or sea-level changes that take place over decadal or shorter timescales, where field and remote sensing datasets are more likely to be available. This has been the focus of most coastal research undertaken in South Africa, based on field or remote sensing methods from individual coastal stretches (e.g. Corbella & Stretch, 2012a; Harris et al., 2011a; Henrico et al., 2020; Knight & Burningham, 2019, 2021; Lubke & Webb, 2016; Mitchell et al., 2005). The advantage of this approach is that it is not dependent on *a priori* understanding of the state of the system and fits with the spatial and temporal scales of coastal morphodynamic behaviour and coastal management (Cowell & Thom, 1994). However, there has been less work on considering how data from such studies can be used to evaluate the vulnerability of different coastal stretches in South Africa, and how vulnerability and risk arise as a result of climate forcing and human activity in combination (Colenbrander et al., 2015; Musekiwa et al., 2015).

Sandy coastlines are particularly vulnerable to the effects of climate change because of the relative ease with which sand grains can be moved by wind and water. The vulnerability of sandy coasts to climate change has been noted worldwide (Knight & Harrison, 2009; Luijendijk et al., 2018; Ranasinghe & Stive, 2009). Sandy coasts make up 38% of South Africa's coast, with 29% of the remainder being rocky and 32% being mixed rocky-sandy (Wepener & Degger, 2019), and this likely means that these coasts will be differentially affected by climate forcing. The aim of this study is to critically examine the resilience of different landforms present along the South African coast. This is achieved through consideration of their dynamic behaviour, based on examples of specific landform types. The study highlights that different geomorphic features along coastlines can be considered as 'green infrastructure' that provides natural resilience to the coastline. Further, certain management strategies can increase landform resilience as well as the provision of environmental and ecosystem services along the coast, thereby also increasing societal resilience (Passeri et al., 2021). Focusing on the natural resilience provided by coastal landforms is a nature-based solution to address climate change impacts along coastlines globally, and treats coastlines as integrated biophysical and socioecological systems. This is an integrated and progressive approach to climate change risk management (e.g. Knight, 2021a, 2022b).

2. The definition and scope of resilience

Pachauri & Meyer (2014, p. 127) define resilience as the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation. In a coastal context, Masselink & Lazarus (2019, p. 1) define resilience as 'the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea level rise, extreme events and human impacts, by adapting whilst maintaining their essential functions'. This therefore considers resilience as having both physical and human elements, termed biophysical and socio-ecological resilience, respectively (Poe et al., 2014; Silva et al., 2019), but that there may be complex relationships between them.

Resilience can arise as a result of the properties of coastal landforms themselves (their size, shape, location, geology, ecosystems) and their dynamical behaviour. Here, rapid temporal and spatial changes in landform processes and properties (i.e. highly dynamic behaviour) suggest that the landform has high sensitivity (low resilience) to forcing; landforms that do not change significantly over time or space exhibit more subdued dynamic behaviour and are therefore considered to have low sensitivity (high resilience) to forcing. Resilience can be broadly considered as the opposite of vulnerability (Angus & Hansom, 2021; Masselink & Lazarus, 2019), so when resilience is high vulnerability is low, and *vice versa*. Both terms have been used in the context of coastal physical systems and human activity along coasts (Alexandrakis & Poulos, 2014; Angus & Hansom, 2021; Ballesteros & Esteves, 2021) although societal resilience to coastal events and hazards (which is particularly important in the developing world) has not been well explored in southern Africa (Cabral et al., 2017; DST, 2017; Palmer et al., 2011).

2.1. Resilience along the South African coast

Different landforms present along the South African coast should in theory exhibit different degrees of resilience (and its converse, vulnerability) to forcing. The key landform types under consideration in this study are indicated in Table 1. These landforms are identified based on their commonness along the South African coast (Dardis & Grindley, 1988). These are discussed in detail below. Overall, it can be seen that coastal landforms of different types can provide physical and topographic buffers against sea-level rise and wave erosion and flooding (Hanley et al., 2014; Kim et al., 2021), as these are the major mechanisms of geomorphic change and coastal impacts that are issues along the South African coast (Holmes et al., 2016). Threats and vulnerabilities arise from climate change through sea level and wave forcing, and from different types of human activity along the coast. Both of these sources of vulnerability are amplified along sandy coasts where unconsolidated sand is easily eroded, transported and deposited, resulting in rapid geomorphic change and thus higher sensitivity to forcing (Hanley et al., 2014; Knight, 2022a; Luijendijk et al., 2018). Rocky shorelines exhibit completely different styles of vulnerability, influenced by geologic structure and elevation of the shore platform (Payo et al., 2015).

3. Examples of the dynamics of coastal landforms in South Africa

Every coastal landscape comprises different landforms that may exhibit different controls, dynamics and thus varying levels of resilience to forcing (Hapke et al., 2013; Schultz & Smith, 2016). Examples of the dynamics of the different major landforms found along the South African coast are now discussed (Table 1), with the aim of relating their dynamic behaviour to their potential for coastal resilience.

3.1. Coastal sand dunes

Coastal sand dune locations in South Africa have been mapped by Tinley (1985, p. 19) who recognized a number of dune types: bare; vegetated; related to topographic barriers; associated with temporary wetlands; and relict/gully eroded dunes. These are located in different positions around the coast, in particular in the southern Cape where headland – embayment systems dominate. However, in detail, these mapped locations are often incorrect and dune types are incorrectly assigned (Knight, 2021b). A morphological classification of coastal dunes in South Africa, however, identifies seven types: estuary barrier, headland bypass, mainland beach, prograding beach ridge, transverse, parabolic/migrating and climbing (Jackson et al., 2014). Rates of coastal dune migration have been examined in only a few studies, mainly from unvegetated transverse dunes located in the supratidal zone of sandy beaches, where these dunes respond dynamically to seasonal

Table 1. Key landform types and their contributions to resilience along the South African coast.

