ELEMENTA
Science of the Anthropocene

Pfaff, MC, et al. 2019. A synthesis of three decades of socio-ecological change in False Bay, South Africa: setting the scene for multidisciplinary research and management. *Elem Sci Anth,* 7: 32. DOI: https://doi.org/10.1525/elementa.367

REVIEW

A synthesis of three decades of socio-ecological change in False Bay, South Africa: setting the scene for multidisciplinary research and management

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Over the past three decades, marine resource management has shifted conceptually from top-down sectoral approaches towards the more systems-oriented multi-stakeholder frameworks of integrated coastal management and ecosystem-based conservation. However, the successful implementation of such frameworks is commonly hindered by a lack of cross-disciplinary knowledge transfer, especially between natural and social sciences. This review represents a holistic synthesis of three decades of change in the oceanography, biology and human dimension of False Bay, South Africa. The productivity of marine life in this bay and its close vicinity to the steadily growing metropolis of Cape Town have led to its socio-economic significance throughout history. Considerable research has highlighted shifts driven by climate change, human population growth, serial overfishing, and coastal development. Upwelling-inducing winds have increased in the region, leading to cooling and likely to nutrient enrichment of the bay. Subsequently the distributions of key components of the marine ecosystem have shifted eastward, including kelp, rock lobsters, seabirds, pelagic fish, and several alien invasive species. Increasing sea level and exposure to storm surges contribute to coastal erosion of the sandy shorelines in the bay, causing losses in coastal infrastructure and posing risk to coastal developments. Since the 1980s, the human population of Cape Town has doubled, and with it pollution has amplified. Overfishing has led to drastic declines in the catches of numerous commercially and recreationally targeted fish, and illegal fishing is widespread. The tourism value of the bay contributes substantially to the country's economy, and whale watching, shark-cage diving and water sports have become important sources of revenue. Compliance with fisheries and environmental regulations would benefit from a systems-oriented approach whereby coastal systems are managed holistically, embracing both social and ecological goals. In this context, we synthesize knowledge and provide recommendations for multidisciplinary research and monitoring to achieve a better balance between developmental and environmental agendas.

Keywords: Ecosystem-based management; Integrated coastal management; Marine ecosystem; Review; Cape Town; Coastal system; Climate change; Human dimension

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1. Introduction

The past 30 years have seen a global paradigm shift in natural resource management practices, from a sector-by-sector approach, whereby resources are largely managed in isolation, towards system-oriented multistakeholder frameworks. This shift has given rise to now widely accepted concepts of ecosystem-based management and integrated coastal management (ICM). In concert, research and monitoring practices have shifted towards multidisciplinary assessments of ecosystems, which benefit from an integrated approach to data collection and analyses (Petitgas and Santos Vásquez, 2018). Modern technologies, such as automated systems and various remote sensing tools, provide opportunities for greater data coverage; however, their optimal deployment is contingent on an understanding of knowledge gaps and data requirements from multiple disciplines, including mathematical, physical, biological and social sciences. A more integrated approach is of particular importance when a large number of stakeholders draw resources from a limited area, and sustainable solutions are of imminent importance to the livelihoods of many people. Such a case is presented here for False Bay, South Africa, a large marine embayment near the metropolis of Cape Town.

False Bay is a southward facing bay of almost 1,000 km^2, bounded by the Cape Peninsula to the west and Cape Hangklip to the east (**Figure 1**). Sailors returning from the east occasionally mistook Cape Hangklip for Cape Point (at the southwestern tip of Africa) and navigated into the 'false bay' instead of around the Cape Peninsula to reach Table Bay; hence the name False Bay. Due to its proximity to the rapidly expanding urban center of Cape Town, the bay has been a site of considerable socio-ecological importance since before the Dutch colonization of the Cape region in 1652.

The oceanography of False Bay is influenced by contrasting circulation patterns and is highly dynamic at sub-seasonal to decadal time scales (Dufois and Rouault, 2012). Conditions range from cold, seasonally pulsed upwelling events typical of South Africa's southwest coast (Shannon and Field, 1985; Lutjeharms and Stockton, 1991; Largier et al., 1992) to periodic warm-water intrusions from the Agulhas Current system off the southeast coast (Shannon and Chapman, 1983). This range of conditions provides for extraordinary biological diversity (Awad et al., 2002; Griffiths et al., 2010). In pre-colonial times, the bay was already a target for intensive exploitation by the Khoisan hunter-gatherers as evident from shell middens from the past 10,000 years (Goodwin and Peers, 1953). Commercial fishing commenced in the late 1600s shortly after the Dutch settled in the Cape (Griffiths et al., 2005). Over the past 100 years, over-exploitation of various fish stocks has become increasingly apparent (Griffiths, 2000). Owing to persistent user conflict, various fishing practices have been prohibited within the bay, including demersal trawling (in 1924), boat-based purse seine and gill netting (Griffiths et al., 2005). Meanwhile, the substantial increase of the human population of greater Cape Town from about 1.6 million residents in 1980 to a projected almost 4 million in 2018 (Statistics South Africa, 2016), along with the associated infrastructure developments, have intensified anthropogenic pressures on False Bay including pollution, eutrophication, introductions of invasive alien species, habitat modification and over-exploitation of marine living resources.

Amidst growing awareness of anthropogenic threats, the value of False Bay and its ecosystem infrastructure and services has been recognized increasingly (Turpie and de Wet, 2009). Large portions of the bay are currently part of conservation areas, which include marine protected areas (MPAs) with various restricted and controlled-use zones. The effectiveness of MPAs under conditions of insufficient capacity to manage them remains a topic of global concern (Gill et al., 2017) and high levels of illegal fishing in False Bay inclusive of protected areas underscores the need to

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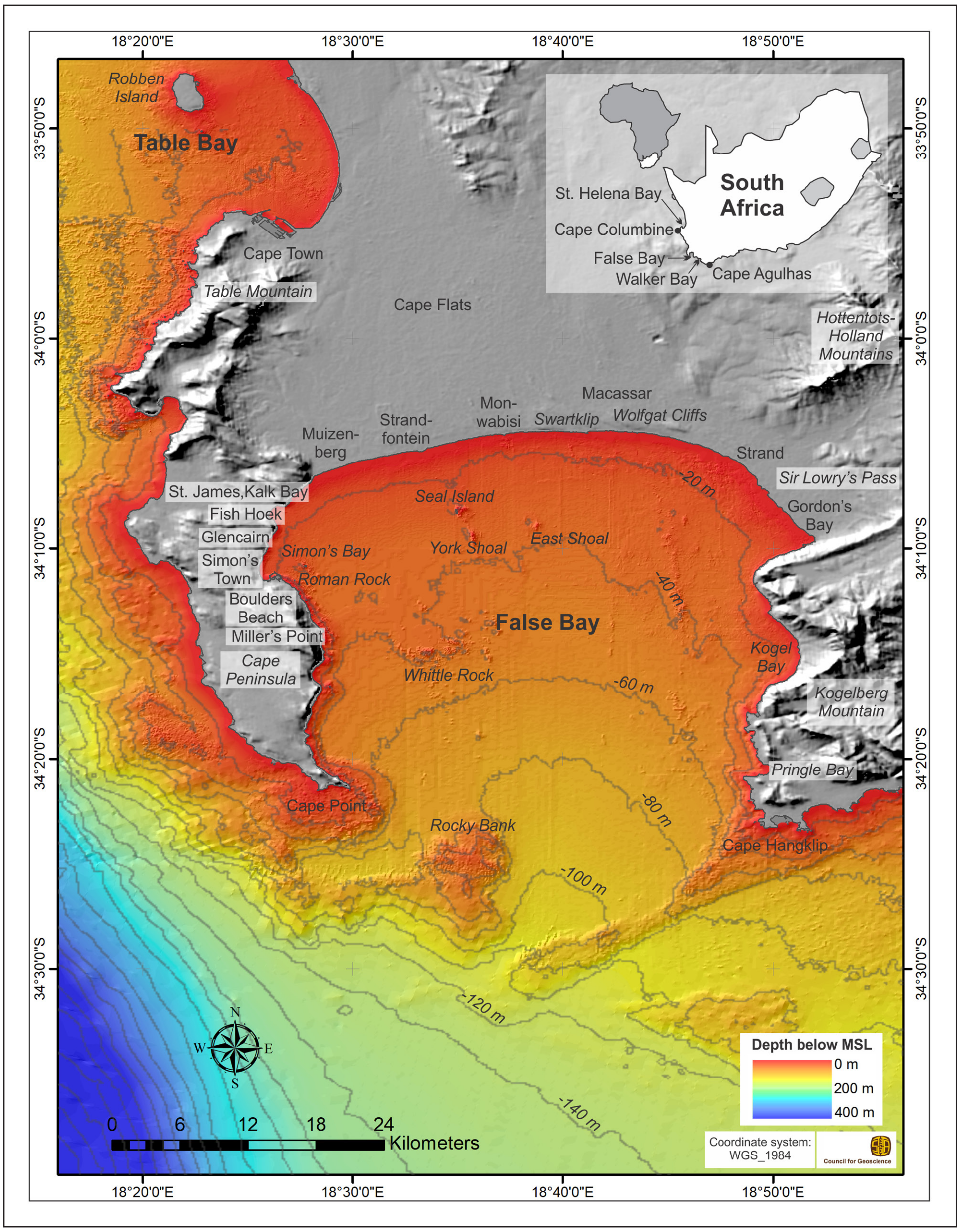

Figure 1: Bathymetry chart of False Bay and the Cape Peninsula. Names of places mentioned in the text are shown here. Source: Council for Geoscience, South Africa. DOI: https://doi.org/10.1525/elementa.367.f1

revisit means of effective enforcement locally. Globally and in South Africa, the need for a more human-centered approach to protected area management has been highlighted, with emphasis on appropriate stakeholder involvement in protected area design and processes, the generation of complementary livelihoods and the equitable sharing of benefits between historically divided segments of society that still persist today (Sowman et al., 2011; Conference of the Parties to the Convention on Biological Diversity 10th Meeting, Decision 31). In general, creating a balance between historically disadvantaged and privileged societal and racial groupings remains the central challenge of South Africa's political and social system, despite considerable transformation since 1994.

In the past few decades, substantial climate-change effects in the coastal and marine environments of South Africa have become evident from measurable ecological changes. Since the 1980s, wind-driven upwelling has increased in the South (Rouault et al., 2010; Blamey et al., 2012), extreme temperature events have become more frequent (Schlegel et al., 2017) and the sea level has risen (Mather et al., 2009). Ecosystem responses over the same period have involved increases of tropical fish and decreases of temperate species on the East Coast where warming is taking place (Lloyd et al., 2012), eastward distributional shifts of a suite of mainly cold-water marine organisms including kelp, rock lobster, pelagic forage fish and seabird species, and range retractions of warm-water species such as the brown mussel *Perna perna* (Blamey et al., 2015). False Bay, which is situated in the transition zone between cool west coast and warmer south coast conditions, has been influenced by many of these changes.

In recognition of the socio-ecological importance of False Bay, marine scientists dedicated two symposia to this theme, in 1968 and 1989, resulting in comprehensive reviews of the bay's oceanography, biology and human impacts (Transactions of the Royal Society of South Africa, Volumes 39: 1–2, 1970, and Jackson, 1991). Considering the burgeoning effects of human population growth and climate changes in False Bay, as well as the considerable research that has taken place over the past three decades, some of it addressing priorities, gaps and opportunities that were identified in 1989, it is appropriate to revisit the socio-ecological status of the bay. The backdrop provided above emphasizes the need for a multidisciplinary approach and knowledge-sharing between social and natural sciences if effective conservation of biodiversity and sustainable utilization of resources is to be achieved. This need is the primary motivation for this synthesis, in which we summarize new findings and changes that have occurred in the oceanography, biology and the human dimension of the socio-ecology of False Bay over the past 30 years, based on published literature and presentation of new results. We further identify gaps in the understanding of the False Bay system and recommend priorities for the development of a concerted multidisciplinary and participatory research and monitoring plan. The concepts and processes outlined in this paper are also applicable and relevant for other locations and settings, especially those that require sustainable solutions for managing wildland-urban interfaces.

2. Geology and physical oceanography of False Bay

2.1. Geological setting

The northern coast of False Bay comprises linear, transient sandy beaches while the western and eastern edges are mountainous and rocky (**Figure 1**). The seabed geology is dominated by unconsolidated sediments with patches of Malmesbury Group shale in the eastern parts and Cape Granite Suite plutons in the western parts of the bay (Figure S1). The seafloor deepens to the south at an average gradient of 1:370 (Terhorst, 1987), reaching a depth of over 100 m between Cape Point and Cape Hangklip, the two rocky promontories that define the margins of the bay. Notable features include the rocky pinnacles and high-relief reefs that crop out at Roman Rock, Seal Island, York Shoal, East Shoal, Whittle Rock and Rocky Bank. Some of the pinnacles and ridges shoal up to 20-m depth, probably impacting oceanographic patterns by creating turbulences and localized upwelling. The Hangklip Ridge, a long submarine westward extension of Cape Hangklip (Hartnady and Rogers, 1990) plays an important role in channeling the cold, nutrient-rich water that is upwelled by southeasterly winds during summer (Grundlingh and Largier, 1991). The marine sediments in the bay generally get finer seaward, and highly calcareous sediments surround granite outcrops (Glass, 1980; Terhorst, 1987). Sediment transport in the bay is dominated by bottom-traction in the western area and lower-bottom and upper-bottom suspension in the east (Flemming, 1982).

The oldest ‘basement’ rocks comprise the Malmesbury Group and the Cape Granite Suite (~550–510 Ma). Overlying deposits of the Cape Supergroup consist of Table Mountain Group sandstones, which dominate the Cape Peninsula and Cape Hangklip, and were deposited along a regionally subsiding shelf from ~500 Ma (Rust and Theron, 1964). Increased downwarping facilitated the deposition of the Devonian Bokkeveld Group shales, and deformation that occurred at ~278–230 Ma (Newton et al., 2006) produced the Cape Fold Belt. With the fragmentation of Gondwana and the opening of the South Atlantic (commencing ~136 Ma), faults were reactivated (Paton et al., 2006) and the newly created space in basins was filled with predominantly terrestrial sediments. A series of northwest-southeast oriented dolerite dykes intruded the rocks of the Cape Supergroup at the time of the last extensional event associated with the fragmentation of Gondwana, and these dykes have been mapped with marine magnetics beneath the sediments in False Bay (Day, 1986). A low-relief coastal plain now stretches from the northern margin of the bay across the Cape Flats to Table Bay, underlain by erodible Malmesbury Group strata. Ancient palaeo-river valleys carved this landscape and have been infilled by at least 20 m of Cenozoic sediment, which form part of the Sandveld Group (Rogers, 1982). Some of these deposits consist of aeolian sediments of the ‘False Bay dune plume’ which is made up of basal cemented Pleistocene rocks overlain by more recent aeolian and marine Holocene sediments of the Witsand Formation (Roberts et al., 2009).

The Pleistocene-age shallow marine and estuarine Velddrift Formation is exposed at the base of the Swartklip Rocks and is overlain by cross-bedded Langebaan Formation aeolianites. The calcretized upper surfaces have kept them relatively resistant to erosion, reaching a maximum height of 50 m at Wolfgat Cliffs, but the encroaching sea level and coastal retreat is systematically cutting into these deposits during high swell events (Fourie et al., 2015). The rate of coastline retreat near Macassar Beach has been calculated by laser scanning and LiDAR to be in the order of 2.2 m yr^{-1} (MacHutchon, 2015). This sequence reflects the variability in repeated Quaternary sea-level fluctuations, and the continuation of these deposits onto the continental shelf in the form of coast-parallel trending reefs is testament to the magnitude of the fluctuations between heights of ~10 m above present, to ~130 m below present sea level. Since 1958, the sea level has been rising 0.19 cm yr^{-1} at Simon’s Town (Figure S2), consistent with findings of earlier studies (Hughes and Brundrit, 1991) and model projections (Watanabe et al., 2010).

2.2. Atmospheric forcing: wind and weather

Wind dynamics drive the ocean circulation and waves in False Bay, and are therefore the main driver of sea surface temperature (SST) patterns (Jury, 1987; 1991). Four distinct wind regimes occur year-round at varying frequencies, each of which represents a phase in the periodic passages of eastward-moving atmospheric Rossby waves across the southern tip of Africa. The southwest regime occurs at the leading edge of an anticyclone, following the passage of a cold front. As the eastward-moving anticyclone merges with the South Atlantic anticyclone (SAA), the pressure gradient is increased, and strong, deep southeasterly winds are produced. With further progression of this high-pressure cell across the southern tip of Africa, it separates from the SAA, leading to a weakening of winds during the shallow southeaster regime. Thereafter follows a coastally trapped low, which is associated with northwesterly winds that precede the next cold front. As the front passes, cool, moist westerly airflow is diverted to the north and south of Table Mountain, converging to produce a strong northerly flow over False Bay.

The SAA, which is centered at about 30°S, experiences seasonal shifts in longitude and latitude, causing significant seasonal modulation in wind fields. During summer (December to February), its southward position results in a dominant southeasterly wind regime over False Bay. However in winter (June to August), the SAA and the mid-latitude low-pressure systems migrate north, effectively resulting in a more persistent and stronger northwesterly wind regime. The seasonal changes in the atmospheric circulation over False Bay are well captured in the dataset of the National Centers for Environmental Prediction Climate Forecast System Reanalysis (Saha et al., 2010). A strong polarization at an angle of 138° from the north (along a northwest/southeast axis) is evident for the winds over False Bay (**Figure 2A, B**); a monthly climatology from the daily-averaged wind fields over the 1979–2010 period in this dataset confirms a distinct seasonal cycle with annual variation in wind along the principal axis explaining 78% of the variance (**Figure 2C**). In the summer, the southeasterly winds dominate, with very rare occurrences of northerly winds; while in winter, northwesterly winds prevail, with a few infrequent southeasterly winds. The southeasterly winds are strongest during the month of January and February with monthly mean speeds of 2 to 3 m s^{-1} and daily averages showing a high frequency of wind speeds in the 8–10 m s^{-1} range. The strongest winds in winter generally occur in June and are associated with northwesterly winds with monthly averages in the 3–4 m s^{-1} range and peak daily averages often greater than 10 m s^{-1} (**Figure 2B**). April (September) is a transition month for northwesterly (southeasterly) winds to become more prominent and southeasterlies (northwesterlies) to weaken.

Significant spatial variability in the wind field over False Bay is generated by the interaction of the wind with the steep and rocky mountain ranges that flank both the eastern and western side of False Bay (Wainman et al., 1987; Grundlingh and Largier, 1991). During a deep southeasterly regime, interactions between the strong, deep air flow and the orography cause the wind to accelerate northwest of Cape Hangklip, in the eastern part of False Bay. During a shallow southeasterly wind regime, winds cannot rise above the coastal mountain range due to the presence of a shallow (ca. 600 m) inversion layer (Jury, 1987). As a result, the southeast winds are deflected seawards and accelerate around Cape Hangklip, while a pronounced wind shadow develops in the lee of the Kogelberg mountain (1,268 m), on the eastern side of False Bay (Jury, 1991). During northwesterly wind regimes, the wind accelerates and flows around the high points of Table Mountain and enters False Bay in varying directions depending on location; i.e., in the north of the bay, the wind is primarily northerly but along the western boundary it is more westerly due to its curving around Cape Point (Jury, 1991). Furthermore, several studies have shown that differential heating between the land masses and the ocean during summer can cause significant spatial and diurnal variability in False Bay (Jury et al., 1985; Wainman et al., 1987; Bonnardot et al., 2005). For example, heating of the Cape Flats to >40°C draws winds into False Bay from the north, while southeast-facing coasts remain cooler at ca. 25°C (Tadross et al., 2012).

Observations from the Cape Point meteorological station suggest that significant changes have occurred in winter and summer winds since the 1980s (Blamey et al., 2012). Upwelling-inducing southerly winds were reduced during the 1980s (winter) but increased during the 1990s (winter and summer). Winter easterly winds dominated from the 1960s to the early 1980s, after which westerly winds became more dominant, while summer easterly winds showed an increasing trend from the early 1990s (Blamey et al., 2012).

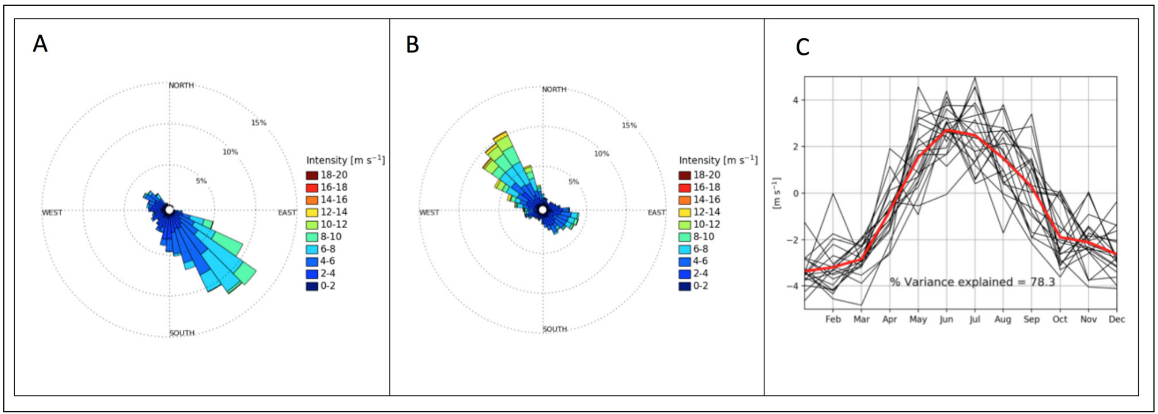

Figure 2: Wind field of False Bay. Wind roses derived from daily averaged winds over **(A)** summer (January–March) and **(B)** winter (June–August) seasons based on a 30-year record (1979–2010); and **(C)** monthly climatology (red line) of wind intensity along an axis directed 138 degrees from true North and individual years (black lines). The direction on the wind roses indicates the direction from which the wind blows with the longest spoke showing the wind direction with the greatest frequency. Source: dataset of the National Centers for Environmental Prediction Climate Forecast System Reanalysis. DOI: https://doi.org/10.1525/elementa.367.f2

2.3. Circulation

Direct observations of the circulation in False Bay are limited and old. They suggest that the general surface circulation inside the bay is clockwise due to the prevailing, cyclonically sheared, southerly winds (cf. **Figures 7–9** in Jury, 1991). Near the mouth of the bay surface currents tend to be westward and are modulated by passing weather, shelf waves, warm Agulhas rings and tides (Grundlingh and Largier, 1991; Nelson et al., 1991).

Due to the limited continuous in situ measurements, models have been used to distinguish between turbulent wind-driven eddies in the north of the bay and conditions in the southern part of the bay, which is characterized by tidal and remotely forced circulation features (van Ballegooyen, 1991). A Regional Ocean Modeling System (ROMS model) was employed to investigate the effects of the wind on the summer circulation in False Bay (Jacobson, 2014). The model results compared favorably with in situ current measurements (De Vos, 2014), showing that southeasterly winds during summer induce offshore transport and upwelling at Cape Hangklip, which penetrates into False Bay, while northwesterly winds during winter cause onshore transport and mixing. The model resolution, tides, and type of forcing data and parameterizations significantly influenced the ability to simulate thermal structures for False Bay (Nicholson, 2012). This model nevertheless consistently predicted that the circulation of the bay comprises standing (mainly clockwise) rotors pulsed by currents across the mouth, although inertial oscillations had low amplitudes. The availability of other published information regarding spatial variability in the circulation of False Bay is limited, highlighting a need for further research.

2.4. Sea surface temperature

Dufois and Rouault (2012) used two monthly SST products (from satellites: moderate-resolution imaging spectroradiometer [MODIS] and Pathfinder) to study the annual cycle and inter-annual variability of SST in False Bay. They showed that during summer (January–March), upwelling at Cape Hangklip leads to an intrusion of cold water into the southern part of the bay (**Figure 3A**). As a result, a strong temperature gradient develops across the bay, with warmer water on the northern and eastern side of the bay and cooler water on the southern and western side. By contrast, when upwelling subsides during winter (June–August), SST tends to be homogeneous within the bay (**Figure 3B**). SST in the northern half of False Bay varies between 13 and 22°C during the course of the year, while in the southern half the SST range is narrower, varying from 14 to 20°C. Variability is higher during summer than winter. Most (>70%) of the monthly variance in the northern half of False Bay was explained by the annual cycle, which explained less than 50% of the variance in the southern part of the bay. The inter-annual variability in False Bay, especially the southern half, is associated with the variability in upwelling along the west coast from Cape Agulhas to Cape Columbine (Dufois and Rouault, 2012).

Interannual variability of SST is correlated with the Niño 3.4 (El Niño/Southern Oscillation or ENSO) index, especially from January to May (Rouault et al., 2010). During El Niño years, upwelling adjacent to the bay is reduced and SST is warmer everywhere in False Bay, while in La Niña years upwelling is enhanced and SST decreases, with anomalies reaching ± 1°C at the seasonal scale. However, the relationship between ENSO and SST in False Bay is not linear; for instance, the strong 1983, 1998 and 2010 El Niño events did not induce a strong warm anomaly during summer, and other SST anomalies, such as in January 2002, were also not linked to ENSO. At a much broader scale, El Niño induces a shift in the SAA high-pressure system and mid-latitude westerly winds in the South Atlantic (Colberg et al., 2004; Rouault et al., 2010; Dufois and Rouault, 2012), which decreases upwelling-favorable southeasterly winds leading to warmer SST. Additionally, decreases in wind speed reduce the cooling due to latent and sensible heat fluxes at the sea surface, thus increasing the net heat flux from the atmosphere to the ocean, which augments warming of the sea surface (Colberg et al., 2004). Surface-layer heating in summer during El Niño promotes the vertical stratification of inshore waters (Dufois and Rouault, 2012; Wainman et al., 1987). The

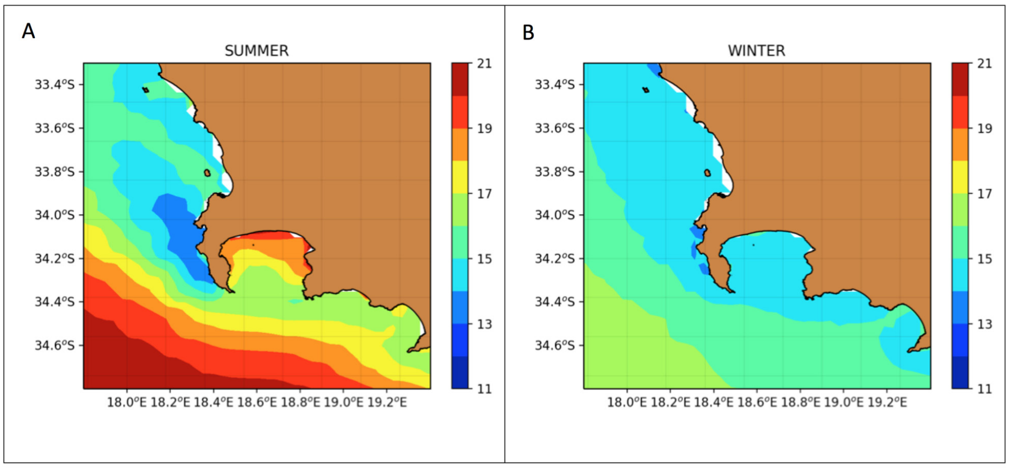

Figure 3: Sea surface temperature in False Bay. Seasonal climatology derived for **(A)** summer (January–March) and **(B)** winter (June–August) using monthly maps of MODIS Aqua SST during the 2000–2010 period (based on Dufois and Rouault, 2012). DOI: https://doi.org/10.1525/elementa.367.f3

stratified layer allows solar heat retention at the surface, which promotes phytoplankton growth in the northern part of the bay (Section 3.3). Upwelling-favorable southeasterly winds, which predominate during summer, perpetuate phytoplankton blooms through nutrient input to the photic surface layer (Grindley and Taylor, 1970; Largier et al., 1992). More detail about this process is given in Section 3. The reverse processes lead to cooler sea surface temperatures and reduced stratification in La Niña years, which affect primary production negatively.

Since the early 1980s, upwelling along the southwest coast of South Africa has experienced significant shifts that fundamentally affect the ecology of False Bay (Blamey et al., 2012; Section 4.1.3). With increasing southerly winds during summer (Section 2.2), the intensity and variability of upwelling increased significantly between the early and mid 1990s, but showed moderate declines in the 2000s. Reasons for this decline are unknown, but likely linked to shifts in wind (Blamey et al., 2012) and the position of the SAA (Jarre et al., 2015) in the mid-to-late 2000s.

2.5. Swell and waves

The general prevailing swell direction around the Cape Peninsula is from the southwest (**Figure 4A**) and characterized by long period swells (12–15 sec) with an average wave height of ca. 3 m (**Figure 4B**). Swell from this direction collides with the eastern shore of False Bay (Kogel Bay) and refracts into the bay resulting in lower wave heights in the west than in the east (**Figure 4C**). So-called "freak" or "rogue" waves occur on the eastern coast; these are due to wave focusing by Rocky Bank, a reef at the entrance of the bay that rises from a depth of 80 m to 20 m (Shipley, 1964). Much of the rest of False Bay is sheltered from the prevailing swell direction and wind waves, hence significant wave heights seldom reach 5 m and periods are usually in the 10–12 sec range. Wave breaking generally occurs as "spilling breakers" along the northern coastline (Muizenberg to Macassar), due to a gentle bottom slope (ratio of 1:50 to 1:100). In summer, strong fetch-limited local winds blow from the southeast and generate choppy waves of short period (ca. 6 sec) and moderate wave height (ca. 2 m). These conditions lead to many rows of spilling waves along the beaches that characterize the shallow-sloping northern shoreline. Its western and eastern peripheries, where the slopes are steeper, can experience strong rip currents and may be dangerous for swimmers. Storms passing south of the Cape create southerly swells with long fetches and durations, giving rise to the highest waves and storm surges that penetrate deep into the bay. These can result in shoreline structural damage such as that seen at the seafront of Kalk Bay (Section 5.4.3). As the bay is semi-enclosed and shallow, an increase in the southerly and easterly components of the offshore winds outside of False Bay (as reported in Section 2.2) will likely correspond to increased swell and storm surge height. However, limited data sources result in contradictory predictions of various (unpublished) models. Further studies are needed to more accurately predict changes in the Southern Ocean weather systems and associated changes in wave parameters and approach for areas such as False Bay.

3. Biogeochemical oceanography of False Bay

3.1. Nutrients

3.1.1. Offshore nutrient distributions

There are relatively few data on macronutrient concentrations for the offshore waters of False Bay, despite the importance of such baseline information for evaluating changes to the nearshore environment driven by anthropogenic activities (Section 3.1.2). To date, only one study has evaluated the large-scale patterns of dissolved nutrients within the bay (Taljaard, 1991). The study considered two wind regimes, with sampling taking place firstly after a week of light southerly winds, and then following an intense southeasterly wind. For both wind regimes, the trends in the surface concentrations of nitrate (NO_3^-) (**Figure 5A, B**), with lower nutrient concentrations inshore than offshore and the lowest concentrations in the northeast corner of the bay, which includes Gordon's Bay. Data for phosphate (PO_4^{3-}) and silicate (Si) are not shown, but their trends were similar. In the summer, the False Bay water column becomes vertically stratified (Atkins, 1970; Gründlingh et al., 1989; **Figure 5C, D**) and SSTs tend to be higher in the east than the west (Section 2.4). A greater degree of nutrient consumption by inshore phytoplankton is expected under these conditions of water column stabilization and high light availability. In addition, offshore False Bay waters are mixed more regularly with the

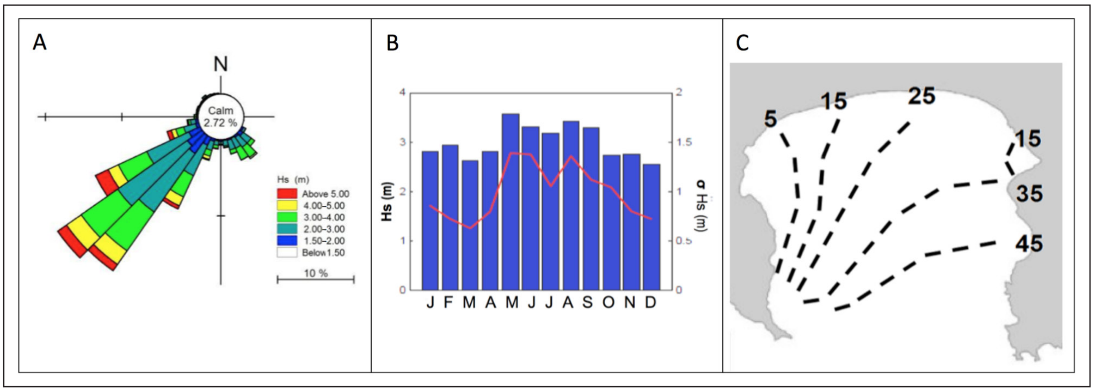

Figure 4: Swell in False Bay. (A) Swell height-frequency rose based on the Wavewatch3 model (Johnson et al., 2012) near Cape Point; **(B)** annual cycle of swell height and standard deviation (red line; Theron et al., 2014); **(C)** wave energy isolines in kW m^{-1} (from Joubert and van Niekerk, 2013). DOI: https://doi.org/10.1525/elementa.367.f4

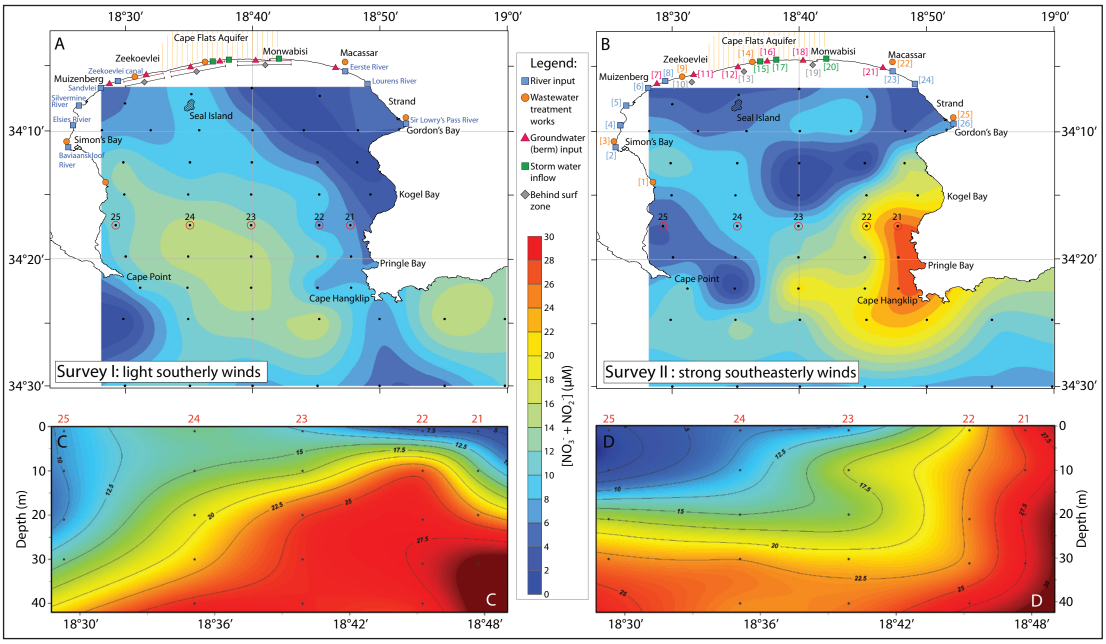

Figure 5: Nutrient (nitrogen) distributions and inputs into False Bay. Offshore $NO_3^- + NO_2^-$ concentrations (µM) in False Bay surface waters following **A)** sustained light southerly winds and **B)** strong southeasterly winds. **C)** and **D)** show a depth section along the transect indicated in A and B by the open red symbols (stations 21–25). Offshore $[NO_3^- + NO_2^-]$ data were collected in April 1989 and are described in Taljaard (1991); no NH_4^+ concentration data are available. Terrestrial inputs to False Bay for which data for dissolved inorganic nitrogen (DIN) concentrations are available (where $[DIN] = [NO_3^- + NO_2^- + NH_4^+]$) are indicated by the colored symbols in panel A. Behind-surf zone samples collected < 1 km from the shore are also shown (grey symbols). The range of available DIN concentrations reported for the various inputs to False Bay are listed in Table 1 and refer to samples collected most closely to the interface with the bay, except in the case of groundwater (magenta symbols), which includes measurements from berm wells. The storm water inflow locations indicated in panels A and B (green symbols) typically include multiple outflows. DOI: https://doi.org/10.1525/elementa.367.f5

open ocean, thereby entraining higher nutrient concentrations to the south of the bay. Gordon's Bay is located in a wind shadow created by the Hottentots-Holland Mountains to the east of False Bay (Grundlingh and Largier, 1991), and is characterized by a semi-permanent anticyclonic eddy creating an anticlockwise gyre circulation that is often in the opposite direction to the larger bay cyclonic circulation (Atkins, 1970; Taljaard et al., 2000). In summer, such circulation likely drives convergence, implying reduced mixing and a longer residence time for waters in the Gordon's Bay area, potentially allowing more time for nutrient uptake by phytoplankton. However, strong southeasterly winds have also been hypothesized to drive upwelling in the vicinity of Strand-Gordon's Bay (Grindley and Taylor, 1970; Jury et al., 1985), which would presumably recharge the nutrients in surface waters. Feedbacks between the region's complex physical conditions and biogeochemistry remain to be confirmed.

Taljaard (1991) recorded elevated surface nutrient concentrations in the center of False Bay following sustained southerly winds, and also to the east near the mouth during a southeasterly wind. These concentrations were attributed to the intrusion and upwelling of a plume of nutrient-rich bottom water from the southeast, most likely South Atlantic Central Water originating on the Agulhas Bank (Shannon and Chapman, 1983; Chapman and Largier, 1989; Taljaard, 1991). Regular summertime observations of cold (presumably nutrient-rich) surface water in the center of False Bay have been hypothesized to derive either from weak in situ upwelling driven by vortex formation associated with the wind-driven clockwise circulation (Atkins, 1970; Cram, 1970; Taljaard, 1991) or from stronger upwelling induced directly by high southeasterly winds. In addition, upwelling off Cape Hangklip, which is driven by strong southeasterly winds, represents a potential source of nutrients to False Bay. However, the relative importance of upwelling outside versus within False Bay for supplying surface waters with nutrients remains unknown, as does the within-bay nutrient distribution in winter when the dominant wind direction is northwest (Atkins, 1970; Taljaard et al., 2000), vertical stratification is minimal (Gründlingh et al., 1989) and SST is relatively homogeneous (Dufois and Rouault, 2012; **Figure 3**).