Landforms	Contribution of these landforms to resilience	Threats and vulnerabilities
Coastal sand dunes	• Buffer of coastal erosion as a topographic barrier • Sediment store for potential reworking between the dunes and beach • Substrate for plant and animal ecosystems • Store of organic carbon in vegetation and soil • Groundwater store and buffer for landward diffusion of salt water • Alteration of microclimate, as windbreak or firebreak for areas inland • Provision of ecosystem and environmental services for local communities and tourists	• Sea-level rise and wave erosion of the foredune foot • Infrastructure development, increased foot/vehicle traffic • Decreased indigenous species biodiversity • Agriculture/overgrazing • Deforestation, introduction of invasive species (e.g. marram grass *Ammophila arenaria*, sea buckthorn *Hippophae rhamnoides*, rhododendron *Rhododendron* spp.) • Fire (natural or caused by people) • Wind erosion and development of blowouts • Sand mining • Development of tourist facilities (car parking, caravan parks, campsites, toilets, cafes) within the dunes • Changes in groundwater position/recharge of dune slacks and ponds
Sandy beaches	• Dissipate wave energy • Buffer against sea-level rise and coastal flooding • Role as sediment store for longshore drift • As sites of recreation/tourism, contributing to societal socioeconomic and cultural resilience	• Sea-level rise and transgressive wave erosion of the shoreface • Storms and the effects of storm waves as extreme events • Sand mining on the beach or adjacent sand dunes, estuaries or nearshore • Changes in river mouth location • Geoengineering of sea walls, revetments, groynes, and development of the back-beach environment (tourist facilities, walkways, apartments) • Updrift developments that may impact on longshore sediment supply • Human overuse, pollution/trash • Human health risks – drowning, rip currents, sharks/jellyfish attacks in the nearshore • Sand dune development in the backbeach/supratidal zone, contributing to beach squeeze
River mouths and estuaries	• Sediment supply to sandy beaches • Barrier protects the river mouth/lagoon from wave erosion • River mouth/lagoon as a store of blue and green carbon • Sites of high biodiversity for plants (see Mangroves, below), animals and birds (including protection as Ramsar sites and Biosphere Reserves)	• Changes in river water and river sediment yield from the catchment inland • Decreased water quality as a result of industrial/agricultural pollution/runoff from within the catchment • Infrastructure development around the river mouth, leading to increased sedimentation/lagoon infilling, or increased erosion • Barrier breaching and increased exposure of the river mouth to wave erosion/increased salt water overwash into the lagoon • Changes in longshore sediment transport; can result in the barrier becoming thinner and thus more vulnerable to wave overwashing • Sea-level rise and barrier overtopping • Changes in barrier opening/closing behaviour, with impacts on lagoon processes, water quality and ecosystems

(*Continued*)

Table 1. (Continued).

Landforms	Contribution of these landforms to resilience	Threats and vulnerabilities
Mangroves	• Areas of higher sedimentation; buffer of wave erosion • Blue and green carbon store • Substrate for associated ecosystems, especially fish and invertebrates	• Water pollution or decreased water quality from incoming rivers or within lagoons, related to industry and agriculture • Sea-level rise and salt water transgression inland • Wave/storm erosion of the mangrove front • Invasive species • Climate change (water temperature, dissolved oxygen content) • Infrastructure development or encroachment into the mangrove area • Agriculture, livestock grazing, deforestation, wood harvesting on the mangrove fringe
Rocky shorelines	• Buffer of sea-level rise • Dissipation of wave energy across the rock platform	• Possibility of sudden cliff collapse • Vulnerable to sea-level rise, increased wave height and energy and enhanced shoreface erosion • Sea-level rise and migration of the intertidal zone, driving ecosystem responses • Effects of wave bores • Invasive rocky shoreline species • Pollution runoff from the adjacent land

changes in wind strength and direction. Tinley (1985, p. 207) gave backbeach dune migration rates in the Algoa Bay dune field of 4 m yr^{-1}, with migration rates in the inland dune field varying between undisturbed (0.1 m yr^{-1}) and disturbed areas (1.3 m yr^{-1}). Examples of calculated rates from different locations and different dune types along the South Africa coasts are 2.9 m yr^{-1} (La Cock et al., 1992), 3.2–12.3 m yr^{-1} (Knight & Burningham, 2019), 3.5 m yr^{-1} (Lubke & Sugden, 1990), 4.44–1.50 m yr^{-1} (Knight & Burningham, 2021), and 7.23–9.00 m yr^{-1} (Henrico et al., 2020). However, these values are calculated over different timescales and employ different methodologies (field, remote sensing), meaning that results from these studies cannot be easily compared. There are also statistically significant differences ($p < 0.01$) between summer (3.99–11.51 m yr^{-1}) and winter (3.55–9.94 m yr^{-1}) transverse dune migration rates (Knight & Burningham, 2021), which indicate the role of seasonal climate forcing in dune dynamics (Burkinshaw & Rust, 1993). A key element influencing dune migration rates is the relationship that the monitored dunes have to surrounding landforms in different coastal contexts. Sand dunes found adjacent to river mouths respond to variations in fluvial sediment supply (Knight & Burningham, 2022; Olivier & Garland, 2003), and this shows that dune dynamics may reflect other controls apart from wind climate. Lucrezi et al. (2014) showed that infrastructure development in South Africa decreases dune width and biodiversity, and thus the vulnerability of the dune system to climate or wave erosion. Sand dune rehabilitation strategies in South Africa have focused on encouraging vegetation growth, monitored through changes in biodiversity and soil properties (van Aarde et al., 1996, 1998; Ott & van Aarde, 2014), and mainly in response to disturbance by mining rather than for mitigation of climate impacts (Mentis & Ellery, 1994; Lubke et al., 1996). Previously, dune stabilization had been achieved through planting of the European marram grass *Ammophila arenaria* (Hellström, 1996), although now indigenous species are preferred as they can result in higher biodiversity and carbon sequestration potential (de Villiers et al., 1999; van Rooyen et al., 2013). A further outcome of vegetation growth is stabilization of the land surface, reduced dune movement and sediment yield from erosion (Hellström, 1996), and thus increased resilience to erosion (Hanley et al., 2014; Jackson et al., 2019).