Taljaard (1991) also recorded elevated surface NO_3^- and PO_4^{3-} concentrations around Seal Island on one sampling occasion, likely due to nutrient-enriched runoff deriving from the large seal population inhabiting the island (i.e., the 'island effect'). This input appears to be dissipated rapidly by mixing with the surrounding waters, as evidenced by the lack of a nutrient concentration gradient near Seal Island during a second survey only days later. The significance of island inputs for productivity and biogeochemical cycling in False Bay has yet to be explored.

3.1.2. Nearshore nutrient distributions and terrestrial inputs

Since the 1980s, considerable attention has been focused on the biogeochemistry of discharges into False Bay; e.g., via rivers, groundwater and waste-water treatment works

(WWTW), with fertilizers, treated effluent, broken sewer pipes, leaking water mains, polluted stormwater and natural organic matter all constituting potential nutrient sources to the bay (Brown et al., 1991; Parsons, 2000; Taljaard et al., 2000). Indeed, eleven rivers drain into False Bay, and all have been modified by humans (Taljaard et al., 2000). A previous estimate indicated that by 2020, the effluent of nearly 2 million people will enter False Bay, with as much as two thirds entering through storm water drains and rivers (Brown et al., 1991).

Average background nutrient concentrations in the surf zone of False Bay as measured between 1987 and 1989 (Taljaard, 1991) were significantly lower (in the case of NO_3^- and Si) or similar (in the case of PO_4^{3-}) to concentrations measured at offshore upwelling fronts (**Figure 5**; **Table 1**). A possible explanation is that NO_3^- and Si are removed more rapidly from the water column than PO_4^{3-} (Taljaard, 1991), most likely by the surf diatom *Anaulus australis* (Campbell and Bate, 1996), which forms dense concentrations on the northern edge of the bay. Terrestrial nutrient inputs to False Bay that have a lower nitrogen-to-phosphorus ratio than is typical for ocean waters may also play a role. Muizenberg Beach experiences higher groundwater-derived nutrient inflow than any other beach along the South African coast due to its proximity to the Cape Flats aquifer (**Figure 5B**; **Table 1**) which is heavily polluted from septic tanks and stormwater runoff (Engelbrecht and Tredoux, 1989), while natural processes may also contribute (Raghunath, 1982). These nutrients are thought to support the high levels of *A. australis* observed in the adjacent False Bay surf zone (Section 3.4), the sustained growth of which may actually protect offshore waters

Table 1: Available data on the dissolved inorganic nitrogen (DIN) inputs to False Bay. DOI: https://doi.org/10.1525/elementa.367.t1

Number on map[a]	Location	[DIN] = [NO_3^- + NO_2^- + NH_4^+] (µM)	References
[1]	Miller's Point WWTW[b]	514–2157	Taljaard et al., 2000
[2]	Baviaanskloof River	30–54	Webb, 2001
[3]	Simon's Town WWTW	2,570	Taljaard et al., 2000
[4]	Elsies River	26	Taljaard et al., 2000
[5]	Silvermine River	24	Taljaard et al., 2000
[6]	Sandvlei	33	Taljaard et al., 2000
[7]	Muizenberg Beach – groundwater input	0–510	Campbell and Bate, 1996
[8]	Zeekoevlei Canal	7–386	Taljaard, 1991; Giljam, 2002; Mtuleni, 2014
[9]	Cape Flats WWTW	579	Taljaard et al., 2000
[10]	Surf zone near Zeekoevlei outlet	3.7–74	Taljaard, 1991; Giljam, 2002
[11]	Groundwater input	5.5–735	Giljam, 2002
[12]	Groundwater input	7.4–287	Giljam, 2002
[13]	Surf zone near Mitchells Plain WWTW outlet	5.9–12.8	Giljam, 2002
[14]	Mitchells Plain WWTW	971	Taljaard et al., 2000
[15]	Storm water inflow	585	Taljaard et al., 2000
[16]	Groundwater input	1,593–10,000	Taljaard et al., 2000; Giljam, 2002; Parsons, 2000
[17]	Storm water inflow	2,286	Taljaard et al., 2000
[18]	Groundwater input	8.2–70	Giljam, 2002
[19]	Surf zone near Monwabisi outlet	9–12	Giljam, 2002
[20]	Storm water inflow	300	Taljaard et al., 2000
[21]	Macassar Beach – groundwater input	5–95	Campbell and Bate, 1996
[22]	Macassar WWTW	1.050	Taljaard et al., 2000
[23]	Eerste River	253–3,158	Taljaard et al., 2000; Mtuleni, 2014
[24]	Lourens River	18–86	Taljaard et al., 2000; Mtuleni, 2014
[25]	Gordons Bay WWTW	26	Taljaard et al., 2000
[26]	Sir Lowry's Pass River	21–44	Taljaard et al., 2000

[a] See Figure 5B.
[b] Waste-water treatment works.

from less desirable phytoplankton blooms driven by eutrophication (Campbell and Bate, 1996).

Concentrations of NO_3^- and PO_4^{3-} up to two orders of magnitude higher than in offshore False Bay and ammonium (NH_4^+) concentrations on the order of 10 mM have been measured in groundwater seepage from the Cape Flats aquifer (Zeekoei River to Kuilsriver; **Figure 5B**; **Table 1**) (Parsons, 2000; Giljam, 2002). Discharge from the aquifer has been reported to persist at distances of 400 to 2,000 m from the shore (Skibbe, 1991; Taljaard, 1991; Ollis, 1997; Giljam, 2002), albeit with significantly diluted nutrient concentrations compared to the source. Webb (2001) showed that high nutrient loads upstream in the Baviaanskloof River, and especially during winter months when flow rates were higher, typically returned to background (i.e., oceanic) levels at the river-bay interface due to dilution with ocean waters, aided by nutrient removal by riverine plant growth (**Figure 5B**; **Table 1**).

When considering False Bay as a whole, the nutrient concentrations supplied to surface waters by upwelling appear to be much higher than those derived from terrestrial sources (Taljaard, 1991; Giljam, 2002). However, land-based pollutants can persist over considerable temporal and spatial scales, potentially negatively impacting coastal ecosystems and recreational activities. Moreover, while exchange with offshore waters appears to be the limiting factor in ensuring good surf zone and nearshore water quality, the roles of microbial processes in transforming and ameliorating terrestrial nutrient inputs (e.g., assimilation, denitrification, nitrification) have yet to be investigated. Finally, a pressing question is how the relative contribution of anthropogenic versus natural sources to the False Bay nutrient load may be changing, given the rapidly growing population and changing wind field in this region.

3.1.3. Atmospheric nutrient deposition

Another potential source of nutrients that could influence both offshore and inshore False Bay waters but that has received little attention is atmospheric deposition of nitrogen derived from anthropogenic activities such as agriculture, industry, and biomass burning (Galloway et al., 2003). As an example, atmospheric deposition has been estimated to account for 25–40% of the anthropogenic nitrogen load entering Chesapeake Bay (Fisher and Oppenheimer, 1991; Sheeder et al., 2002). In Cape Town, nitrogen oxides associated with high wintertime pollution events have been traced to industrial activities in the Mpumalanga Highveld, with transport occurring along the south coast of the country (Abiodun et al., 2014). Atmospheric deposition could thus be a source of both local and remote anthropogenic nitrogen to False Bay, with implications for primary productivity and CO_2 drawdown, N_2O emissions, seawater pH, and ecosystem and human health (Galloway et al., 2003; Duce et al., 2008; Abiodun et al., 2014; Altieri et al., 2016). To our knowledge, while there have been studies of air pollution in the region (e.g., Ritter and Olivier, 1991), no attempt has been made to measure atmospheric nutrient deposition to False Bay.

3.2. Water quality and pollution

Quick (1993) identified bacterial contamination and nutrient loading as the main threats to the water quality of surface water discharges into False Bay. In 2011, Day and Clark (2012) found that approximately 30% of the City of Cape Town's 49 coastal sampling points in the bay did not comply with intestinal *Enterococci*-based human health criteria for intermediate-contact recreation. These authors identified the highest levels of contamination along the northern shoreline between Muizenberg and Strand, with localized contamination hot spots, such as Kalk Bay Harbor. The main sources of contamination comprised leaking sewers and contaminated stormwater, often from poorly serviced areas.

Metal concentrations in False Bay are influenced by the meteorology of the area, coastal topography, geomorphology, and hydrodynamics. These environmental factors also influence the extent of metal contamination caused by anthropogenic activities. Taljaard (2000) provided a comprehensive overview of historical and existing activities, but little monitoring of heavy metals was taking place at the time. Mdzeke (2004) undertook the first survey of metals in False Bay and investigated their effects on the marine ecosystem by conducting biomarker research. Metal concentrations in water and sediment were highest along the northern shore between Muizenberg and Strand, where the most populous and industrialized catchment areas are located. Contamination showed significant spatial variation, suggesting localized inputs with seasonal variability associated with precipitation and runoff. Metal concentrations sampled from biota in False Bay showed that cadmium, copper, nickel, lead and zinc accumulate in invertebrates at concentrations that differed both spatially and seasonally. The high invertebrate cadmium concentrations were thought to derive from phosphate fertilizers that are widely used in catchment areas draining the northern shoreline of the bay. Biomarker research using the Neutral Red retention assay indicated that invertebrates in the northeastern part of the bay (Strand) were stressed by the high contamination levels (Mdzeke, 2004).

More recent research has confirmed that concentrations of metals such as cadmium, lead, and manganese in Western Cape marine ecosystems have increased since 1985 and are influenced by localized sources (Sparks et al., 2014). There is also evidence of bioaccumulation of metals such as arsenic, molybdenum, cadmium, copper and zinc in mussels (*M. galloprovincialis*) in False Bay (Sparks and Mullins, 2017). Further research needs to focus on determining the source of contaminants to False Bay because they pose a potential health risk to the coastal marine ecosystem.

3.3. Chlorophyll a and primary production

Ocean color data from MODIS (4-km resolution) indicate that summertime chlorophyll *a* concentrations in False Bay, which range from 2 to >10 mg m^{-3}, are highest in the northeastern and northwestern corners of the bay (**Figure 6**). Winter, or periods of decreasing SST coupled with offshore advecting winds (from the north) and lower light availability, are associated with phytoplankton bloom decay for most species in False Bay, an

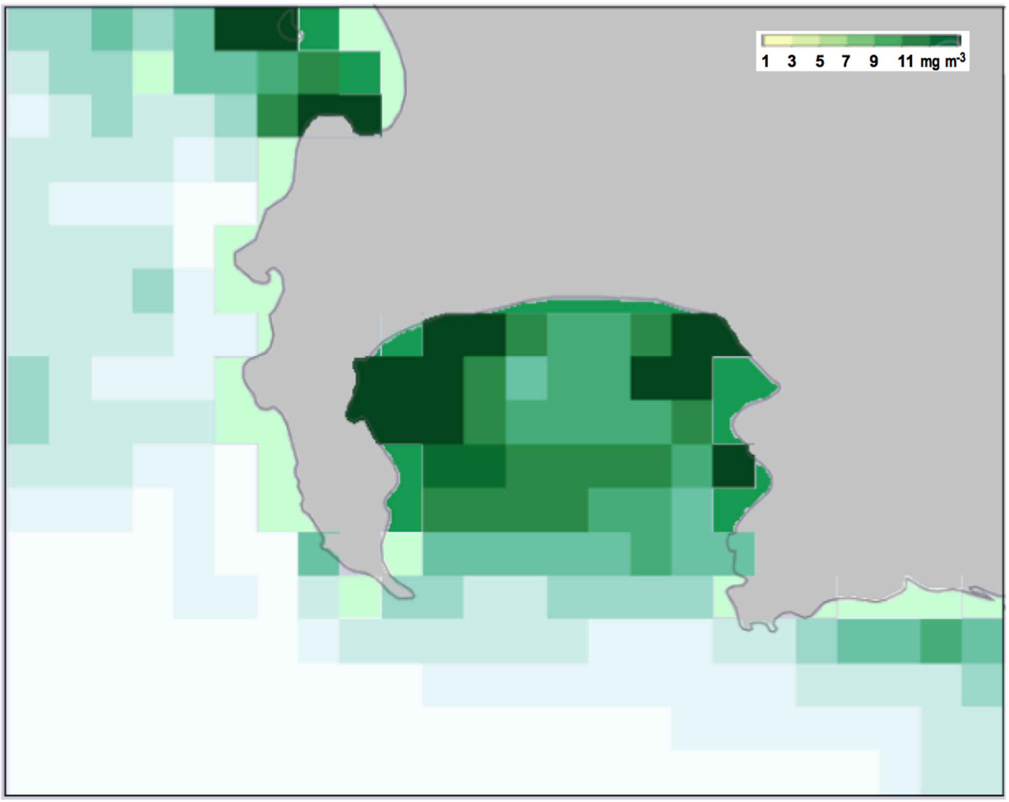

Figure 6: Summertime ocean color data from MODIS at 4-km resolution. The bay shows substantially higher primary production than the immediate surrounding waters, as indicated by chlorophyll *a* concentration (color bar). DOI: https://doi.org/10.1525/elementa.367.f6

exception being *Gephyracapsa oceanica* (Grindley et al., 1964; Grindley and Taylor, 1970). Based on a survey of the entire south and west coast upwelling area, Brown et al., (1991) reported an annual mean chlorophyll concentration of 4 mg m^{-3} for the upper 30 m of the water column in the False Bay area (which included waters to the south and east of Cape Hangklip). Duncan (2000) measured mean chlorophyll concentrations of 5.5 mg m^{-3} for Simon's Bay, and identified no clear relationship between upwelling and chlorophyll concentrations. By contrast, Giljam (2002) observed higher chlorophyll concentrations in Simon's Bay during summer upwelling (5.5 ± 3.0 mg m^{-3}) than during wintertime periods of quiescence (2.1 ± 3.0 mg m^{-3}). More recently, continuous measurements from a moored fluorometer off Miller's Point showed clear seasonality in chlorophyll concentration (Arendse et al., 2018), with maxima recorded in summer and early autumn (December–March; maximum of 14.1 mg m^{-3}), declining to much lower values in late autumn, winter and spring (April–November; minimum of 2.9 mg m^{-3}).

Weitz (2000) measured the evolution of dissolved oxygen throughout the water column at four sites in Simon's Bay during a two-week period in winter and computed an average rate of net primary production (total primary production minus community respiration) of 11 mgC m^{-3} h^{-1}. This value is high compared to annual estimates from the Walker Bay region to the east of False Bay (~5 mgC m^{-3} h^{-1}) and in the range of estimates from west of Cape Point (~10 mg C m^{-3} h^{-1}) and near Cape Columbine/St. Helena Bay (3.4–16 mgC m^{-3} h^{-1}) (Shannon and Field, 1985; Brown et al., 1991). The high concentrations were likely due to the shallow and enclosed nature of the study site, combined with possible land-derived nutrient loading (Section 3.1.2). The large range of net primary prodution values (6–35 mg C m^{-3} h^{-1}) recorded by Weitz (2000) emphasizes the spatial and temporal heterogeneity of the area, and underscores the need to evaluate environmental measurements in the context of physical and biogeochemical data.

In summary, due to the limited availability of in situ chlorophyll *a* and primary productivity data, much remains unknown regarding phytoplankton biomass production in False Bay, including the extent of its spatial and interannual variability. This knowledge gap exists despite the importance of phytoplankton production as an indicator of ecosystem health and implications for fish productivity and marine biodiversity.

3.4. Algal Blooms

As for many other embayments of eastern boundary upwelling systems, False Bay is subject to a high incidence of harmful algal blooms (HABs) caused primarily by dinoflagellate species that either produce toxins or form dense accumulations known as red tides (Pitcher et al., 2010). Also, as is common with other bays, the development of dinoflagellate blooms in False Bay is favored by the hydrographic conditions of increased retention and stratification. Indeed, strong seasonal stratification patterns provide an environment most conducive to HAB development during late summer and autumn (Horstman et al., 1991; Pitcher and Calder, 2000).

In False Bay, red tides are considered local expressions of widespread dinoflagellate populations, with the bay serving as a site of bloom incubation and accumulation (Pitcher et al., 2008). Under conditions of upwelling, blooms are introduced into the bay by cyclonic circulation. During late summer, bloom development is advanced in a clockwise direction under increasingly stratified conditions (Horstman et al., 1991). Blooms may become entrapped in Gordon's Bay where they are retained in a semi-permanent anticyclonic eddy (Section 3.1.1), rendering this area more vulnerable to HABs and their negative impacts (Grindley et al., 1964; Pitcher et al., 2008). Reversal of upwelling-favorable winds, particularly towards the end of the upwelling season, tends to force a reversal of surface currents in False Bay, favoring leakage and export of blooms from the bay and their entrainment into the Benguela jet current off the Cape Peninsula (Pitcher et al., 2008).

Reports by Gilchrist (1914) of summer blooms of *Noctiluca* provide the earliest accounts of red tides in False Bay, while Horstman et al. (1991) later identified *N. scintillans* as the dinoflagellate most often responsible for red tides in the bay. Other non-toxic dinoflagellates now known to form blooms in the bay include *Gonyaulax polygramma, Prorocentrum rostratum*, *P. triestinum* and *Scripsiella trochoidea* (Pitcher and Calder, 2000). Occasional discoloration of False Bay waters is also caused by the photosynthetic ciliate *Mesodinium rubrum* and the coccolithophorid *Gephyracapsa oceanica* (Grindley and Taylor, 1970). However, apart from their visual impact, these blooms are seldom harmful.

Grindley (1964) provided the first account of a mortality of marine life in False Bay linked to the presence of a red tide. In March and April 1962, a bloom of *G. polygramma* accumulated near Gordon's Bay, reaching concentrations of approximately 10^7 cells L^{-1}. At this time, an estimated 100 tons of dead and dying fish and invertebrates washed up on the beaches between Gordon's Bay and Strand, apparently due to the depletion of dissolved oxygen by decaying plankton. In 2007, a bloom of *G. polygramma* was again responsible for the extreme discoloration of large areas of False Bay (Pitcher et al., 2008). This bloom persisted for two months, and at night the bay was brilliantly luminescent. By late February and early March, cell concentrations of 2×10^7 cells L^{-1} were recorded in the region of Gordon's Bay, where minor mortalities of marine organisms were again thought to be a consequence of oxygen depletion following bloom decay.

Brown (1979) reported a fish mortality in the Strand and Gordon's Bay areas in 1976 in response to a dark brown discoloration of the sea attributed to a bloom of an unidentified *Gymnodinium* species. On this occasion, clogging of the gills was assumed to be the likely cause of the mortality because some fish appeared to be coated with the dinoflagellate. The first mortalities of marine life in False Bay associated with a toxin-producing dinoflagellate were observed in 1988 and 1989, with the latter event including the mortality of an estimated 40 tons of abalone (Horstman et al., 1991). These blooms caused an olive green discoloration of the sea and were associated with the production of an aerosol toxin that affects humans. The causative dinoflagellate was initially identified as a *Gymnodinium* species but later described as a new species, *Karenia cristata* (Botes et al., 2003). Blooms of this dinoflagellate were again prevalent in 1995–1996 when they occurred during the peak of the summer holiday season, causing beachgoers and seaside residents severe coughing, burning of the nasal passages, breathing difficulties, stinging eyes, and irritation to the skin (Pitcher and Matthews, 1996). The noxious gases associated with the bloom were initially reported from the Fish Hoek, St James, and Muizenberg areas, but later the effects were also reported on the eastern side of the bay before spreading to Walker Bay and impacting the coastal resort of Hermanus.

Initiation of routine sampling of the plankton in Gordon's Bay in 1992 demonstrated a further threat to human health by identifying *Dinophysis acuminata* as a regular component of the plankton community of False Bay (Trainer et al., 2010). *D. acuminata* is recognized as the most common cause of diarrhetic shellfish poisoning on the South African coast, primarily through production of the toxin okadaic acid (Pitcher et al., 2011). A fifteen-year time series off Gordon's Bay shows a clear peak in *D. acuminata* concentration during autumn (Trainer et al., 2010; **Figure 7A**). Despite marked interannual variability (**Figure 7B**), *D. acuminata* is present in sufficiently high concentrations during most years to render shellfish in this part of False Bay unsafe for human consumption.

Two types of discoloration of coastal waters along the northern shore of False Bay commonly draw the attention of the concerned public, but are fundamentally harmless: a brown discoloration of surf zone waters related to blooms of the diatom *A. australis* (Section 3.1.2) and a very sharp front between milky white-green water and darker green-blue water. The first reports of *A. australis* in False Bay were made by Grindley (1970). These diatoms form brown patches in the surf on a semi-permanent basis and are generally confined to the surf-zone with few cells occurring behind the breaker line. Suitable conditions for their growth are thought to include long sandy beaches of moderate to high energy, rip current activity and an associated dune system providing nutrients by groundwater flow (Campbell and Bate, 1996). Indeed, surf zone blooms in False Bay are thought to attain particularly high cell concentrations in response to local nutrient inputs (Section 3.1.2). These blooms are particularly pertinent in the Muizenberg area where high concentrations of nutrients are supplied through river outfalls (which contain waste water from the adjacent sewage purification system) and submarine groundwater discharge (Campbell and Bate, 1996). The cause of the milky white-green water is less well understood despite two studies that have sampled across the frontal feature (Shannon et al., 1991; Waldron et al., 2008). The earlier study found that plankton community composition was identical on either side of the front, but densities of phytoplankton, zooplankton and particulate matter were higher in the milky waters. The latter study reported that the milky water was warmer, less saline, and more turbid, with higher nitrate, silicate and chlorophyll *a* concentrations, and was rich in calcium. Pollution from land-based sources was not identified as a

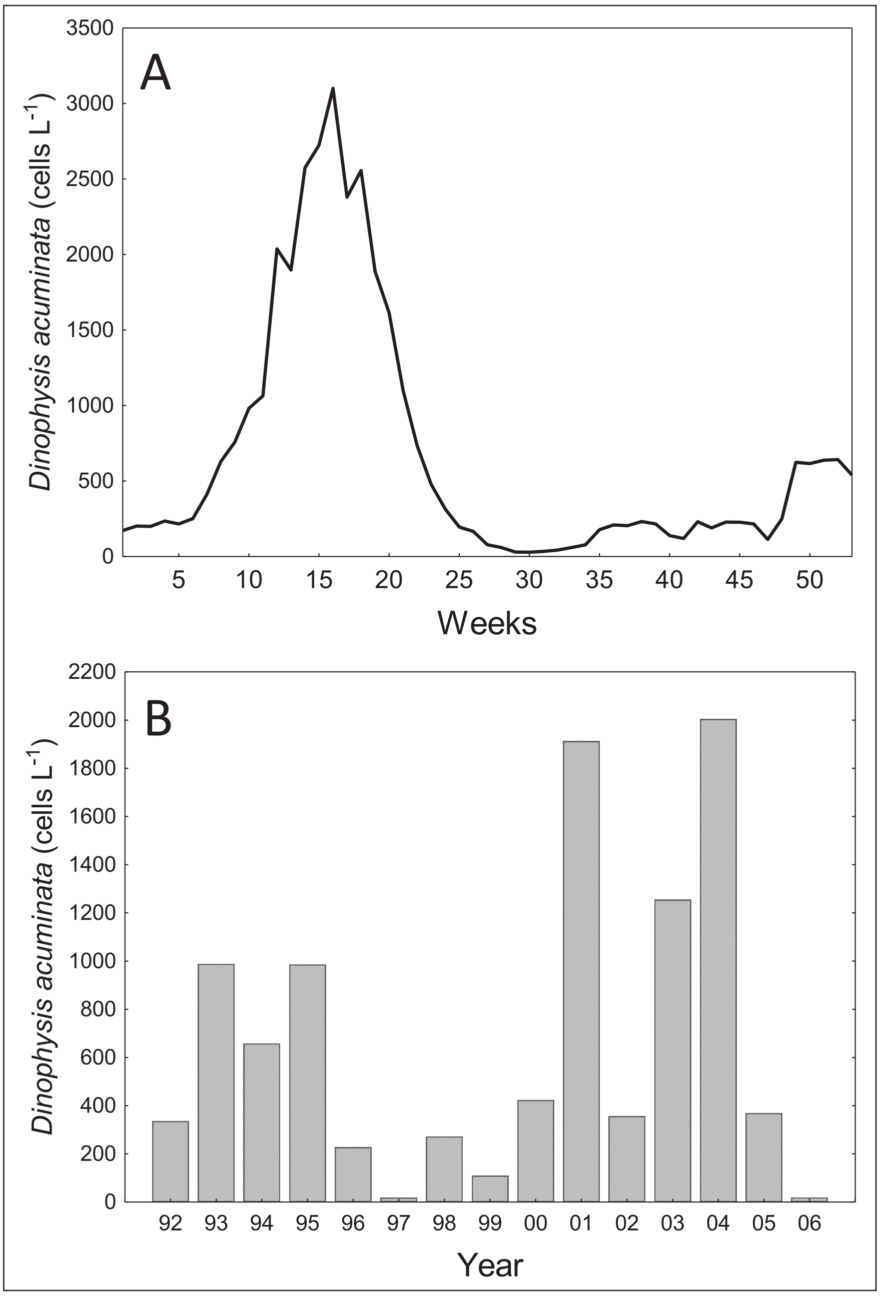

Figure 7: Variability of *Dinophysis acuminata* blooms in False Bay. (A) Seasonal occurrence depicted as a composite of weekly means, and **(B)** interannual variability depicted as the mean daily concentration. Both (A) and (B) are derived from the collection of daily phytoplankton samples from Gordon's Bay from 1992 to 2006. Numbered weeks run from first week in January to the year end (adapted from Trainer et al., 2010). DOI: https://doi.org/10.1525/elementa.367.f7

factor in the formation of the frontal feature and neither was the presence of aragonite needles, as initially hypothesized. Instead, temperature, wind-driven turbulence and the suspension of calcrete (limestone) sediments found in the northwestern part of the bay have been put forward as the likely causes of the milky discoloration (Shannon et al., 1991; Waldron et al., 2008).

4. Ecosystems and biota of False Bay

4.1. Ecosystem types and their communities

4.1.1. Estuaries

Eleven relatively small estuaries discharge into False Bay (**Figure 8**). The largest, Zandvlei, is about 1.55 km^2 in estuarine area, while most others are less than 0.1 km^2 (van Niekerk et al., 2013). Under natural conditions, most of the northern coast of False Bay was a temporary floodplain, but present-day estuaries are the result of extensive dredging. All of the mouths of the estuaries were seasonally closed under the natural regime, with the exception of the Steenbras River, which was (and still is) permanently connected to the sea. However, flow modification (e.g., abstraction, flow diversions, waste-water discharges) has disrupted these seasonal patterns, increasing the closed period in some smaller systems and causing permanently open-mouth conditions in two estuaries (van Niekerk et al., 2015). Catchment areas are small, averaging about 100 km^2 (the largest is the Eerste Estuary at ca. 650 km^2), and predictably deliver relatively low combined annual runoff

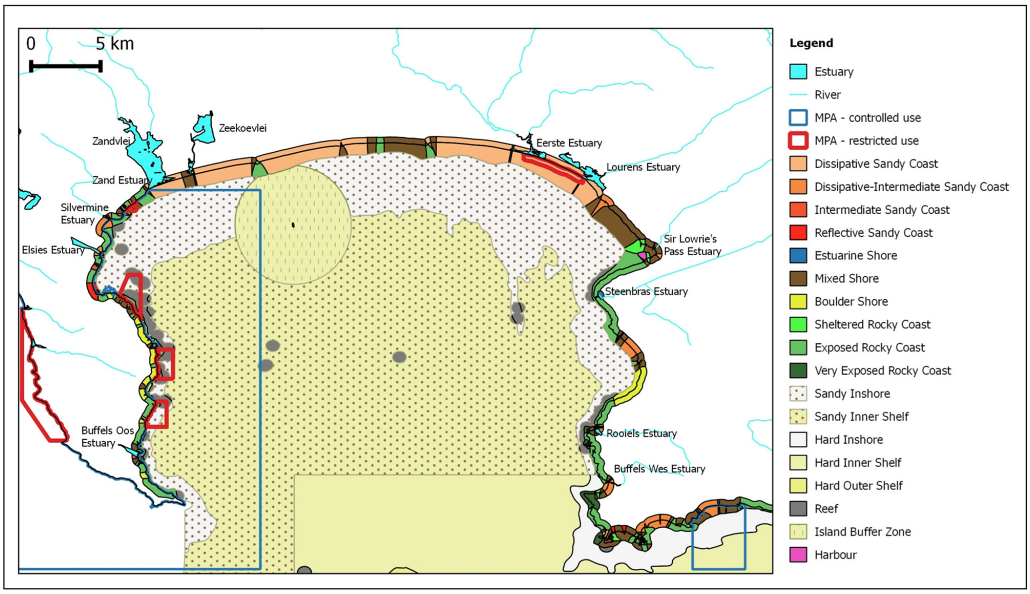

Figure 8: Benthic coastal habitat map for False Bay. Data layers are derived from the National Biodiversity Assessment (Sink et al., 2012; Van Niekerk and Turpie, 2012). The low resolution of existing data for offshore environments is reflected in the straight lines providing approximate delineations of offshore substrate types, highlighting the need for updated surveys. DOI: https://doi.org/10.1525/elementa.367.f8

of about 300 × 10^6 m^3 yr^{-1} to False Bay (van Niekerk et al., 2015), ranging from 0.1 × 10^6 m^3 yr^{-1} for the Sir Lowry's Pass River to 114 × 10^6 m^3 yr^{-1} for the Eerste River (see Table S1 for a breakdown of ecological features, health state, flow modifications, infrastructure pressures, exploitation levels, degradation of specific ecosystem functions, and management status of each estuary). Urban developments have led to the reduction of natural estuarine habitats in the bay, from ca. 15 km^2 to 5.4 km^2, which at present comprise intertidal saltmarsh (0.12 km^2), supratidal saltmarsh (0.02 km^2), reeds and sedges (1.07 km^2), sand and mud banks (0.21 km^2), and open water area (4 km^2). Few detailed ecological studies have focused on these estuaries in the past 25 years (Quick and Harding, 1994; McQuaid and Griffiths, 2014), yet significantly more is known now than what was documented in the last comprehensive review of False Bay estuaries (Morant, 1991).

Due to their small size, the False Bay estuaries only support a limited number of fish species, ranging from 2 to 40 in the Elsies and Zandvlei, respectively (Brown and Magoba, 2009; van Niekerk et al., 2015; Department of Water and Sanitation, 2016). With the exception of the Zandvlei, Rooiels and Steenbras systems, estuarine fish abundance and diversity are in decline. Alien or extralimital fish contribute 12–50% of ichthyofaunal diversity and are only confirmed absent from the Rooiels Estuary, which is in a near pristine condition (Brown and Magoba, 2009). The estuaries on the northern shore of False Bay support a high number of waterbird species, including waterfowl, cormorants, darters, pelicans, gulls and terns (Brown and Magoba, 2009). Overall bird abundance has decreased over the past decades, likely as a result of human impacts (Department of Water and Sanitation, 2016).

The conservation importance of most of the estuaries along the False Bay coast is ranked low to average (Table S1), with the exception of Zandvlei, which ranks highly in terms of its size, type, habitats and biota (Turpie et al., 2002). However, all of the estuaries have the potential to contribute meaningfully to ecosystem-type conservation targets, with five of the eleven systems occurring within, or abutting, formal protected areas (Turpie and van Niekerk, 2012). That said, False Bay estuaries reflect the high degree of urbanization in and around them (Table S1), with only four in a "good" to "excellent" condition, namely the Buffels (Wes), Steenbras, Rooiels and Buffels (Oos) systems (van Niekerk et al., 2013; 2015; Department of Water and Sanitation, 2016). The remaining systems are rated "fair" to "poor", with the Eerste and Zeekoei being in a severely degraded condition (van Niekerk et al., 2015). Major pressures on the 11 estuaries include flow modification, the discharge of WWTW and industrial effluent, urban and agricultural runoff, development or cultivation in the estuary functional zone, severely degraded catchments (sedimentation), infilling of open water areas, development of marinas, mouth manipulation (stabilization, artificial breaching and closures), overfishing, bait collection, recreational activities (e.g.; disturbance of birds) and obstruction by roads, bridges, causeways, and culverts (van Niekerk et al., 2015). Most of the development-related pressures pre-date 1985 and have stabilized over the last 25 years; however, significant further declines in water quality have occurred in a number of systems as a result of increased WWTW discharges, increased urban runoff and return flow from agriculture and golf courses. The Eerste and Zeekoevlei estuaries are subject to extremely elevated base flows, as waste water currently contributes more than 71% and 42% of inflow to the two estuaries, respectively (Table S1), resulting in permanently open-mouth conditions in these systems, which would have been temporarily open-closed under natural conditions.

Very little active estuarine management and monitoring occurs along the False Bay coast, with the exception of Zandvlei which boasts a formal Estuary Management Plan, an active Estuary Management Forum (Zandvlei Trust), and regular monitoring of a suite of ecological parameters by a number of organs of state (Table S1). Monitoring also occurs at the Silvermine, Zeekoei, Eerste and Lourens estuaries, with a focus on water quality (Table S1). While most False Bay estuaries have declined in condition over the past 25 years, the condition of the Zandvlei Estuary emphasizes that active management, monitoring and intervention can halt, and even redress, some of the impacts of urbanization. Several key interventions at Zandvlei have led to improved ecological functioning since the 1990s, including lowering of the rubble weir at the mouth to increase tidal flows, artificial breaching just before spring tides to allow for significant saline penetration, and improved management of a sewage pump station that used to fail regularly. However, the poor water quality of the estuary indicates that the ecosystem is still stressed by eutrophication, low oxygen events, blooms of the invasive and toxic golden algae (*Prymnesium parvum*) and resultant fish kills.

4.1.2. Sandy beaches and subtidal unconsolidated-sediment habitats

Most of the False Bay substratum comprises soft sediments, which form sandy beaches and subtidal unconsolidated sediment habitats (**Figure 8**). The sediments and their communities provide a number of regulatory and supporting ecosystem services including the filtration of water, nutrient cycling and resilience to global change (Weslawski et al., 2004; Armstrong et al., 2012). Despite the prevalence and importance of these habitats in False Bay, very little research has targeted the associated biological communities in the last 25 years.

Sandy beaches, including reflective, intermediate, and dissipative-intermediate beach types, dominate the northern shoreline of False Bay (Sink et al., 2012; **Figure 8**). The sandy beaches provide habitat for nesting birds such as the white-fronted plover *Charadrius marginatus* (Ryan, 2013). In all, 18 macrofaunal and 17 foredune plant species are known for the sandy beaches of False Bay, two-thirds of which are endemic to southern Africa (Harris et al., 2014), although none are unique to the bay. Common taxa include various species of gastropod scavengers *Bullia* spp., and filter-feeding surf clams *Donax serra* and *Scissodesma spengleri*, which are an important food source for gulls and are commonly harvested for bait.

Biological surveys of subtidal unconsolidated sediment habitats of False Bay were conducted in the late 1960s, but have not been repeated since then. More than 150 species were identified from 20 dredge samples (Field, 1970) and 256 infaunal species were identified from benthic grab samples taken along a transect that spanned a depth of 2–100 m (Field, 1971). These studies identified distinct community types associated with different sediment types and depth zones. Furthermore, a recent study on coastal seeps yielded 63 infaunal species from depths between 1 and 8.6 m off Gordon's Bay (F.U. Gluek, unpublished results). The surf zone of False Bay is known to be a refuge for juvenile fish of several species (Clark et al., 1996). A comprehensive study of the subtidal benthic habitats using baited remote underwater video is currently underway to address the gap in the knowledge of benthic subtidal fish and invertebrate communities associated with the unconsolidated sediment substrata of the bay (L. De Vos, personal communication).

False Bay beaches are impacted heavily by recreational use, invertebrate harvesting for bait, beach grooming, pollution and coastal development, with Muizenberg beach recently identified as the most impacted beach in the Western Cape province (Harris et al., 2015). In addition, beaches are under threat from 'coastal squeeze', as they are diminishing between a rising sea level (Section 5.4.3) and ongoing coastal developments (Harris et al., 2015). As a result of human impacts, the bay has seen a 59% decrease in the abundance of white-fronted plovers, which nest above the high-water zone (Ryan, 2013), and declines in the abundance of the giant isopod *Tylos granulatus*, also a high-shore inhabitant (N. Karenyi personal communication). Pollution and fishing practices in False Bay are mainly responsible for the poor condition of the subtidal sediment habitats in the bay, although their impacts have not been quantified. Some of the sandy beach and subtidal unconsolidated-sediment habitat within False Bay is formally protected within two MPAs, namely the Helderberg MPA and the Table Mountain National Park (TMNP) MPA. The former consists of a 4-km stretch of sandy beach and narrow strip of adjacent shallow-subtidal habitat on the north-eastern side of False Bay. The latter extends along the entire western shore of the bay protecting seven isolated beaches between 100 m and 1.5 km in length and a significant portion of subtidal unconsolidated sediment habitat (**Figure 8**). However, enhanced protection from extracted uses is de facto limited to a few designated 'restricted use' zones.

4.1.3. Rocky shores, shallow reefs and kelp ecosystems

False Bay's rocky substrata are mostly confined to its western and eastern shores, with the exception of a few rocky pinnacles and ridges that protrude from the sandy seafloor in the center and south of the bay (**Figure 1**). The western shores comprise a mix of Table Mountain sand stone and Cape granite, while the eastern shores are dominated by Malmesbury shale (Section 2.1, S1). The entire western shore of the bay falls within the TMNP MPA, which comprises four restricted ('No-take') areas, interspersed with controlled-use zones, while the eastern shore is not formally protected (**Figure 8**). However, the most significant known threats to ecosystem health of hard-bottom communities are climate change, alien invasions, over-exploitation and pollution (Branch et al., 2008), and it is uncertain whether the MPA can provide adequate protection from these pressures.