3.2. Sandy beaches

There are few studies on the morphodynamics of sandy beaches in South Africa, but dissipative, reflective and intermediate beach states have all been identified (Harris et al., 2011a). Several studies highlight the role of storm waves as the driver of coastal erosion, in particular by steepening the shoreface and decreasing beach width (Smith et al., 2010; Corbella & Stretch, 2012a, b). Shoreline change is most significantly related to wave peak period and wave direction, and these attributes are influenced by episodic storms (Smith et al., 2013; Corbella & Stretch, 2012a). There are very little field-based data on the dynamics of sandy beaches, including short-term changes in beach profile and volume, although low-resolution but long term (1973–2010) profile data suggest a beach recovery response time of two years after storm events with a volume flux of 90 m^3 m^{-1} yr^{-1} (Corbella & Stretch, 2012b), reflecting the timescale of system resetting and thus the degree of resilience of such coastlines. It is not clear to what extent the dynamic behaviour of different beaches may vary spatially or temporally, or between different beach types (Harris et al., 2011a). Some previous work highlights the close coupling within integrated beach – dune systems in South Africa, where sediment moves from beach to dune storage and back again (Hellström, 1996), and where storm-forced reductions in beach width lead to reduced accommodation space for supratidal dune development (Knight & Burningham, 2021). However, volume fluxes and the rates of morphological change of the beach systems have not been widely presented. Systematic mapping of sandy beach width along the South African coast does not show consistent variations in gross morphological properties between different coastal stretches. However, it highlights how bedrock outcrops can act as pinning points, stabilizing the beach front and thus beach width variability, and reducing beach dynamics (Knight & Burningham, 2022). These bedrock-pinned beaches are therefore sites of higher resilience along sandy coasts.

Sandy beach dynamics may refer to variations in their volume, surface slope, intertidal width, supratidal width, surficial landforms (embryo dunes, beach cusps) or longshore volume fluxes. Different studies may measure one or several of these elements using different methods and this means that their results may not be comparable. At a site scale, monitoring of changes in beach properties over time has been undertaken in several studies in South Africa (e.g. Guastella & Smith, 2014; Mitchell et al., 2005). The most detailed beach morphological study is along different sectors of the KwaZulu-Natal coast, which describes the results of near-monthly beach surveys between 2011 and 2020 (Leuci et al., 2022). Seasonal variations in swell wave frequency and longshore processes give rise to variations in beach aggradation/erosion behaviour. Reduced fluvial sediment input and downstream sediment starvation from the development of the Port of Durban results in net beach erosion, with increased sediment yield and net aggradation in a down-drift direction. Such long-term variations in beach state have implications for coastline resilience, with beaches being more vulnerable where they are narrower and sediment-starved. Aeolianite and beachrock are also found extensively along sandy stretches of the eastern

South African coast (Cawthra & Uken, 2012; Wiles et al., 2018). Progressive development of these lithified coastal sediment through the late Quaternary has 'hardened' the coastline, increasing coastal resilience and providing a fixed substrate that can reduce net longshore sediment transport and promote differential erosion on 'harder' and 'softer' sandy beaches. There has also been consideration of how beach properties and dynamics can influence population viability and species richness of marine/intertidal macrofauna (Dye et al., 1981; Harris et al., 2013,). This highlights that beach dynamics can also influence ecological resilience (Kombiadou et al., 2019) and that this can arise as a result of different beach and environmental properties (beach geometry, sediment grain size, tidal/wave regime, seasonal/interannual volume flux) (Harris et al., 2013,).

3.3. River mouths and estuaries

The dynamics of river mouths in South Africa have been mainly investigated in terms of changes in the size, shape and open/closed status of the lagoons or small estuaries that are commonly found there. These water areas are impounded behind a sandy beach bar or barrier located at the end of the river mouth that separates the river from the sea (e.g. Cooper, 2001; Garden & Garland, 2005; Green et al., 2013; Magoro et al., 2020). Variations in river discharge cause changes in the position of the river channel, changes in river sediment supply and river/coastal geomorphic activity (Cooper et al., 1990; Cooper, 1989; Fernandes & Adams, 2016; Magoro et al., 2020; Marker, 2004; Pillay et al., 2003). A beach bar or barrier that extends across the river mouth serves to hold back freshwater in the lagoon at the river mouth, and separates the functioning of the river system from the coastal system that is influenced by waves and tides (Bate et al., 2017; Cooper, 2001). The development or erosion of this barrier by coastal longshore processes means that river mouths may be variously open, closed or partly open at different times, according to phases of wave overwashing and barrier breaching (Garden & Garland, 2005; Green et al., 2013; Magoro et al., 2020). Although measurements of rates of change of different elements around river mouths and tidal inlets can be made, these do not necessarily inform on system resilience where the major morphological control is the fronting barrier system (Green et al., 2013). Here, phases of barrier overwashing (wave forcing) and lagoon overspilling (river discharge forcing) reflect the exceedance of a critical threshold in system behaviour. It is likely that this behaviour is cyclic (Marker, 2000), by patterns of sediment redistribution by river channel migration, or by seasonal wave climate (Lubke & Webb, 2016; Pillay et al., 2003). This means that barrier resilience is also cyclic and in response to both fluvial and marine forcing.

3.4. Mangroves

Mangroves can offer significant coastal resilience as they can buffer coastal erosion and sea-level rise (Barbier, 2016; Blankespoor et al., 2017; Gedan et al., 2011). They can also be considered as a coastal 'landform' where their roots stabilize the substrate and encourage sediment aggradation, especially around the margins of river mouths (Adams, 2020; Charrua et al., 2020). Bedin (2001) showed a rapid rate of mangrove colonization across a developing delta as part of the Mhlathuze River estuary, KwaZulu-Natal, at initial rates of 20–55 ha yr^{-1} (1976–1982) and then at a steady 5.4 ha yr^{-1} (1986–1999). Mangrove ecosystems are found in river mouths and estuaries at 41 locations on the east coast of South Africa with around half of these sites being less than 1 ha in area (Steinke, 1999). Several studies have examined recent changes in mangrove area along the South African coast. For example, in the period 1982–1999 mangrove area in the Eastern Cape Province decreased by 6.5% with local extinction at three estuary sites (Adams et al., 2004). Analysis of changes in mangrove forest area at 17 sites in the Eastern Cape Province (1982–2012) shows a decrease at 9 sites and increase at 7 sites (one site shows no change) (Hoppe-Speer et al., 2015). Overall, however, there is a decrease in total mangrove area in the region by 12% over this time period. Rajkaran et al. (2009) showed that mangroves along the KwaZulu-Natal coast were only present in river estuaries that remained open to the sea for more than 56% of the time, in the period 1982–1999. When closed from the sea by a barrier, river mouths experience environmental stresses (higher water salinity and pore-water content) that result in a decrease in mangrove survival (Charrua et al., 2020; Hoppe-Speer et al., 2013). This is particularly the case for micro-estuaries formed at the mouths of small rivers (Bate et al., 2017) which, by virtue of their size, are sensitive to changes in rainfall inland (driving river discharge), lagoon water properties, and wave climate (driving longshore drift and lagoon barrier dynamics) (Charrua et al., 2020). Vertical and horizontal erosion and/or accretion rates in South African mangrove systems have not been evaluated, but rates elsewhere are highly variable, with averaged lateral erosion rates of 0.27–0.96 m yr^{-1} along mangrove coasts in Bangladesh, but with short-term storm-forced rates of 5 m yr^{-1} (Mullick et al., 2020). In India, decadal-scale shoreline erosion rates are 0.91–3.12 m yr^{-1} (Jayanthi et al., 2018). Vertical sediment accretion in Senegal is 0.2–0.3 cm yr^{-1} (Sakho et al., 2011). Thus, mangrove ‘landforms’ can change in both area and height. The impacts of climate change on the distributions and productivity of mangrove ecosystems in South Africa have been examined based on trajectories of historical data (Hoppe-Speer et al., 2015; Peer et al., 2018) and on future climate and ecological modelling (Yang et al., 2014). Both these approaches suggest a poleward spread of mangrove distributions but a net decrease in area, mainly as a result of human activity (agriculture, pollution, urbanization) rather than sea-level rise and coastal squeeze. However, likely sites at which these changes may take place have not yet been identified (Peer et al., 2018).

3.5. Rocky shorelines

Rocky shorelines include the morphological elements of rock cliffs and rock shore platforms. Despite being relatively common in South Africa (Emery & Kuhn, 1982; Illgner, 2008), rocky shoreline morphology and dynamics have not been examined in detail, either along extensive shore platforms or as part of headland – embayment systems of sandy shorelines (Knight & Grab, 2015). Different rock landforms along the Eastern Cape coast include prominent sea cliffs whose heights are geologically controlled, in addition to caves, arches and stacks (Illgner, 2008; Knight & Grab, 2015). Rock headlands can provide accommodation space within their intervening embayments for sediment accumulation and can therefore protect these deposits from erosion by the process of wave refraction (Shaw et al., 2001). Coastal caves in South Africa are key sites for the preservation of geological records of Quaternary coastal environmental, archaeological and sea-level changes (Hendey & Volman, 1986; Jacobs et al., 2003), and based on different radiogenic dating methods are over 1 million years old (Pickering et al., 2013). This may in turn indicate the resilience of rock coast features in the landscape, and their survival over multiple Quaternary climate cycles.

Most work along South African rock coasts has been undertaken on shore platforms where microscale variations in rock surface hardness and weathering features reflect differential exposure to subaerial weathering (which softens the bedrock surface) and wave erosion (which removes weathered rock revealing a harder bedrock surface) (Knight & Burningham, 2020a, b). Wave detachment of bedrock blocks takes place in the lower part of the platform below mean high water spring tide positions; wetting and drying associated with wave-splash around highest astronomical tide positions; and land surface runoff in a landward position on rock platforms above highest astronomical tide (Knight & Burningham, 2020a). Bioerosion takes place mainly in seaward locations. Rock platform erosion rates have not been calculated locally, but long term (1973–2003) microerosion monitoring in New Zealand yields a rate of 1.09 mm yr^{-1} (Stephenson et al., 2010). However, such an averaged rate should be considered as highly spatially and temporally variable (Naylor & Stephenson, 2010). Rock cliff collapse or rock platform erosion can potentially protect the rocks behind from wave attack, reducing future erosion.

Different molluscan and macrophyte ecosystems are also found along rocky shorelines in South Africa, and these have been examined in terms of their relationships to bedrock properties and wave regime (Bustamante & Branch, 1996; Dye, 1998; Tucker et al., 2017). Sink et al. (2005) also identified different rocky shoreline intertidal ecosystems in KwaZulu-Natal, thus different biogeographical regions, according to water temperatures and therefore upwelling conditions. The growth of organisms on rock surfaces can also decrease wave velocity and protect against rock erosion (Baxter et al., 2022; Gowell et al., 2015). Ecological resilience along rocky shorelines therefore arises where the shoreline itself provides suitable habitats for certain species, enhancing coastal biodiversity (Malherbe & Samways, 2014), and where ecosystem development contributes to coastal protection (Mead et al., 2013).