False Bay features a variety of intertidal rocky shores that vary in terms of wave exposure, temperature regime and rock type, all of which influence community structure and functioning. Rocky shore zonation and macrofaunal assemblages have been well studied and were described in detail in the earlier False Bay review (Griffiths and Branch, 1991). Since then, upwelling intensity and frequency have increased (Blamey et al., 2012) and wave action is predicted to increase in future (Section 2.5). These processes are known to have strong influences on rocky shore community dynamics by modulating top-down and bottom-up regulation (Menge et al., 2003). Larval supply and recruitment in False Bay are, for instance, strongly influenced by upwelling intensity, with an order of magnitude higher recruitment of mussels and barnacles inside the bay (at Fish Hoek), where upwelling is moderate, than at the Cape Hangklip upwelling center (Pfaff et al., 2011). However, an increase in upwelling frequency would likely have benefited the proliferation of the introduced Mediterranean mussel *Mytilus galloprovincialis*, which utilizes upwelling and swell for its larval transport and settlement on rocky shores (Pfaff et al., 2015). By contrast, the indigenous brown mussel *Perna perna* experienced a significant reduction in range since the 1990s, retreating eastward and disappearing from False Bay (Mead et al., 2013; **Figure 9A, B**), probably as a result of reproductive failure under cold-water conditions associated with increased upwelling (Tagliarolo et al., 2016). Furthermore, human harvesting of rocky shore organisms acts as powerful top-down control of community structure. This trophic cascade was demonstrated in a five-year experimental exclusion of the grazing limpet *Cymbula oculus* at Kalk Bay, which led to the proliferation of algae and other invertebrate species (Maneveldt et al., 2009). With increasing human populations and poverty along the shores of False Bay, harvesting pressure on limpets and other intertidal organisms have likely increased over the past decades; however, no studies have addressed associated impacts despite the relevance to conservation management. Other anthropogenic threats to rocky shore ecosystems include pollution and biological invasions and are covered in Sections 3.2 and 4.2, respectively.

South African kelp forests comprise two main species of kelp, *Ecklonia maxima* and *Laminaria pallida*, which occupy rocky reefs from the shallows to 30-m depth and create a sheltered habitat for a suite of associated marine species. Much of the pioneering research on the ecology and functioning of kelp ecosystems was conducted on the west coast (west of the Cape Peninsula) during the 1970s and 1980s (e.g., Field et al., 1977; 1980; Velimirov et al., 1977), and reviewed by Branch (2008). No such studies emanated from False Bay because even though the distribution of kelp forests extended as far east as Cape Agulhas at the time, those that occurred in the bay were not very prominent and were considered to be atypical (J.G. Field, personal communication). The only kelp forests in False Bay at that time were restricted to the southwest and the southeast of the bay at cooler upwelled regions such as Cape Point and Cape Hangklip (Day, 1970). Over the past 3–4 decades, the range of *E. maxima* has extended east of Cape Agulhas (Bolton et al., 2012) and its density in parts of False Bay has increased, becoming more prominent, particularly in the subtidal region along the northwestern shores of the Bay (Reimers et al., 2014; **Figure 9C**, **D**). Reasons for the densification and expansion of kelp forests are thought to be linked to cooling inshore waters and increased nutrients related to an increase in coastal upwelling (Blamey et al., 2015). Kelp forests now extend from along the entire western rocky shoreline of False Bay and along the southern half of the eastern shore. They are still absent from the northeastern part of the bay where water temperatures are warmest (Section 2.4) and rocky substrata are uncommon.

False Bay kelp ecosystems are strikingly different from those to the west of Cape Point. On the West Coast, red algae, mussels and West Coast rock lobster *Jasus lalandii* characterize the benthos of subtidal reefs where kelp

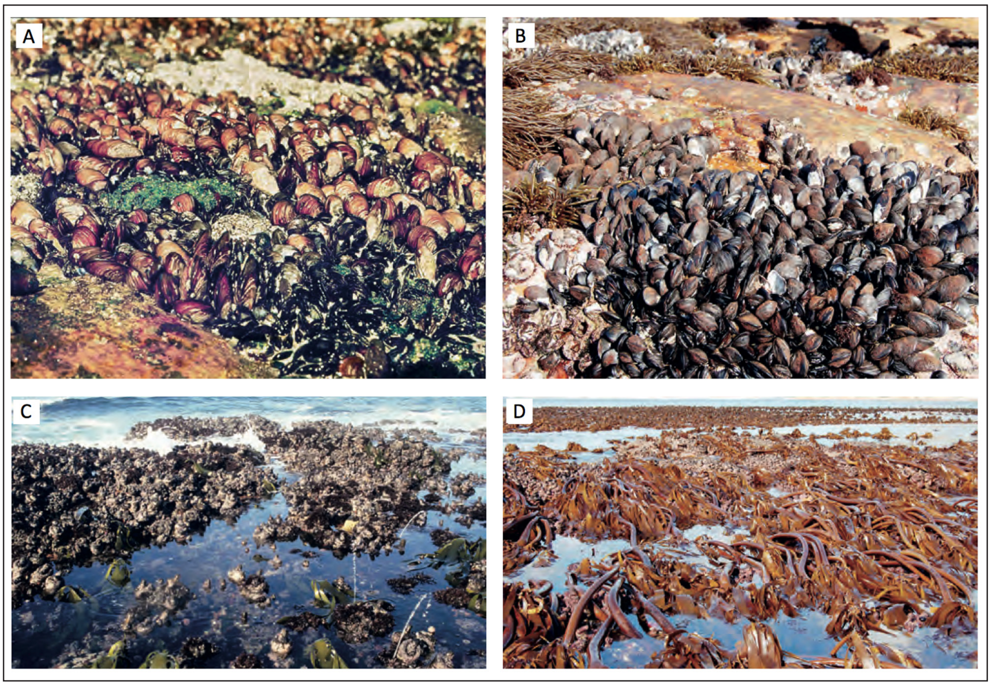

Figure 9: Ecosystem changes of rocky shores and reefs with an increase of upwelling and cooling of False Bay. **(A)** Mussel beds at Dalebrook (Kalk Bay) were dominated by the brown mussel *Perna perna* in 1980, while **(B)** only the introduced Mediterranean mussel *Mytilus galloprovincialis* was present in 2011. **(C)** Densities of kelp *Ecklonia maxima* at Wooley's Pool (Kalk Bay) were low in 1992, but high at the same locality in 2011. (Source: Reimers et al., 2014; photographs by C.L. Griffiths). DOI: https://doi.org/10.1525/elementa.367.f9

occurs (Field et al., 1980; Branch and Griffiths, 1988). East of Cape Point including in False Bay, encrusting corallines and herbivores dominate on the reefs and understory algae are less abundant, particularly Rhodophyta species (Anderson et al., 1997; Morris and Blamey, in press). The urchin *Parechinus angulosus* is the most abundant herbivore; others include the sea snails *Turbo cidaris*, *T. sarmaticus*, *Oxystele sinensis*, a number of patellid limpets and the abalone *Haliotis midae* (Field et al., 1980; Anderson et al., 1997). Despite the abundance of *P. angulosus*, it appears to have little influence on algal communities, given that it feeds predominantly on drift kelp (Velimirov et al., 1977; Velimirov and Griffiths, 1979; Day and Branch, 2000), as does *H. midae* (Tarr, 1989). Because *P. angulosus* remains largely sedentary, it affords protection and nourishment to juvenile abalone that take refuge beneath its spines (Day and Branch, 2000; 2002a; 2002b), while abalone recruits have been shown to selectively settle on encrusting corallines, which is also a preferred substrate of the urchins (Day and Branch, 2000).

Jasus lalandii is a major benthic predator on shallow subtidal reefs in kelp ecosystems. West of Cape Point it feeds predominantly on mussels (Newman and Pollock, 1974; Pollock, 1979; Griffiths and Seiderer, 1980), whereas their preferred prey in False Bay (and further east) are urchins and juvenile abalone (Mayfield et al., 2001), probably because mussels are scarce subtidally (Field et al., 1980). Historically, *J. lalandii* was not abundant east of Cape Point (including False Bay), likely due to the presence of large predatory reef fish (Pollock and Beyers, 1981). However, over the last 25 years, their abundance has declined along the west coast and increased further south, particularly east of False Bay (Cockcroft et al., 2008). This decline has resulted in a complete shift in benthic community structure and functioning (Blamey et al., 2010) and has been detrimental for abalone populations in the area (Blamey et al., 2013). The eastward shift of *J. lalandii* is considered to be an expansion of the False Bay population and, although not fully understood, thought to be linked to changes in the environment (Cockcroft et al., 2008).

4.2. Introduced and invasive species

Presently, 89 introduced species are known from the South African coast (Robinson et al., 2016) of which 53 are recognized as being invasive (i.e., they have self-replacing populations over several generations and have spread from their points of introduction). While the highest numbers of introduced species are known from the west coast (Mead et al., 2011), the number recorded in False Bay has increased markedly in recent times. This increase has been driven by (1) the spread of species around Cape Point and into False Bay, including the intertidal Pacific barnacle *Balanus glandula* (Robinson et al., 2015); (2) new research in previously un-surveyed habitats, such as surveys of fouling communities that were conducted in Simons Town and Kalk Bay harbors (Peters et al., 2014); and (3) the documentation of species previously unknown from the South African coast, including the first record of the amphipod *Caprella mutica* (Peters and Robinson, 2017) and the intertidally and subtidally occurring mussel *Semimytilus algosus* (Skein et al., 2018; Zeeman et al., 2018). To date 24 introduced species, of which 83% are considered to be invasive, are known from False Bay (**Table 2**). Four of these are notable for their abundance and/or impacts on native systems.

The most conspicuous of the invasions in False Bay is that of the Mediterranean mussel *M. galloprovincialis* (**Figure 9B**). This species occurs at an average biomass of 10.2 kg m^{-2} in the mid-intertidal zone along the western shores of the Bay. The biomass drops to an average of 5.8 kg m^{-2} along the relatively wave-sheltered shore between Gordon's Bay and Rooi Els, and increases again on the open coast to the east of False Bay (T.A. Robinson, unpublished results). The bisexual mussel *S. algosus* has entered False Bay within the past decade (Skein et al., 2018). It is slow-growing, has a fragile shell and weak byssal attachment, but has the potential to recruit in exceptionally high densities (Zeeman et al., 2018). The associated mass recruitment events facilitate the spread of this alien species, and have also been observed to induce excessive mortalities of benthic species that are smothered by the masses of mussel spat (M.C. Pfaff, unpublished results). Another significant intertidal invasion is that of the barnacle *B. glandula* which was recorded in the bay for the first time in 2012 (Robinson et al., 2015). Although densities presently remain below 700 individuals m^{-2} within False Bay, laboratory studies have found that this invader exhibits heightened feeding under the prevailing conditions (Pope et al., 2016), suggesting that it may become dominant along this coastline.

Although estuarine invasions are not particularly common along the South African coast, Zandvlei Estuary has undergone notable long-term changes in invertebrate biomass and diversity as a result of the invasion of the polychaete worm *Ficopomatus enigmaticus* (McQuaid and Griffiths, 2014). The development of a marina and artificial hardening of the sides of the estuary are thought to have aided the expansion of this worm, which has increased in total biomass from just 0.3 tons in 1942 to over 56.8 tons in 2012 (McQuaid and Griffiths, 2014).

4.3. Seabirds and shorebirds

Twelve of the 15 seabird species that breed in southern Africa have nested at localities in or around False Bay. Six species are endemic to the region: African penguin *Spheniscus demersus*, Cape gannet *Morus capensis*, Cape cormorant *Phalacrocorax capensis*, bank cormorant *P. neglectus*, crowned cormorant *Microcarbo coronatus*, and Hartlaub's gull *Chroicocephalus hartlaubii*, as well as two subspecies: kelp gull *Larus dominicanus vetula* and greater crested (swift) tern *Thalasseus bergii bergii*. The four more widely distributed species are great white pelican *Pelecanus onocrotalus*, white-breasted cormorant *Phalacrocorax lucidus*, grey-headed gull *C. cirrocephalus* and Caspian tern *Hydroprogne caspia*.

African penguins were first reported breeding on Seal Island, False Bay, in 1772 (Shaughnessy, 1984). In 1874, 7,500 penguin eggs were harvested, suggesting a population of at least 5,000 penguins. By 1979 there were only 82 pairs, likely as a result of egg collections, an increased

Table 2: Introduced marine species known from False Bay, after Robinson et al. (2016). DOI: https://doi.org/10.1525/elementa.367.t2

Taxonomic group	Species	Status	Habitat
Hydrozoa	*Obelia dichotoma*	Alien	Subtidal[a]
	Pinauay larynx	Alien	Subtidal[b]
Polychaeta	*Boccardia proboscidea*	Invasive	Intertidal[c]
	Ficopomatus enigmaticus	Invasive	Intertidal[d]
	Neodexiospira brasiliensis	Invasive	Intertidal[e], subtidal[a]
Cirripedia	*Balanus glandula*	Invasive	Intertidal[f]
Amphipoda	*Caprella mutica*	Invasive	Subtidal[g]
	Ericthonius difformis	Alien	Subtidal[a]
	Jassa slatteryi	Invasive	Subtidal[b]
	Jassa morinoi	Invasive	Subtidal[b]
	Monocorophium acherusicum	Alien	Subtidal[a,b]
Bivalvia	*Mytilus galloprovincialis*	Invasive	Intertidal[h], subtidal[a]
	Semimytilus algosus	Invasive	Intertidal[i], subtidal[i]
Bryozoa	*Bugula dentata*	Invasive	Subtidal[a]
	Bugula flabellata	Invasive	Subtidal[a]
	Bugula neritina	Invasive	Subtidal[a]
	Cryptosula pallasiana	Invasive	Subtidal[a]
	Watersipora subtorquata	Invasive	Subtidal[a,b]
Ascidiacea	*Ascidiella aspersa*	Invasive	Subtidal[a]
	Ascidia sydneiensis	Invasive	Subtidal[b]
	Botryllus schlosseri	Invasive	Subtidal[a]
	Ciona robusta (formerly *C. intestinalis*)	Invasive	Subtidal[a]
	Cnemidocarpa humilis	Invasive	Subtidal[a,b]
	Diplosoma listerianum	Invasive	Subtidal[a]

[a] Peters et al. (2014), [b] Mead et al. (2011), [c] David (2014), [d] McQuaid and Griffiths (2014), [e] T.A. Robinson (unpublished results), [f] Robinson et al. (2015), [g] Peters and Robinson (2017), [h] Robinson (2005), [i] Skein (2018).

abundance of Cape fur seals *Arctocephalus pusillus pusillus* and disturbance from sealing operations (Shelton et al., 1984). Competition with seals for breeding space was partially mitigated through the deployment of nesting pipes (Crawford et al., 1994), but the population remains at around 50 pairs (Department of Environmental Affairs [DEA], unpublished results). A penguin colony formed on the mainland at Boulders (Simon's Town) in 1985 and increased rapidly, mainly through immigration, concomitantly with an increase of sardine *Sardinops sagax* in South Africa in the late 20th century (Crawford et al., 2000; 2001). The Boulders colony has since become one of the major attractors of foreign visitors to the Western Cape (Lewis et al., 2012). Following a shift to the south and east in the distribution of their two main prey species, sardine and anchovy *Engraulis encrasicolus* (Hockey et al., 2005; Roy et al., 2007; Coetzee et al., 2008), numbers of penguins breeding west of Cape Point collapsed in the 21st century but remained stable in False Bay and increased at Stony Point, east of False Bay (Crawford et al., 2011; **Figure 10**).

In South Africa, anchovy and sardine are also important prey of Cape cormorants, Cape gannets and greater crested terns (Hockey et al., 2005). Numbers of Cape cormorants increased in False Bay in the late 2000s beyond previously observed levels, after they experienced substantial decreases farther north (Crawford et al., 2016). They breed mainly on the cliffs at Batsata Cove and Cape Point in the Table Mountain National Park. Bank cormorants, which breed at Partridge Point, Seal Island and Cape Hangklip in False Bay, declined during 1978–1980 (113 breeding pairs)

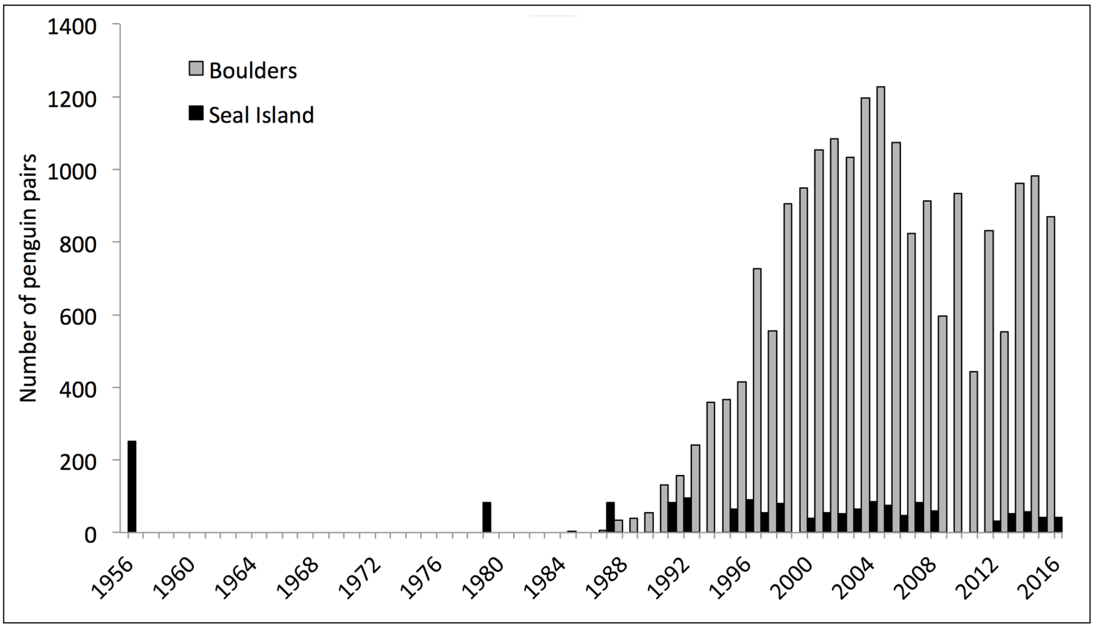

Figure 10: Abundances of African penguins *Spheniscus demersus* in False Bay. The number of penguin breeding pairs at Seal Island remained constant and low due to competition with seals, while a new colony on the western shore (Boulders) grew through immigration until the mid 2000s, then declined until stabilizing at around 1,000 pairs. Gaps in the time series are due to missing data. DOI: https://doi.org/10.1525/elementa.367.f10

and 1995–1997 (49 pairs), but increased slightly (59 pairs) by 2011–2013 (Crawford et al., 1999; Crawford et al., 2015). The recent increase corresponds with a south-eastward shift in the distribution of an important prey of bank cormorants, the west coast rock lobster, which resulted in declines in bank cormorant numbers at some West Coast localities north of Cape Town but stable or increasing numbers from Robben Island to Stony Point, including False Bay (Crawford et al., 2008). A long-term decline in the number of breeding bank cormorant pairs at Seal Island from the 1950s (88 pairs in 1956) to the present (29 pairs in 2016) has been attributed to competition with seals for space (Crawford et al., 1999; Rand, 1963; DEA, unpublished results). Crowned cormorants have bred at four localities in False Bay and white-breasted cormorants at seven. Respectively, 45 pairs and 120 pairs of these species were breeding in 1977–1981 and 15 and 41 pairs in 2008–2012 (Crawford et al., 2012; 2013). Kelp gulls have bred at nine localities in and around False Bay, where numbers breeding increased from 310 pairs during 1976–1980 to more than 2,000 pairs currently (Whittington et al., 2016; P.G. Ryan, unpublished results). Numbers of all three species have decreased on the west coast, but have increased in the south of South Africa (Crawford et al., 2015; Whittington et al., 2016).

Some breeding colonies of seabirds have disappeared from the False Bay area. Cape gannets bred at Seal Island in the late 17th century but not since the late 18th century (Crawford et al., 1983; Shaughnessy, 1984), and great white pelicans also bred at the island from the late 1920s until 1954 but moved to Dassen Island in 1956 because of human disturbance (Crawford et al., 1995). Greater crested terns bred on a small island at Strandfontein sewage works during 1976–1982 but no longer do so (Cooper et al., 1990; Crawford, 2009), probably because the island is now densely vegetated (B.M. Dyer, personal communication). Up to 2,000 pairs of Hartlaub's gulls and a few pairs of grey-headed gulls and Caspian terns used to breed with the terns at this location and at another wetland on the north coast of False Bay in the 1970s and early 1980s (Brooke et al., 1999; Cooper et al., 1992; Williams et al., 1990), but no longer do.

At times, False Bay is an important feeding area for seabirds breeding elsewhere in the region or farther afield. Cape gannets from Malgas Island and greater crested terns from Robben Island, both on the West Coast, often feed in False Bay, the gannets moving around the Cape Peninsula but the terns crossing over it to do so (Lewis et al., 2012). Large numbers of non-breeding pelagic seabirds (mainly sooty shearwaters *Ardenna grisea* and white-chinned petrels *Procellaria aeqinoctialis*) feed on pelagic fish in the bay, often joining groups of gannets, Cape cormorants, terns, Cape fur seals, common dolphins *Delphinus capensis* and Bryde's whales *Balaenoptera brydei*. The most common migrant terns feeding in the bay are common terns *Sterna hirundo* and sandwich terns *Thalasseus sandvicensis*, both of which breed in Europe. Counts of coastal roosts in False Bay in 2010 were only 20% the size of roosts in 1980, with common terns showing the most marked decrease (from almost 7,000 birds to less than 250; Ryan, 2013).

Numbers of migrant shorebirds from the northern hemisphere also have collapsed by more than 95% over these three decades, but these trends occurred throughout the Western Cape, suggesting that large-scale impacts affect these species (Ryan, 2013). Their niche on the shoreline has been filled to some extent by a marked increase in all three ibis species found in the region (Ryan, 2013). Among coastal-breeding shorebirds, the white-fronted plover has declined by 30% on False Bay beaches, having disappeared from Fish Hoek beach and sections of the northern coast. This species is vulnerable to disturbance while breeding, with chicks in particular vulnerable to predation by dogs (Lloyd, 2008). The African black oystercatcher

Haematopus moquini is the only shorebird that increased in False Bay over the last three decades, with the population having more than doubled, likely due to increased food availability following invasion of the intertidal by the mussel *M. galloprovincialis* (Ryan, 2013).

In summary, False Bay is an important locality for breeding and foraging by seabirds and shorebirds. It may well have been even more so but for habitat changes at some adjacent wetlands, substantial earlier exploitation and disturbance of seabirds, and competition with seals for breeding habitat at Seal Island. Recent shifts along the coast to the southeast in the distributions of some forage resources have led to large decreases of several seabird species further north on the west coast of South Africa (Crawford et al., 2015), enhancing the importance of False Bay. As the human population in the greater Cape Town area has increased, seabirds have become a source of enjoyment for many people and, penguins in particular, a major generator of revenue for the Western Cape (e.g., Lewis et al., 2012). However, predation by natural and introduced predators (dogs and cats) is an issue at some mainland colonies, and some gull colonies are subject to illegal disturbance and subsistence exploitation (Whittington et al., 2016). Specialist coastal birds have for the most part decreased due to increased development and disturbance, as well as larger-scale challenges facing long-distance migrants.

4.4. Megafauna

4.4.1. Great white sharks

Historically, False Bay has been described as the South African center of white shark *Carcharodon carcharias* abundance (Barnard, 1925; Wallett, 1978). Trophy hunting for large white sharks was prolific during the 1970s and 1980s, which likely meant that the population of the bay sustained heavy losses over this period (Ferreira and Ferreira, 1996; Cliff, 2006). In 1991, South Africa became the first country to protect white sharks, making it illegal to kill or harass them (Compagno, 1991). This restriction was followed by rapid growth in tourism and research centered on white sharks. False Bay is used primarily by juvenile and sub-adult white sharks ranging in size from 2 to 5 m (Ferreira and Ferreira, 1996; Hewitt et al., 2018). They occur year-round, but how they utilize the bay varies seasonally (Kock et al., 2013). In austral autumn and winter, both sexes aggregate around Seal Island to prey upon Cape fur seal young (Martin et al., 2005; Kock et al., 2013). In spring and summer, however, males either stay near the island or depart from the bay, while females move closer inshore (Kock et al., 2013). Shark activity along the inshore of False Bay is greatest along the northern shore from Muizenberg to Macassar, corresponding with beaches that are highly popular for recreational use, and lowest at the eastern and western headlands (Kock et al., 2018).

The population of white sharks at Seal Island has been estimated to be 723 ± 132 (standard error) individuals, with a range of 12–287 individuals estimated to be present in any year (2004–2012) (Hewitt et al., 2018). Since 2003, shark sightings at Seal Island have exhibited annual peaks and troughs, with an overall decreasing trend in sighting rates, although this was not statistically significant (Hewitt, 2014). Conversely, shark sightings inshore, at Muizenberg and Fish Hoek, exhibited a significant increase over a similar period (Weltz et al., 2013). Fluctuations in sighting rates remain poorly understood, but are likely related to environmental factors and associated prey availability (Weltz et al., 2013; Hewitt et al., 2018). Over the last two years (2016–2018), white shark sightings in False Bay have been the lowest on record (A. Kock, unpublished results). The reasons for the low sighting rates are unknown, but might be related to more favorable prey conditions along the east coast of South Africa inducing a temporary shift in the white shark distribution. The increased presence of killer whales *Orcinus orca* that target white sharks (and, specifically, their livers) as prey, might also play a role in their decreased presence in the bay.

The attractiveness of Seal Island to the white sharks and associated predator–prey interactions is the foundation for commercial shark cage diving and viewing that takes place there primarily over the autumn and winter months. A single study concluded that provisioning associated with these activities at the island probably has a minor impact on the behavior of white sharks (Laroche et al., 2007). Since 2005, considerable attention has been given to the predator-prey relationship at the island. Studies have documented white shark predation strategies, predation rates and factors influencing predation success (Martin et al., 2005; Hammerschlag et al., 2006; Laroche et al., 2008; Fallows et al., 2012) physiological stress response of seals to natural variation in predation rates (Hammerschlag et al., 2017) as well as anti-predator strategies employed by seals (Laroche et al., 2008; De Vos and O'Riain, 2010; Martin and Hammerschlag, 2012; De Vos et al., 2015a, 2015b).

4.4.2. Cape fur seals

Aerial photographic censuses of new born Cape fur seal pups that have been conducted for Seal Island in most years since 1970 showed that a peak of over 20,000 pups was reached in 1996 (Kirkman et al., 2007; Kirkman et al., 2013; **Figure 11**), after commercial seal harvesting there had ended in the 1980s (Wickens et al., 1991). Subsequently, numbers appear to have declined somewhat (Kirkman et al., 2013) and have not exceeded 17,000 in the four censuses since 2010 (DEA, unpublished results), but numbers are stable. Extrapolating from pup counts, the total population is ca. 60,000–75,000 seals, compared to 36,000–65,000 for the 1970s and 1980s (David, 1991). Statistical models could not describe the trend meaningfully because of very high between-year variability in pup counts, with low counts in some years (ca. 13,000 pups) most likely being associated with large numbers of pups being swept off the island and drowned by high seas between birth and the time of the aerial census (Kirkman et al., 2006). This explanation is borne out by large numbers of dead young pups that wash up on False Bay beaches in some years, especially during the December pupping season. The high density of the seal colony and the exposed nature of the island to rough seas, which tend to occur from the south and southeast at this time of year (Section 2.5), are accountable for incidences of high wave-induced mortality (Kirkman et al., 2006). The only other

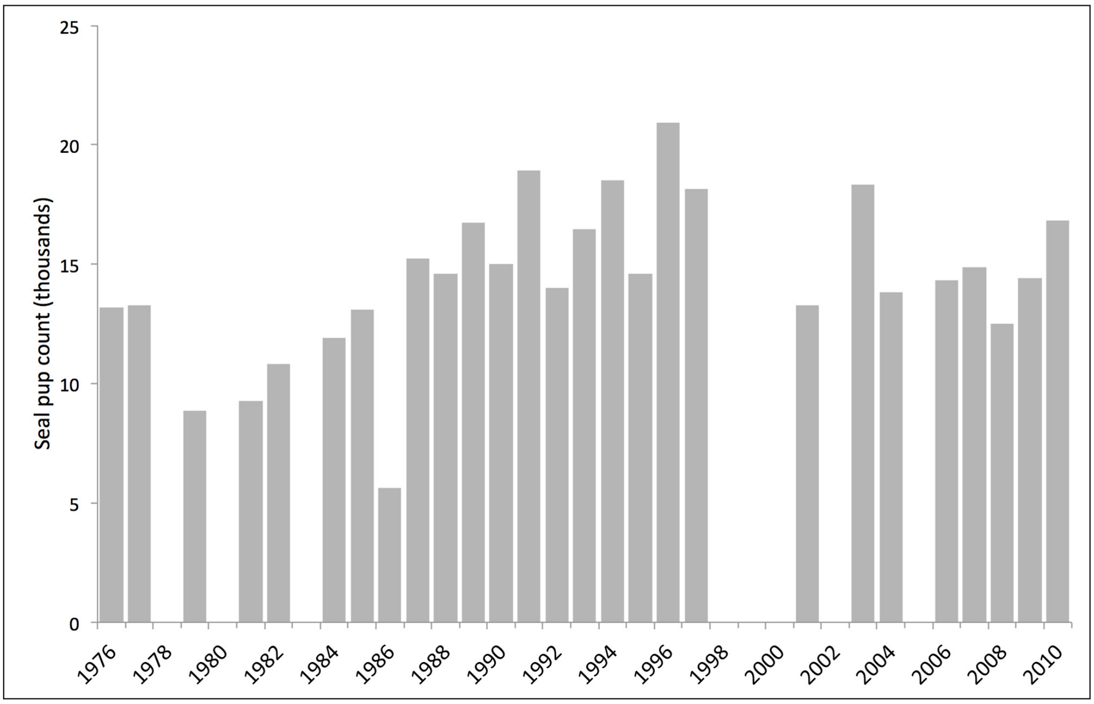

Figure 11: Counts of Cape fur seal pups from Seal Island (False Bay). Derived from aerial photographic censuses during the breeding season over 35 years (adapted from Kirkman et al., 2013). Gaps in the time series are due to missing data, and do not reflect absence of seal pups. DOI: https://doi.org/10.1525/elementa.367.f11

sites in the bay where seals regularly haul out is on the False Bay side of Cape Point and rocks off Partridge Point (where no breeding occurs); there are a few other "resting" sites (David, 1991).

According to Rand (1959) young seals from the island tend to remain close to the island and within the safety of the bay, whereas older animals forage further offshore, sharing feeding grounds with seals of other colonies. Diet consists predominantly (approximately two thirds) of teleost fish including horse mackerel *Trachurus trachurus capensis*, hake *Merluccius* spp., sardine, anchovy and others, with cephalopods and crustaceans comprising the remainder of the prey (David, 1987). Conflict between seals and fishermen in False Bay mainly concerns the line-fisheries for snoek *Thyrsites atun* and hottentot *Pachymetopon blochii* (Section 5.5.2).

4.4.3. Cetaceans

The location of False Bay, close to the edge of the continental shelf and between the cool upwelling of the Benguela ecosystem and the influence of the warm Agulhas Current, results in a unique microcosm of the cetacean diversity in the southern African subregion, which in itself is recognized as a global hotspot of cetacean diversity (Best and Folkens, 2007; Pompa et al., 2011). At least three species of baleen whales regularly occur in the bay: the migratory southern right whale *Eubalaena australis* and humpback whale *Megaptera novaeangliae*, and the non-migratory Bryde's whale. Of these, only Bryde's whales feed regularly in the bay, mainly on small pelagic fish (Best, 2001). Numbers of humpback whales peak in winter and spring (July–October), suggesting that they are *en route* to tropical breeding grounds north of the Benguela Ecosystem (International Whaling Commission, 2012), or that they may be part of a non-breeding migration of animals that aggregate to feed on the west coast of South Africa during spring–summer (Barendse et al., 2010; Findlay et al., 2017). In contrast, the Cape coast is the migratory destination of southern right whales, which take advantage of the sheltered bays for mating, calving and nursing. False Bay lies near the western limit of the main distribution of this species in southern Africa (Elwen and Best, 2004). The pygmy right whale *Caperea marginata*, the smallest of the baleen whales, also occurs in the bay but is very rarely observed.

The distribution of delphinids in False Bay is particularly interesting, and the bay is possibly unique in the world in that it encompasses the regional distributional boundaries of four species. The heaviside's dolphin *Cephalorhynchus heavisidii* and dusky dolphin *Lagenorhynchus obscurus* are both associated with the cold waters of the Benguela Ecosystem to the west of Cape Point, but range occasionally into False Bay, while Indo-Pacific bottlenose *Tursiops aduncus* and the endangered Indian Ocean humpback dolphin *Sousa plumbea* range eastwards from False Bay into the warmer waters of the Indian Ocean (Best and Folkens, 2007), and are only rarely observed to the west of Cape Point. The most abundant dolphin species in False Bay is the long-beaked common dolphin, which has a mostly pelagic habitat over the continental shelf (Best and Folkens, 2007) and is known to be hunted in the bay by the killer whale (Best et al., 2010). There is also increasing evidence of killer whales preying upon broadnose sevengill cowsharks *Notorynchus cepedianus* in the bay (Engelbrecht et al., 2019).

The abundance and diversity of baleen whales in False Bay has naturally resulted in high levels of human interaction, much of which has been exploitative in nature. Native Khoisan people took advantage of stranded animals as a food source in pre-colonial times, open boat whalers operated in the bay in the late 18th century and a small shore-based whaling industry, which included several stations operating in False Bay between 1807 and 1917, targeted primarily right whales around the Cape (Best and Ross, 1989). Since the late 1990s, the development of a successful and well-managed whale watching industry in South Africa has resulted in non-consumptive use of whales (Hoyt, 2001; 2005), and currently one boat-based whale-watching company is permitted to operate in False Bay (DEA, unpublished results).

Whereas both the southern right and humpback whale stocks around Africa have shown clear signs of recovery since the end of commercial whaling in 1979, with exponential growth over multiple decades (Best, 2001; Roux et al., 2015; Findlay et al., 2017), in the case of the former there has been an apparent hiatus in this trend along the Southern Cape coast, including False Bay. Specifically, reduced numbers and changes in the population structure have been recorded, including a decrease in numbers of non-cow/calf pairs observed (Roux et al., 2015) and an increase in inter-calf intervals, which is indicative of poor maternal condition (A. Brandão unpublished results). The driving force behind these changes is not yet fully understood but in other populations these signals have been linked to climate anomalies and decreased krill densities in Southern Ocean feeding grounds (Leaper et al., 2006; Seyboth et al., 2015).

Over the past thirty years, the increasing numbers of whales around the Cape coast, including False Bay, have resulted in increasing entanglement events, particularly in lobster and octopus trap fisheries (Meyer et al., 2011; Section 5.5.2). Vessel-whale strikes are an increasing concern, especially in light of the unknown levels of population changes that are occurring.

5. The human dimension of False Bay

5.1. Governance

Currently, activities in the False Bay area are governed by a plethora of policies and laws (**Table 3**) under various government departments from national to local level. For example, the establishment of a system of integrated coastal and estuarine management and conservation of biodiversity are the responsibility of the national Department of Environmental Affairs (DEA), conservation and sustainable use of marine living resources fall under the national Department of Agriculture, Fisheries and Forestry (DAFF), and management of the TMNP MPA is governed through an agreement between South African National Parks (SANParks), DAFF and DEA, that gives SANParks officials enforcement powers with regards to fisheries-related and other environmental crimes. Small harbors and landing sites along the False Bay coast are managed by a Harbor Steering Committee of representa-

Table 3: Key policies and legislation relevant to coastal and marine resource governance and management in False Bay. DOI: https://doi.org/10.1525/elementa.367.t3

Key legislation	Responsible agency
National Environmental Management (NEM) Act (1998)	DEA[a]
NEM: EIA[b] regulations (2014)	DEADP[c] or DEA
White Paper for Sustainable Coastal Development in South Africa (2000)	DEA
NEM: Integrated Coastal Management Act (2008) and Amendments (2014)	DEA (certain responsibilities delegated to Province and local authorities)
NEM: Protected Areas Act (2004)	DEA with support from SANParks[d], Cape Nature, CoCT[e], Overstrand Municipality
Marine Living Resources Act (MLRA; 1998) and MLRA Amendment Act (2015)	DAFF[f]
Commercial Fisheries Sector Policies (2015), Small-scale Fisheries Policy (2012) and Regulations (2016)	DAFF
Land Use Planning Act (2015)	DEADP
Western Cape Coastal Zone Policy (2007)	DEADP
Mineral and Petroleum Resources Development Amendment Act (2008)	DMR[g]
Local by-laws, e.g., CoCT Municipal Planning By-Law (2015), Stormwater Management By-Law (2005)	CoCT
CoCT Integrated Metropolitan Environmental Policy (2006)	CoCT
CoCT Integrated Coastal Management Policy (2014)	CoCT
CoCT Coastal Management Program (2015)	CoCT

[a] Department of Environmental Affairs.
[b] Environmental Impact Assessment.
[c] Department of Environmental Affairs and Development Planning.
[d] South African National Parks.
[e] City of Cape Town.
[f] Department of Agriculture, Forestry and Fisheries.
[g] Department of Mineral Resources.

tives from DAFF, Department of Public Works, the City of Cape Town (CoCT) and National Treasury, while applications for a change in land-use or approval of development plans fall under local government. Responsibilities such as the management of storm water, waste, beach access and beach amenities as well as the determination of the coastal protected zone and management lines (previously set-back lines) are the responsibility of local authorities (CoCT for most of the False Bay coast, and the Overstrand Municipality in the southeast). Given the limited resources and capacity to fulfill their main functions, government departments tend to focus on issues and problems within their mandate, resulting in a sectoral approach to environmental and coastal governance (Celliers et al., 2015; Davison et al., 2016; Sowman and Malan, 2018).

Addressing bay-wide issues in an integrated and holistic manner is compromised by the sectoral nature of government and the fact that the socio-ecological system of False Bay does not fall under the jurisdiction of a single municipality (Davison et al., 2016). Each municipality has its own pressures and priorities as well as local policies, strategies and plans to address local development needs and coastal issues. Fostering a coordinated and systems-oriented approach is further undermined by the absence of a common vision and integrated management plan for the False Bay coastal and marine environment. However, various recent local government initiatives, including the development of an ICM Policy (City of Cape Town, 2014) and Coastal Management Programme (City of Cape Town, 2015) in terms of the ICM Act (Republic of South Africa, 2008), aim to achieve a more integrated and coordinated approach to coastal governance. Balancing the objectives of promoting ecologically sustainable development while meeting justifiable socio-economic needs under circumstances of poverty and inequality poses a challenge to all governance actors involved in charting a sustainable path forward (Celliers et al., 2015; Colenbrander and Sowman, 2015; Davison et al., 2016).