4. Coastal landforms as ‘green infrastructure’

This survey of different coastal landform types in South Africa highlights their potential to exhibit resilience to coastal forcing (Table 1). As such, these landforms can be considered as ‘green infrastructure’ that acts as a buffer against coastal processes such as wave erosion and sea-level rise (Ruckelshaus et al., 2016; Sohn et al., 2021; Sutton-Grier et al., 2018), and can thus reduce hazard risk and impacts, and promote resilience (Kombiadou et al., 2019; Monteiro & Ferreira, 2020; Saleh & Weinstein, 2016). The concept of green infrastructure emphasizes how the three-dimensional nature of coastal landforms can be used in the same way as hard engineering structures to reduce coastal hazard impacts (Cohn et al., 2022; Pontee et al., 2016; Schoonees et al., 2019). The role of coastal landforms in buffering coastal change and providing the context for sustainable coastal management has been examined in several studies globally (Chang & Mori, 2021; Silva et al., 2019; Sohn et al., 2021). Most commonly, such green infrastructure has been framed in the context of providing a physical barrier that helps protect against negative coastal change – for example, a sand dune ridge that has a greater height than the height of any incoming waves (Kombiadou et al., 2019; Ranasinghe & Stive, 2009). This is, however, a very narrow definition of the meaning and application of green infrastructure. This is because coastal landforms do not just provide resilience against *physical* change (e.g. beach width, volume), they can also promote the resilience of the *properties* of the coastline, such as its environmental and ecosystem services (Spalding et al., 2014). The ability of coastal properties to maintain or enhance these environmental and ecosystem services (Knight, 2021a) is important in the context of climate change. For example, clearing invasive plants, maintaining boardwalks, planting unstable sand surfaces and fencing off areas such as dune slacks are management strategies that can enhance coastal dune ecosystems, protect endangered species, encourage carbon storage, and reduce erosion (Itzkin et al., 2020; Keesstra et al., 2018; Morris et al., 2019). These are all strategies that can promote dune system resilience to climate change (e.g. Farrell & Connolly, 2019; Itzkin et al., 2020), independent of a dune system existing as a geomorphic barrier. This highlights that considering the natural resilience of coastlines, and then identifying ways in which management strategies can strengthen this resilience, can help reduce coastal hazard risk and impacts (Hanley et al., 2014; Knight & Goff, 2016; Schultz & Smith, 2016). Thus, coastal landforms can provide 'nature-based solutions' to environmental and climate changes, both locally and globally. The potential of coastal landforms in South Africa to be used as 'green infrastructure' as part of coastal management strategies is now examined (Table 2). However, most work on coastal management policies and practices has focused on the legislative context of coastal management, the nature of engagement with stakeholder communities and developing frameworks for management decision-making (e.g. Colenbrander, 2019; Goble et al., 2017, 2019, 2020; Taljaard et al., 2019). There have been few studies that have considered the management of coastal landscapes, their properties and dynamics, or that have employed ongoing monitoring or modelling of their behaviour to evaluate the success of management strategies. In South Africa, these activities have been undertaken in three major contexts, as described in the literature.

(1) *Estuary and river mouth* studies show how anthropogenic changes in river dynamics can impact on estuary sedimentation. For example, damming along the Umgeni River (KwaZulu-Natal) from the 1980s onwards resulted in a decrease in river discharge, decreased downstream sediment yield, and fining of sediment reaching the river mouth (Garland & Moleko, 2000). Land use change in the Salt River catchment (Eastern Cape) has influenced sedimentation in the lower part of the estuary, and channel migration patterns (Marker, 2004). The sensitivity of estuary ecosystems to pollution and other anthropogenic changes has motivated different management strategies, especially in estuaries whose mouths may be periodically closed to the sea, which can negatively impact on water quality, benthic and planktic organisms, and sediment dynamics (Claassens et al., 2020; Whitfield et al., 2012). As a result, controlled artificial breaching, as was done in the Umdloti River estuary (KwaZulu-Natal) in February 2004, can be used to drain anoxic lagoonal water. Artificial breaching also worked successfully on the Nkongweni River mouth (Margate, KwaZulu-Natal) where lagoon drainage relieved pressure on coastal infrastructure (Guastella et al., 2014). However, a similar breaching strategy used in the St Lucia estuary system from the mid-1950s to 2001 resulted in seawater incursion and hypersaline conditions, causing

Table 2. Management strategies that can increase the resilience of coastal landforms, drawn from the literature worldwide but with specific reference to South Africa.

Landforms	Actions and their likely outcomes
Coastal sand dunes	• Banning new sand mining and requiring full ecological and geomorphological rehabilitation of existing/closing sand mines • Restrict groundwater extraction • Revegetation/planting for increased dune surface stability • Sand or brushwood fences, to reduce wind speed and encourage sand deposition • Planting and wind fencing in the supratidal zone, to encourage embryo dune formation • Moving existing beach sand to engineer an artificial dune, which is then planted and stabilised • Clearance of scrub and invasive species, to promote indigenous plant species growth • Maintain dune slacks and ponds by shallow excavation, to encourage habitat diversity especially for birds and amphibians • Construct and maintain boardwalks/fences to keep pedestrians from wandering • Fencing off areas seasonally for ground-nesting birds and flowering of rare plants • Provide litter bins and information signs to guide good visitor behaviour
Sandy beaches	• Beach nourishment by dredging/pumping to increase beach width • Building groynes to obstruct or slow longshore drift • Planting of the supratidal zone to encourage embryo dune growth and to increase the surface elevation of the supratidal zone • Build or maintain offshore shoals/surf breaks to decrease nearshore wave height • Where the beach is narrow or with high wave energy: stabilize the landward position of the beach with a sloping seawall, gabion, tetrapods, riprap • Build and maintain a landward barrier to the beach to prevent storm wave overwashing or sand blow inland, especially where urban development gets very close to the beach. This barrier may include (hard engineering): a seawall, revetment, gabion, riprap (soft engineering): engineered beach ridge, planted low dune or sand fences • Support beach users by providing car parking, toilets and other facilities, places to dispose of trash, accessible entry to the beach environment, information and safety/signage boards
River mouths and estuaries	• Manage any river mouth barrier, by artificial breaching/dredging (to drain lagoon water or to encourage seawater ingress) or building up the barrier (to keep water in the lagoon in dry periods) • River mouth stabilization by jetties/training walls • Ensure a low-elevation riparian fringe around river/lagoon margins, to encourage plant succession, reduce river flow velocity, promote carbon storage and support other plants/animals • Manage and increase water quality within the river system, in particular from agriculture, industry and wastewater treatment plants • Monitor water quality within the lagoon to reduce the likelihood of anoxic conditions and water stratification in hot/dry periods, removal of invasive species (e.g. water hyacinth *Pontederia crassipes*) • Sea defences around tidal flats/saltmarsh around estuaries can be breached to allow for tidewater ingress, which increases tidal flat elevation through enhanced deposition, and increases biodiversity and carbon storage • Banning sand mining within estuaries and river mouths • Ensuring that roads/bridges/railways spanning the river mouth or estuary have pilings that do not interfere with water or sediment flow
Mangroves	• Replant areas of lost vegetation • Decrease pollution from upstream industrial and agricultural sources • Maintain tidal creeks to prevent them from closing up due to sediment aggradation • Manage the activities of other mangrove users (e.g. farmers, wood harvesters) • Remove any invasive plant species • Clear overgrown mangrove patches to encourage fresh regrowth and provide softground habitats for fish/invertebrates • Restrict infrastructure development that would either reduce the mangrove area or cause enhanced erosion of the mangrove fringe

(*Continued*)

Table 2. (Continued).