An initiative in 2012 by the CoCT to bring various governance actors together to identify coastal issues of concern and suggest appropriate actions led to the creation of a multi-agency task team – Cape Town Marine and Coastal Law Enforcement and Compliance Task Team – comprising members from all relevant agencies including DEA, DAFF, CoCT, SANParks, South African Revenue Service Customs, South African Police Service, National Prosecuting Authority, TMNP Marine Unit, Cape Nature and the South African Maritime Safety Authority. Furthermore, a specialized Marine and Environmental Law Enforcement Unit was established within the CoCT to work with the Task Team, which has significantly enhanced co-ordination and communication among key governance actors with enforcement and compliance mandates. This coordinated approach is proving to be effective in curbing illegal activities.

There is a long history of civil society involvement in environmental issues in the False Bay area, and several NGOs and other civil society organizations have played an important role in raising awareness, challenging decisions and proactively tackling coastal issues of concern. Civil society and NGO initiatives include coastal signage, implementing educational programs on marine and coastal conservation issues (e.g., Save our Seas, Macassar Environmental and Nature Conservation Society, AfriOceans, Cape Town Education Trust, SeaChange Project), lobbying for the rights of traditional fishers (e.g., Masifundise Development Trust, Artisanal Fishers Association of South Africa, Kalk Bay boat owners association), challenging decisions deemed unsustainable (e.g., Wildlife and Environment Society of South Africa), proactively engaging in estuary management (e.g., Zandvlei Protected Area Advisory Forum) and providing a platform for organizations and individuals to raise issues of concern and to share ideas (e.g., Simons Town Coastal Forum).

5.2. Consumptive utilization of marine living resources

The exploitation of resources from False Bay likely dates back thousands of years to when Khoisan hunter-gatherers collected marine resources for subsistence from the Cape region (Volman, 1978; Siegfried et al., 1994). Commercial fishing in False Bay has been around since the late 1600s, but in the present time the only commercial fisheries that operate in the bay are the linefishery, the lobster and beach-seine fisheries, as well as new experimental fisheries (e.g., for octopus *Octopus vulgaris*). Sporadically, the demersal shark longline fishery also operates on the southeastern side of the bay. Some of the oldest forms of commercial exploitation targeted whales (until 1975), fur seals (until 1984) and seabirds (penguin egg harvesting until 1968; guano scraping until 1991). By the time these activities had come to an end, the respective target populations had been depleted severely. Commercial abalone diving has been restricted substantially due to resource concerns and an ever-increasing illegal fishery (Brill and Raemaekers, 2013). Demersal trawling, purse-seining and gillnetting, which were introduced to the area during the 1800s, are no longer operational in the bay, although illegal gillnetting remains a problem. These restrictions are attributable to economic considerations, preventing effects of unsustainable fishing gears (e.g., trawling on the benthos) and avoiding conflict with other fisheries and users.

5.2.1. Fish

Commercial line-fishing in False Bay has changed little in its approaches over the last 300 years and still entails mostly hand-line fishing using baited lines. Technological advances have resulted in a massive increase in fishing power but not necessarily in catches. There were few limitations on the commercial line-fishery until the mid-1980s, when regulations and a licensing system were introduced. By 1990 more than 600 licensed commercial line-fish boats were registered in False Bay, landing 1,000–1,600 tons yr^{-1}. Of these catches, ca. 30% was snoek; 10–15% (each) was hottentot, kob *Argyrosomus* spp. and white stumpnose *Rhabdosargus globiceps*; and <5% (each) was geelbek, yellowtail and roman *Chrysoblephus laticeps* (Penney, 1991; **Figure 12A**). In the 1990s, declining line-fish catches throughout the South African coast (Griffiths, 2000; **Figure 12**) saw the declaration of a "State of Emergency" in the line-fishery in 2000 (Republic of South Africa, 2000), and the disbandment of the previous licensing

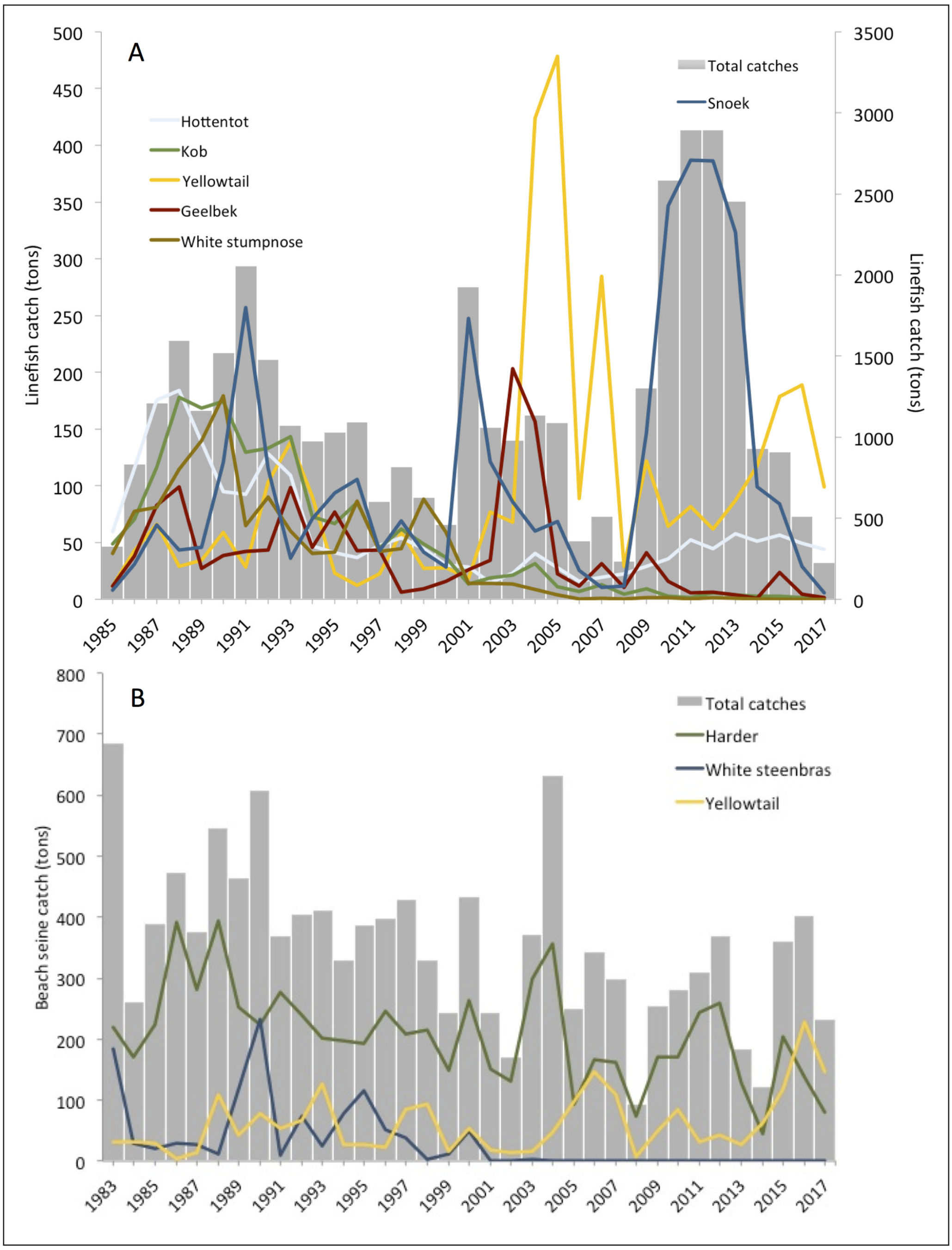

Figure 12: Commercial fish catches in False Bay. Trajectories of **(A)** the boat-based Traditional Linefishery and **(B)** the Beach Seine Fishery in False Bay since the beginning of mandatory catch reporting in each of these fisheries. Total catch is depicted as columns; catches of the most important target species are shown as lines. Note that the catch for snoek (blue line in A) is presented with total catches on a secondary y-axis (right), reflecting that catches are an order of magnitude greater than for other stocks. DOI: https://doi.org/10.1525/elementa.367.f12

system to curb effort subsidization and to favor the establishment of a viable commercial boat-based fishery, also referred to as the "Traditional Line-fishery". The fishing effort in this fishery has since been restricted to a total allowable effort of 316 boats (with average length of 7 meters) within the Management Zone A (from Port Nolloth on the west coast to Cape Infanta on the south coast of South Africa). A number of species-specific regulations apply, but the most commonly targeted species, such as snoek, are not restricted by catch limits. In recent years the traditional line-fishery catch in False Bay of up to 2,900 tons per annum comprises of more than 80 different species. The catch composition has changed and is now overwhelmingly dominated by snoek, which constitutes more than 90% of the reported catch in some years (2010–2013), and a few other primary targeted species, such as hottentot, yellowtail, geelbek, kob and white stumpnose. While there was a declining trend in the catch of most other incidentally caught species until the early 2000s, catches have been relatively stable in recent years. Although catches of the local white stumpnose are in steady decline as reported for other areas (Parker et al., 2017), there are signs of stock recovery for some of the species, most notably hottentot (DAFF, unpublished results).

Recreational fishing in False Bay took off during the twentieth century and, in terms of participation (>200,000 fishers), it is now the largest and most valuable fishery in the bay. Recreational fishing in its current form includes shore and boat-based angling (including fishing charters), angling in estuaries as well as spearfishing and cast-netting, but only shore and boat-based angling are expanded upon here. Prior to the 1960s, most shore-angling effort was on the rocky eastern and western shores of False Bay where deep-water and reef fish such as red stumpnose *Chrysoblephus gibbiceps* and Roman *C. laticeps* were found close to the shore (Bennett, 1991). Since then, declining catches along these shores, improvements in fishing gear such as geared fishing-reels, the advent of the prawn-pump (used for bait collection on sandy shores) and the availability of off-road vehicles saw effort shift towards the sandy northern shore. Changes in catch composition reflected this shift towards sandy habitats, and catches became dominated by kob *Argyrosomus* spp., white steenbras *Lithognathus lithognathus* and slender bellman *Umbrina robinsoni*. Bennett (1991) predicted that if effort levels remained unchanged, the shore-anglers' catches would decline to near zero by 2010. Although there has been an increase in the frequency of unsuccessful angler trips, catches have not yet approached zero, partly due to a suite of new catch limitations and closed areas imposed countrywide since 1985, as well as a further switch in targeting by sports-anglers from teleosts to elasmobranchs to maintain catch mass, and a move towards catch-and-release. Nevertheless, overfishing has continued and there has been further stock depletion of the top five target species: silver kob *A. inodorus*, dusky kob *A. japonicas* (Hutchings and Griffiths, 2010; Mirimin et al., 2016; Winker et al., 2017), white steenbras, slender bellman and galjoen *Dichistius capensis* (Attwood, 2003; Hutchings and Griffiths, 2010; Winker et al., 2012; Bennett and Lamberth, 2013). Consequently, elf *Pomatomus saltatrix* has become relatively more important, comprising about 50% of catches, although they are also depleted (Winker et al., 2012).

The beach-seine fishery has been an important source of fresh fish for more than 300 years. For the most part, it has been in conflict with other fisheries in the bay, some of which no longer exist. Prior to 1975 there were more than 100 licensed beach-seine operators in False Bay. By 1998 these were reduced to 21 operators based on performance and socio-economic reliance of applicants. Despite this reduction, various angler and other interest groups continued to lobby for the complete removal of beach-seining from False Bay, their rationale being that this fishery is detrimental to stocks of "angling" species such as white steenbras and yellowtail, that large quantities of juvenile fish are caught and killed, especially near river mouths, that large quantities of "non-edible" (cartilaginous) and other illegal species (e.g., sardine and galjoen) are caught, and that dragging of nets over the sea bed was damaging to the benthic ecosystem (DAFF, 2010, 2012b, 2014, 2016; Lamberth and Bennett, 1992, Lamberth et al., 1994, 1995a, 1995b, 1995c, Lamberth, 2006). An investigation into these claims in the early 1990s revealed that, while the impacts of this fishery on the ecosystem were negligible, stocks of most of the target species, especially white steenbras (but not yellowtail), were severely depleted (Lamberth et al., 1995b; 1995c; van Niekerk et al., 2015). Importantly, however, the investigation found that within the limitations of the resource, the beach-seine fishery had a right to continue catching fish that they had targeted traditionally (Lamberth and Bennett, 1992). Subsequent management measures saw some species, such as white steenbras and bellman, "de-commercialized" (removed from the market) and a further reduction in effort applied, so that currently there are only five beach-seine operators. These operators land approximately 300 tons yr^{-1} of which 70% is harder *Chelon richardsonii*, 20% yellowtail and the remainder silver kob, elf and other mostly line-fish species (recorded on DAFF's Netfish System).

Traditional fishing communities exist along the False Bay coast (Clark et al., 2002) and account for much of the harvest of marine living resources within the traditional line-fish, lobster, and beach-seine fisheries, as crew or rights-holders, or by illegal fishing (Stibbe and Moss, 1998; DAFF, 2012a). In particular the snoek and harder play an important role in the informal trade system within traditional fishing communities (Isaacs, 2013) and contribute significantly to local food security. Recently, efforts have been made to accommodate more traditional fishers within the framework of the small-scale fisheries policy to enable them to legally utilize various nearshore resources as co-operatives.

Many of the fisheries in False Bay have experienced some level of depletion, mostly as a result of excessive effort and overfishing in various forms. Direct targeting of yellowtail and white steenbras by a relatively small component of the purse-seine fishery contributed to the collapse of both these stocks by the early 1980s (Bennett, 1993). Records of purse-seine catches of yellowtail are limited largely due to these having been reported as line-caught or not at reported all, whereas catches of white steenbras in False Bay peaked in 1982 at 300 tons yr^{-1} (Bennett, 2012). Since the prohibition on purse-seining of linefish species, yellowtail have recovered to optimally exploited levels of 40–50% of pristine, whereas white steenbras declined further from 6% of pristine to critical levels (Bennett, 1993; 2012; Winker et al., 2012). The lack of recovery of white steenbras might be attributed to continued targeting by recreational anglers and legal and illicit beach-seine and gillnet fisheries, as well as environmental factors such as reduced freshwater flow and loss of estuarine nursery function countrywide (Hutchings and Lamberth, 2003; Lamberth et al., 2008; Bennett and Lamberth, 2013).

False Bay contains a considerable diversity of chondrichthyans (22 sharks, 14 batoids and one chimera) as recorded from landings of various fisheries (Best et al., 2013) and baited remote underwater video systems (De Vos et al., 2015c). Chondrichthyans used to constitute a minor component of the catch or were caught as bycatch; however, with new markets for sharks and rays emerging, they have become a primary target of the demersal shark longline fishery. Furthermore, with a decline of other targets there has been an increasing trend of retaining elasmobranch catches in other fisheries, which has raised concern about their non-sustainable exploitation levels in the bay (Best et al., 2013). The role of chondrichtyans as top (or high-order) predators suggests that they influence the structure of marine food webs, which makes them suitable as indicators of ecosystem health and functioning. The relative abundance, diversity and seasonal distribution of this group have recently been described for False Bay (De Vos et al., 2015c), providing a baseline for future monitoring of ecosystem effects of continued exploitation and other environmental drivers.

5.2.2. Invertebrates

The west coast rock lobster and the abalone are two of the most important fished invertebrates in South Africa. Historically, the commercial fishery for the west coast rock lobster has been located primarily along the west coast, but since the 1990s, catches east of the Cape Peninsula, including in False Bay, have increased (**Figure 13**). This change was partly due to drastic declines in the resource along the west coast, but also due to an eastward shift of lobster in the south (Cockcroft et al., 2008). This shift in rock lobster allowed the commercial fishery to expand east of False Bay in the early 2000s. Catches from the east of the Cape Peninsula now contribute over 70% of the total commercial catch (Blamey et al., 2015), but the portion taken from False Bay is small (ca. 5% of total catches) (**Figure 13**). The total value of the west coast rock lobster fishery off the Cape Peninsula (half of which borders False Bay), based on recreational, small scale, large scale and illegal sectors, plummeted between the 1950s (ca. \$121 million yr^{-1}) and the 1980s (<\$10 million yr^{-1}) due to overexploitation and habitat degradation, but has since recovered slightly (\$22 million yr^{-1} in 2015) (Ward et al., 2018). However, in recent years the long-term survival of the rock lobster resource and the fishing communities that depend on it are compromised as illegal fishing has intensified and unsustainable levels of the resource have been allocated by authorities who have largely disregarded scientific projections (Johnston and Butterworth, 2017). The commercial fishery for the abalone has historically been located the east of False Bay, but a combination of increased poaching (Brill and Raemaekers, 2013) and the indirect effects of the rock lobster shift have resulted in severe declines in abalone populations and consequently in commercial catches (Plagányi and Butterworth, 2010; Raemaekers et al., 2011; Blamey et al., 2013), which led to a closure of the commercial abalone fishery in 2008, although it was reopened the following year.

In the past, both rock lobster and abalone have formed important recreational fisheries in the Western Cape (Cockcroft et al., 1999). However, as a result of overfishing, recreational fishing of rock lobster has been downscaled considerably (reduction in recreational season from five months to 21 days) while the recreational abalone fishery has been closed since 2003. Although the West Coast, including the western side of the Cape Peninsula, is still a hotspot for recreational lobster fishing, Cape Hangklip has become a popular fishing spot since the eastward shift in lobsters during the 1990s. Other invertebrates that continue to be exploited and are managed through a permiting system include mussels (mostly *M. galloprovincialis*), clams (*Donax serra, Scissodesma spengleri*), various species of limpets (e.g., *Cymbula granatina*) and the giant turban snail *Turbo sarmaticus*. Whether regulations such as size and catch limits are achieving sustainability of these stocks is unclear, because no dedicated stock assessments exist for most of them.

In recent years there have also been experimental fisheries in False Bay for the whelk *Bullia laevissima* (and a bycatch of the three-spotted swimming crab *Ovalipes trimaculatus*) and octopus (DAFF, 2014). Operational challenges resulted in the closure of the whelk fishery, but the octopus fishery remains ongoing in order to assess its commercial viability in the region (DAFF, 2016). The experimental fishery is located on the western side of the bay. Whale entanglements are a concern with the octopus fishery (Section 5.5.2).