Landforms	Actions and their likely outcomes
Rocky shorelines	• Rock armouring on the landward edge of rock platforms, to reduce wave impacts on rock cliffs or infrastructure • Understand the landward limit of extreme tide/wave events and do not allow infrastructure development seaward of this limit • Monitor the stability of rock cliffs or caves, warn users to keep away from these areas • Support unstable rock slopes and reduce mass movements by rock bolts, rock nets/mesh, geotextiles, planting of soft-rock cliffs, grading slopes. This can also support plant biodiversity and provide bird nest sites • Reduce risk of waves to users by providing safety equipment and safety warning signage • Support intertidal ecosystems by ensuring that rock pools are maintained, and removing invasive macrophyte and mollusc species • Reduce land-derived water runoff onto the rock platform

die-back of shore vegetation (Taylor et al., 2006). Dredging has also been done to maintain the river mouth channel during low rainfall periods: 600,000 m^3 of sediment accumulated at the St Lucia estuary mouth between February 1988 and November 1989, of which 466,000 m^3 was subsequently dredged, although this has not resolved ongoing problems of sediment aggradation (Wright & Mason, 1993). Floods and droughts also cause problems of estuary mouth stability and infrastructure erosion in other estuary systems (Schumann, 2021). Catchment land use changes, in particular agricultural practices and invasive species, can lead to macrophyte and invertebrate habitat loss as well as changes in estuary water quality and the potential for coastal erosion (Adams, 2020; Fernandes & Adams, 2016; de Villiers et al., 2021). For example, pollution from sugarcane plantations has reduced natural habitat area and species richness in the uMkhomazi and Mvoti estuaries (KwaZulu-Natal) (Fernandes & Adams, 2016), and this can be considered to have resulted in estuary system resilience (e.g. Claassens et al., 2020; Rajkaran et al., 2009).

(2) *Sand dune revegetation and afforestation* has taken place along some South African coasts over the last ~100 years, undertaken as a management strategy to stabilize dune surfaces and reduce dune and blown sand migration (Hertling & Lubke, 1999; Lubke, 2022). The causes of sand dune destabilization in South Africa include overgrazing, deforestation/vegetation clearance, sand mining, fire, population pressure through tourism and development, coastal erosion and the development of new dunes by river mouth migration (Hellström, 1996; Lubke & Sugden, 1990; Mentis & Ellery, 1998). Sand dune or blown sand movement is seen as a problem where it impacts on people or infrastructure, by blocking roads or silting up drainage channels (Nichols, 1996; La Cock & Burkinshaw, 1996; Lucrezi et al., 2014). Dune revegetation and planting is a recognized standard coastal management strategy and has been undertaken along many sandy coasts worldwide (e.g. Hayes & Kirkpatrick, 2012; Lithgow et al., 2013). Although its impacts are most clearly evaluated in terms of reduced dune migration and sediment transport (Nichols, 1996), planting of non-native and often invasive species such as European marram grass (*Ammophila arenaria*) and *Acacia* spp. can have significant impacts on plant and animal biodiversity (Ott & van Aarde, 2014; van Aarde et al., 1996). Lubke (2022) reviewed the history of marram grass

revegetation strategies and successes on sand dunes along the temperate Eastern Cape coast, highlighting that it helps in dune stabilization and does not tend to outcompete indigenous species. This should also be considered in combination with sand fences, which reduce windspeed and encourage sand deposition to form embryo dunes (Itzkin et al., 2020). Along the KwaZulu-Natal coast under subtropical conditions, dune revegetation appears to be a less common strategy, but here the major driver of sand dune degradation is sand mining, followed by piecemeal environmental rehabilitation (Lubke et al., 1996; Mentis & Ellery, 1998; van Aarde et al., 1998). Stands of high-density secondary succession and climax dune forests in KwaZulu-Natal stabilize much older backdune systems (Goble et al., 2014) and thus can be considered to increase the resilience of the dune cordon as a whole.

(3) *Beach and shoreline manipulation* includes a number of management strategies. Beach nourishment focuses on maintaining sediment supply to sandy beaches, thus maintaining beach width and promoting resilience, and often as a direct response to the effects of inappropriate coastal management updrift (Castelle et al., 2009). Infrastructure development and building of groynes/piers around the Port of Durban in the period 1982–1988 led to downdrift sediment starvation to KwaZulu-Natal beaches north of Durban. After 1990, around 265,000 $m^3\ yr^{-1}$ of marine sand was pumped onto the beaches in order to broadly maintain shoreline position following sediment redistribution by longshore processes (Rautenbach & Theron, 2018). The continual need for artificial beach maintenance along this coastal stretch, caused by Port of Durban development, has led to this coastline being deemed to be on 'life support', where it cannot survive without regular human intervention (Cooper & Jackson, 2019). Coastal reclamation, by extending the land surface seaward by port, harbour or urban development, can also be considered as a strategy to develop coastal cities and to increase the resilience of the coastline by stabilizing it with built structures. Coastal reclamation has been done extensively in Cape Town and also around the ports of Durban and Richards Bay (Nichols, 1996), and there is a government White Paper on this topic (2017). However, such development can create further problems with changing coastal erosion/deposition patterns, and may increase flood risk and the vulnerability of infrastructure to extreme events (e.g. Griggs & Patsch, 2019). Coastal setback, which is based on a coastal buffer zone of varying width (or height above mean sea level) within which development is restricted, is also promoted in South Africa as a means to manage coastal risk (Colenbrander et al., 2015; Desportes & Colenbrander, 2016). However, this is based on risk aversion rather than working with coastal properties to increase resilience and reduce climate change impacts.

As outlined above, these three major approaches to coastal management in South Africa only apply to certain coastal types like sand dunes or estuaries. This is not to say, however, that coastal management has not been undertaken in other ways or in different coastal contexts. However, it is notable that many other coastal types (like rock coasts) and many low-population rural coasts have not been systematically evaluated for their biophysical dynamics, the human activities that take place there, or their management needs. There is simply a lack of data on many coasts. As a result, Table 2 lists a range of potential management interventions that can help increase coastal resilience. These are drawn from practices globally but focusing in particular on the physical landforms and properties the different coastline types found in South Africa that are discussed herein, and that are presented in Table 1. Many of the suggested interventions (Table 2), however, have not been done extensively or even at all in South Africa, but these can form part of a menu of options for increasing coastal resilience, and working with – not against – the natural biophysical processes that take place along coastlines on different scales (Cohn et al., 2022; Hamin et al., 2018; Morris et al., 2019; Spalding et al., 2014).

5. Discussion

5.1. Resilience and coastal systems

Resilience is a useful concept when applied to coastal landforms and systems, because it describes the nature of changes to landform properties in response to forcing by climate and/or human activity. Such forcing – response relationships are the basis of understanding coastline responses to climate change in the Anthropocene (Kittinger & Ayers, 2010; Luijendijk et al., 2018; Martínez et al., 2017). Despite these advantages, the focus of coastline analysis in South Africa has been on mapping spatial vulnerability, not resilience, and consideration of the role of human activity along different coastal stretches (Musekiwa et al., 2015; Palmer et al., 2011). These few studies are also very generalized and do not explore in detail either the physical or human environments along these coasts. However, socioecological vulnerability has been well described in the literature (e.g. Bevacqua et al., 2018; Lloyd et al., 2013) and is especially important in the developing world where coastal populations may be poorer as well have closer relationships to the environmental and ecosystem services provided by the coast (Ballesteros & Esteves, 2021). It is very likely that this is also significant in South Africa although this has not been well explored, especially in rural areas (Palmer et al., 2010). Reconciling and considering the interplay of biophysical and socioecological resilience (vulnerability) along coasts, as has been done in other environments such as mountains (Knight, 2022b), should be considered as a key future research aim (Nichols et al., 2019; Glaser & Glaeser, 2014; Martínez et al., 2017; Sutton-Grier et al., 2018).

A key factor in resilience is the role of coastal geoengineering (sea walls, revetments, groynes, river mouth jetties, port/harbour construction) and changes in land use in the coastal hinterland (affecting runoff and sediment yield). These can affect the properties, dynamics and therefore the resilience of coastal landforms (e.g. Brown et al., 2016; Floerl et al., 2021; Griggs & Patsch, 2019; Hamin et al., 2018; Kittinger & Ayers, 2010). Overwhelmingly, geoengineering has resulted in negative impacts on coastal landforms and ecosystems, in which system integrity, connectedness and service provision have been degraded, resulting in decreased resilience (Berry et al., 2014; Schoonees et al., 2019; Tejada et al., 2007). However, more recent approaches to coastal (hard and soft) geoengineering such as managed realignment, dune afforestation, sandscaping and beach nourishment can increase coastline resilience when used appropriately (Nichols et al., 2019; Hamin et al., 2018; Masselink & Lazarus, 2019). These can also contribute to the morphological development of coastal landforms, by encouraging dune and beach growth and ecosystem change, thus making these landforms more ‘green infrastructure’ that can better withstand the impacts of climate forcing.

5.2. Nature-based solutions and green infrastructure to increase coastal resilience

There has not been a detailed examination of how green coastal infrastructure can be engineered or managed to provide nature-based solutions to coastal change impacts (Cohn et al., 2022; Floerl et al., 2021; King et al., 2021; Saleh & Weinstein, 2016). Studies have mainly focused on managing the properties of specific coastal landforms such as sand dunes (De Jong et al., 2014; Eichmanns et al., 2021) rather than coastal landscapes as a whole. However, understanding the sediment system dynamics of sandy coastlines (Knight & Goff, 2016) can better inform on not only their resilience but also how changes in the properties of dynamics of one landform can impact on other landforms or coastal properties (Floerl et al., 2021) (Figure 1). The concept of green (or ecological) infrastructure has also not been widely discussed in South Africa (e.g. Malan & Swart, 1997; Mbopha et al., 2021) although the ideas of riparian vegetation or footslope wetlands as a flood buffer, or bioremediation of water pollution in riparian wetlands, are well established in the literature in South Africa (e.g. Abiye et al., 2018; Belle et al., 2018), albeit without using the term ‘green infrastructure’. Table 2 describes the management activities that can be employed to increase the resilience of specific coastal landforms as green coastal infrastructure. This highlights the potential of these activities to positively impact on both the maintenance of the coastal landforms themselves (in providing morphological resilience), and landform properties through their environmental and ecosystem services. National- and regional-scale coastal management strategies employing nature-based solutions and green infrastructure have been developed in the USA, the Netherlands, the UK and Australia, and these have focused on both specific landforms and coastal systems as a whole (e.g. Cohn et al., 2022; Davis et al., 2022; Morris et al., 2019). As such, there is an appreciation of coastal landforms as green infrastructure, and this is embedded as part of (some) coastal management strategies. However, these concepts have not really been considered in South African coastal management strategies at all, although the importance of landforms and ecosystems generally is implicit rather than explicit throughout.

5.3. Promoting green infrastructure and nature-based solutions for coastal management in South Africa

In South Africa, coastal management is undertaken at different levels by national, provincial and municipal governments under the Integrated Coastal Management Act (Act No. 24 of 2008), which is also informed by the Natural Environment Management Act (Act No. 107 of 1998) and other relevant instruments including the Coastal Management Policy Programme (1992–97), the National Water Act (Act No. 36 of 1998), and the Biodiversity Act (Act No. 10 of 2004), amongst others. Goble et al. (2014, pp. 168–169) present a table outlining the roles and responsibilities of different spheres of government in terms of the Integrated Coastal Management Act, and this highlights the multiple contexts in which coastal management takes place in South Africa (Celliers et al., 2015; Colenbrander et al., 2015; Desportes & Colenbrander, 2016; Guastella et al., 2014). Although this provides the legislative and policy framework for coastal management in the country, the strategies enacted in any one place may be highly variable, related to local expertise, finances and management priorities (Goble et al.,

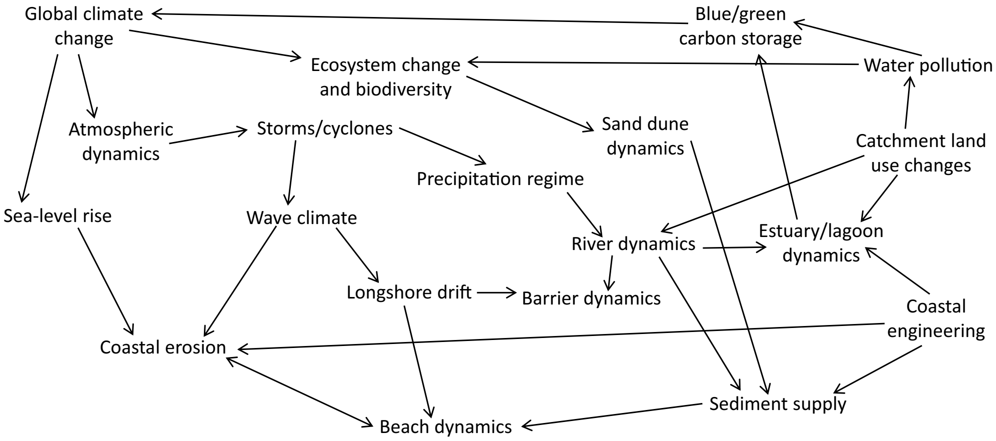

Figure 1. Schematic model of how coastal resilience can be enhanced through working with the 'green infrastructure' of existing coastal landforms and their properties.

2020). The outcome is that this can lead to inconsistencies and contradictions in coastal management practices.

A management approach that works with – not against – the natural sedimentary and ecological processes of coasts (Hanley et al., 2014; Knight & Goff, 2016; Sutton-Grier et al., 2018) can more effectively increase biophysical resilience and reduce hazard impacts whilst also promoting sustainable socioeconomic development of local communities and thus socioecological resilience (Floerl et al., 2021). Coastal resilience in its totality in South Africa and elsewhere can be enhanced following two main approaches (see examples in Table 2):

- Supporting the continuation or the enhancement of the natural physical and ecological processes that take place in specific coastal environments (biophysical resilience). In allowing sediments to move from one location to another within the coastal zone (by wind, waves, tides, river flow), sedimentary landforms can naturally readjust to changing environmental conditions (De Jong et al., 2014; Hanley et al., 2014). In this way, they can be incorporated as soft (rather than hard) engineering structures (Gijsman et al., 2021; Pontee et al., 2016; Schoonees et al., 2019) that can contribute to coastline protection. This has been done specifically, for example, on mangroves (Gijsman et al., 2021), wetlands (Liu et al., 2021; Van Coppenolle & Temmerman, 2019), sand dunes (De Jong et al., 2014) and beaches/barriers (Hanley et al., 2014; Orchard & Schiel, 2021). Coastal ecosystems can be maintained and enhanced where indigenous species exist in areas that are protected from development or human overuse, and where invasive species are removed (De Battisti, 2021; Lithgow et al., 2013). This includes working with existing ecosystem succession and ecological conditions in order to achieve habitat rehabilitation (Ott & van Aarde, 2014; van Aarde et al., 1996). These ecosystems can contribute to coastal risk reduction by their stabilizing effects on the land surface (Spalding et al., 2014) as well as their contribution to carbon storage, biodiversity and ecosystem services (Lithgow et al., 2013; van Rooyen et al., 2013).

- Building the adaptive capacity of coastal communities (socioecological resilience). This focuses on understanding the relationship between coastal users and the coastline ecosystem and environmental services that contribute to socioeconomic and cultural activities and human wellbeing. In the developing world, coastal communities may be impoverished and have greater vulnerability, lower adaptive capacity and lower socioecological resilience (Almutairi et al., 2020; Ferro-Azcona et al., 2019). They may also rely on coastal properties and resources for livelihoods (through agriculture, fishing, tourism). Enhancing these coastal resources while also diversifying socioeconomic activity can better safeguard coastal communities against coastal change.

Biophysical and socioecological resilience are connected to each other, and studies highlight how one can enhance the other (e.g. Arkema et al., 2017; McFadden, 2010; Sutton-Grier et al., 2018; Trégarot et al., 2021). The nature of these interconnections is summarized in Figure 1, which describes the interplay between coastal biophysical and socioecological properties and dynamics, and how these can contribute to resilience (Silva et al., 2019). This means that effective and sustainable coastal management focusing on the integrity and dynamics of coastal landforms as an integrated system can help enhance the physical landscape and provide environmental and ecosystem services, and so in turn lead to wider societal and socioeconomic benefits.

6. Conclusions and future research directions

Resilience is a contested and multifaceted topic, but in different physical environments, biophysical and socioecological resilience (and its flip side, vulnerability) can be identified. In coastal environments, biophysical and socioecological properties and processes are strongly interlinked through the provision of ecosystem and environmental services and resources. However, changes in coastal environments globally – caused by ongoing climate change as well as increasing human development, land use change and pollution – are decreasing the resilience of natural coastal processes and landforms (Figure 1). This is a key issue when making use of coastal landforms as 'green infrastructure' (Hanley et al., 2014). These landforms also support the ecosystem and environmental services that contribute to socioecological resilience; thus, the effective management of coastal landforms can lead to positive impacts for coastal communities. This is particularly the case in the developing world such as South Africa.

Relationships between coastal resilience and risk management under climate change is important for the sustainable development of coastlines and coastal communities (Saja et al., 2021; Wood et al., 2021). To adequately address coastal resilience in countries such as South Africa, three systemic requirements are needed:

(1) An integrated Earth Systems approaches to coastal risk, vulnerability and morphodynamics, that is evidence-based and founded on an understanding of the dynamics of coastal biophysical systems (Figure 1). This is currently lacking in many areas of the world, including many South African coasts, and this means that (when done) managers are having to make decisions without the best information being available;

(2) Routine and ongoing monitoring of coastal properties and dynamics across different coastal sectors and different coastline types. This can include both biophysical and socioecological elements of coastal landscapes and include a combination of field and remote data types;
(3) Engagement with stakeholder communities, not just at the outset but as co-partners in coastal management at the local level. This is currently missing in many locations and contexts but is also important in terms of education, community empowerment and governance.

Employing these approaches as well as specific management strategies appropriate to particular coastal types (Table 2) can result in positive outcomes for both coastal landforms and communities.

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