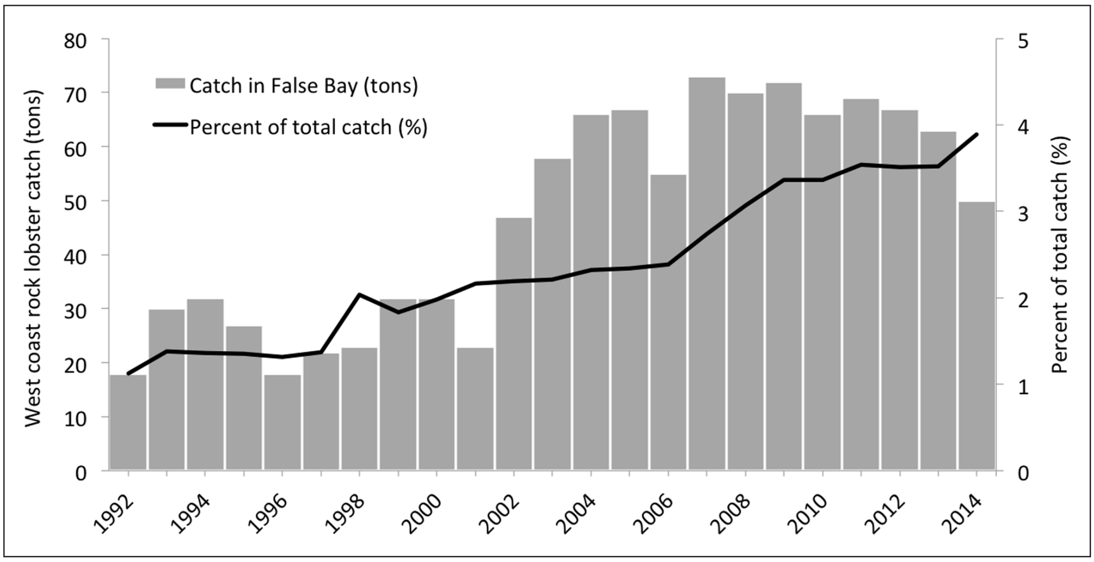

Figure 13: Commercial catches of west coast rock lobster in False Bay. Catch (in tons) between 1992 and 2014 (grey bars) in False Bay and the percentage contribution of the False Bay catch to the overall total commercial catch of west coast rock lobster (black solid line). DOI: https://doi.org/10.1525/elementa.367.f13

5.2.3. Seaweed

The only seaweed harvested from False Bay is the kelp *Ecklonia maxima*. False Bay makes up one of 15 kelp-harvesting areas along the South African coast, with both whole kelp and kelp fronds being harvested for use as feed for farmed abalone and as a plant growth stimulant (Anderson et al., 1997). In most kelp-harvesting regions, including False Bay, the kelp resource is considered optimally or under-exploited (DAFF, 2014). From 2006 to 2014 the average harvest from False Bay was 40 tons yr^{-1}, far less than the allocated total allowable catch of 2,048 tons yr^{-1} fresh weight of "whole" kelp or 1,024 tons yr^{-1} of fronds only (R. Anderson, personal communication). Beach-cast kelp is also collected and averages 56 tons yr^{-1} (dry weight).

5.3. Non-consumptive utilization: amenity, recreation and tourism values

False Bay contains some of the most spectacular scenery and prime recreational areas and tourism attractions of the Western Cape. Located close to the international destination of Cape Town and its satellite towns and townships, the area is heavily used and highly valued (**Figure 14**). The western arm of the bay from Muizenberg to Cape Point is first on the itinerary of a large proportion of the Western Cape's international tourists, while the eastern arm from the Strand and Gordon's Bay to Cape Hangklip is a major holiday destination for domestic tourists as well as a part of the itinerary of a significant number of overseas tourists. In between, the mostly untamed beaches that stretch from Strandfontein to the Strand are frequented by anglers, surfers and swimmers.

There have been several studies of the value of different parts of the False Bay area, or of specific attractions. Ballance (2000) estimated that almost one million locals and about 180,000 foreigners spent R5 million (ca. US$ 350,000) visiting the Fish Hoek, Muizenberg, Strandfontein and Monwabisi beaches in 2000, and showed that the value of beaches was strongly influenced by their cleanliness. Turpie (2001) estimated that 100,000 visitor days were spent at Zandvlei, generating a consumers' surplus of about R700,000 (ca. US$ 50,000) per year. In a study of the 100-km Kogelberg Coast, Turpie and Clark (2007) estimated that tourists spent 4.3–5.3 million visitor days per year with a total expenditure of R191–R235 million (ca. US$ 13–16 million) per annum. The 35-km stretch of this coast that is within False Bay accounted for approximately R135 million (ca. US$ 9.4 million) of this amount. Coastal activities contribute 71% to all users' enjoyment of the Kogelberg coast, through beach activities (26%), and coastal nature (27%), fishing (13%) and water sports (5%). The same study also showed that coastal cleanliness and personal safety were the most important factors influencing value (Figure S3). Indeed, it was estimated that the value of these beaches, if completely safe, would be over 60% more.

The penguin colony at Simon's Town is another important tourist attraction. Visitor numbers to the colony doubled from the mid-1990s to over 500,000 people in 2010, generating R14.5 million (ca. US$ 1 million) in entrance fees and R4.5 million (ca. US$ 313,000) of consumer surplus and making a significant contribution to local business (Lewis et al., 2012). Revenue for all operators of

Figure 14: Idealized map highlighting marine resources and human activities in False Bay. Various components of the socio-ecological system are depicted, including animals (maroon markers), habitats (green markers), activities (orange markers), buildings (blue tags) and marine protected areas (red lines). (Source and credit: artist A. de Korte under commission of the Save Our Seas Foundation for their Magazine). DOI: https://doi.org/10.1525/elementa.367.f14

white shark cage diving and boat-based whale watching in False Bay can be estimated at approximately R29.5 million (ca. US$ 2 million) and R1.6 million (ca. US$ 111,000), respectively (DEA, unpublished results). Both industries have direct (e.g., employment) and multiplier effects (e.g., hospitality industry) that benefit the local economy.

A map of tourism value generated by attractions (nature and other) in South Africa, which was based on the densities of photographs uploaded to Google Earth's Panoramic layer (Turpie et al., unpublished results), shows that the False Bay coast is estimated to generate over R900 million (ca. US$ 63 million) per year in direct expenditure by domestic and overseas tourists (**Figure 15**). Nearly 80% of this amount is along the west coast of the bay (**Table 4**). This area is important not only in the context of the south-western Cape, but also nationally.

In addition to these national values, coastal property makes a significant contribution to the regional economy. In the Kogelberg Coast, the total of all premiums paid for proximity to the coast or coastal views amounted to R37 million (ca. US$ 8.8 million) in Rooiels and R248 million (ca. US$ 17.3 million) in Pringle Bay, which was 14% and 17% of property value, respectively. A similar figure applied to property in the several villages along the west coast would demonstrate willingness to pay for having permanent access to these coastal areas as a resident or holiday home owner. Thus, coastal property contributes significantly to the gross domestic product by generating income in the real estate and financial sectors.

5.4. Education and awareness

Public awareness is now widely recognized as a key factor for effective compliance and effectiveness of protected areas, which are particularly challenged in the vicinity of urban settlements. A key factor contributing to the general increase in conservation and awareness around False Bay has been the increase in eco-tourism and eco-sport-tourism, both in local and international markets. Among others, activities include penguin viewing, SCUBA diving, kayak tours, boat-based whale and seal watching, swimming-with-seals and white shark cage-diving. Many areas in the TMNP MPA, which is managed by SANParks,

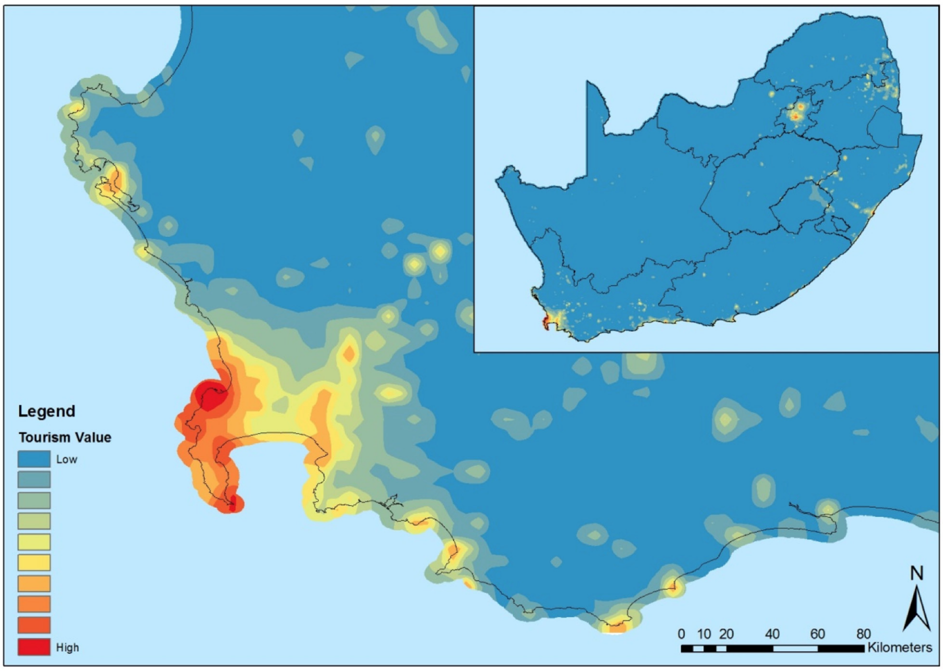

Figure 15: Recreational and tourism value of the False Bay area. Data are based on densities of photographic uploads (J.K. Turpie, G. Letley and K. Forsythe, unpublished results) and shown in relation to the local region and the rest of South Africa (insert). DOI: https://doi.org/10.1525/elementa.367.f15

Table 4: Estimated contribution of different parts of the False Bay coast to tourism value in South African Rand (ZAR) and US$. DOI: https://doi.org/10.1525/elementa.367.t4

Coastal stretch	ZAR millions	US$ millions
Cape Point to Muizenberg	711.8	49.5
Strandfontein to Lourens Estuary	32.4	2.3
Strand to Gordon's bay	39.1	2.7
Kogelberg coast up to Cape Hangklip	125.9	8.8
		63.3
TOTAL	909.2	63.3

are now key tourist attractions and conservation hubs with public outreach, such as the Boulders Beach Penguin Colony area and the Cape of Good Hope park section. Other formally protected areas of False Bay include the Helderberg MPA in the Gordon's Bay region, which is managed by the CoCT and the Kogelberg Biosphere Reserve, which is managed by CapeNature. The formation of the Shark Spotters and its adoption by the CoCT in 2004 was another big step forward in terms of balancing the needs of both people and white shark conservation by proactively reducing the interaction and conflict between recreational water users and sharks, while contributing to research on shark behavior and ecology (Section 5.5.2). In addition, official 'Friends' groups are active in many areas of False Bay, such as Friends of Cape of Good Hope, Friends of Silvermine Nature Area, Friends of Zandvlei, etc. These groups are independent associations that interact with conservation and/or protected areas, but have their own public voice.

5.5. Environmental challenges

5.5.1. Marine litter

Concern about the impacts of plastic litter on marine ecosystems is increasing (Bergmann et al., 2015). False Bay is one of the few locations in South Africa (and indeed in the southern hemisphere) where the distribution and composition of subtidal litter has been studied. Rundgren (1992) surveyed benthic litter at 18 sites around the bay. Most litter was plastic packaging (single-use applications), especially flexible packaging (bags and food wrapping comprised ca. 75% of all litter items) and bottles (ca. 20%). Densities were generally low, especially on sandy bottoms, and most litter was found in reef areas, where it was trapped among rocks or on benthic biota. At a larger scale, litter densities were greater along the northern shore of the bay, and particularly in the northeast corner at Gordon's Bay, presumably driven by the predominantly easterly longshore current that runs along the northern shore of False Bay (Rundgren, 1992).

Rundgren (1992) suggested that beach users were a significant source of subtidal litter, but this notion was not supported by fine-scale studies of surf zone litter. Daily samples collected over the summer season at Muizenberg in 2013–2014 showed an inverse relationship between beach users and the amount of litter in the surf zone (Massot Mascaró, 2015). Large spikes in the amounts of plastic waste occurred 1–3 days after northwest winds drove local upwelling events, suggesting that there is a pool of debris circulating near the seabed in False Bay. Synoptic surveys at 10 sandy beaches confirmed that surf zone litter was concentrated along the northern shores of the bay. The highest litter loads were near the mouths of the Zeekoei, Eerste and Lourens Rivers, confirming the importance of water-borne run-off as the major source of pollutants (Massot Mascaró, 2015).

Surveys of beach litter standing stocks are compromised by increases in beach-cleaning effort (Ryan and Swanepoel, 1996). Most popular bathing beaches are now cleaned daily by the municipality. Despite this bias, standing stocks of macro beach litter (>10 mm) at two False Bay beaches with limited formal cleaning efforts increased five-fold over the last two decades (**Figure 16**). Data for meso-litter (2–10 mm) are more variable, but densities of plastic pellets peaked in the early 2000s, declining following efforts to reduce pellet spillages by the plastics industry (e.g., Operation Cleansweep). However, there has been a steady increase in other types of meso-litter (**Figure 16**), 98% of which is plastic.

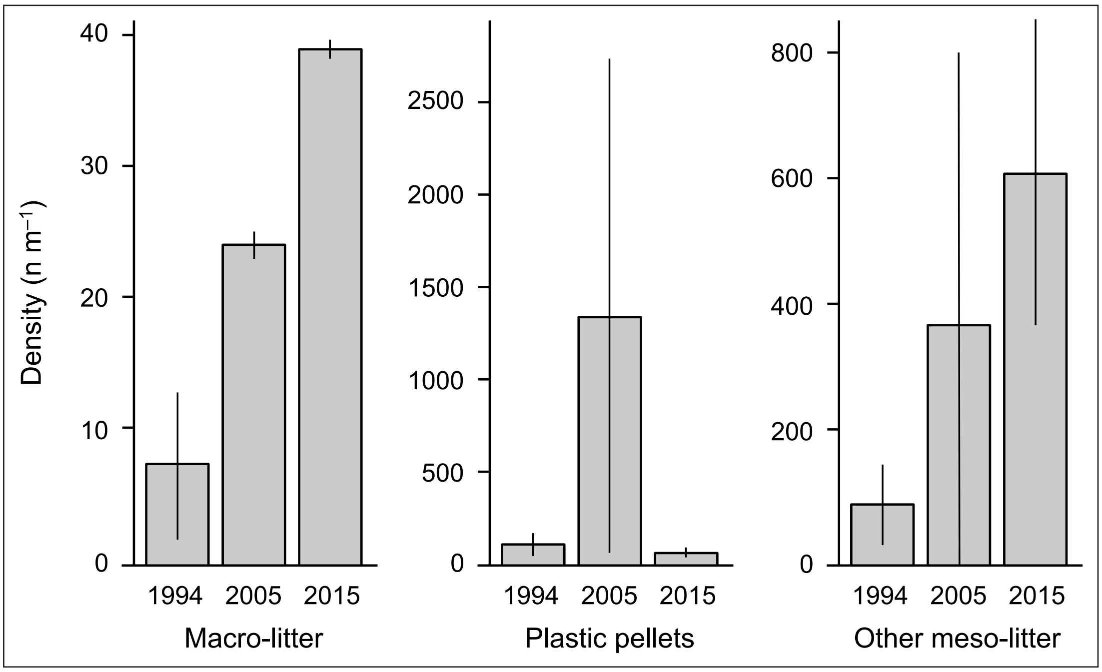

Figure 16: Marine litter in False Bay. Trends in the densities of macro (>10 mm) and meso (2–10 mm) beach litter at two infrequently cleaned beaches on the northern coastline of False Bay near Muizenberg and Strand over the last two decades; error bars show ±95% confidence intervals of the mean (P.G. Ryan and C.L. Moloney, unpublished results). DOI: https://doi.org/10.1525/elementa.367.f16

Litter can have direct impacts on wildlife in False Bay. More than 60% of Kelp Gull nests at the colony at Strandfontein, close to the False Bay Coastal Park dump site, contain human litter (Witteveen et al., 2017). Even in the Kogelberg Wilderness Area near Gordon's Bay, 13% of Kelp Gull nests contained some litter, carried to this remote site after being ingested along with food items (Witteveen et al., 2017). Most of these litter items are made of plastic, and those gulls that use fishing line, rope and plastic strapping for nesting material run the risk of becoming entangled in debris, sometimes with lethal consequences. Plastic ingestion and entanglement are significant issues for a variety of other marine organisms in False Bay (e.g., Ryan, 1990; Section 5.5.2).

5.5.2. Human-wildlife conflicts

Human-wildlife conflict in False Bay is inevitable given the abundance of wildlife on the doorstep of a major city. However, the bay has also been a site for innovative ways of resolving some of the conflicts.

The Cape Peninsula including the west side of False Bay, and Cape Hangklip including some of the area on the east side of False Bay, have been identified as hotspot areas for entanglement of large whales in fishing gear (Meÿer et al., 2011). The southern right, humpback and Bryde's whale are the species that are most prone to being entangled, usually in gear associated with the West Coast rock lobster or experimental octopus fisheries (Meÿer et al., 2011; DEA, 2016). These fisheries deploy traps or pots set along the seafloor, and whales can become entangled in lines connecting the bottom gear to surface buoys. Incidents of large whale entanglement have been on the increase on the southwest coastline of South Africa including in False Bay, due to recovery of whale stocks from past over-exploitation (Section 4.4.3) and increased spatial as well as seasonal overlap between their distributions and those of the above fisheries (Meÿer et al., 2011; DEA, 2016). Where possible, entangled animals are released by trained response teams of the South Africa Whale Disentanglement Network, which was formed under the auspices of the Department of Environmental Affairs and Tourism (now Department of Environmental Affairs) and became operational in 2006 (Meÿer et al., 2011). However, considering likely further increases in numbers of whales and in fishing effort, modifications to the fishing gear (e.g., weighted ropes) and seasonal area closures in the bay would need to be implemented to adequately mitigate for whale entanglement.

Conflict also exists in the bay between the Cape fur seal and fisheries, in particular line-fisherman for snoek and hottentot. Costs to snoek hand-line fishermen resulting from loss of catch or fishing tackle because of seals are estimated to be high relative to costs incurred by other fishery sectors in South Africa from seal interactions, and losses may exceed catches on certain days (Wickens et al., 1992; Wickens, 1996). Moreover, because of no catch limits, each fish taken by seals represents a loss from a fisherman's income. While efficient and humane methods of deterring seals have been explored, none has been consistently successful largely due to the ability of seals to learn and adapt (Shaughnessy, 1985; Wickens et al., 1992; Wickens, 1995), and line fishermen sometimes resort to illegally killing or harming seals in their vicinity (Wickens, 1996; Meÿer et al., 2011). Other forms of fishing with which seals interact elsewhere, such as demersal trawling (Wickens, 1994; Wickens and Sims, 1994) and purse-seining are not permitted in False Bay (Section 5.2), but seals from the bay do interact with these fisheries at feeding grounds further offshore (Section 4.4.2). In the mid-1980s a seal disturbance program (termed a "seal shooing" program), devised by members of the fishing industry to reduce the local seal population, was sanctioned by the relevant Minister and implemented at Seal Island in the bay (Wickens et al., 1991). Personnel were stationed on the island during the breeding season to interfere with the breeding habits of the seals. Pregnant cows were chased off the island and many came ashore on False Bay beaches to give birth. However the aim of the program, to disrupt the mating process and so reduce the subsequent year's pup production, failed — the pup count of the following year was the highest since 1971. The Government's policy was criticized heavily for its lack of scientific justification and its cruelty and was discontinued (Butterworth et al., 1988; David, 1991; Wickens et al., 1991).

Arguably the most notable human-wildlife conflict in False Bay is that between humans and sharks. The first documented shark attack in South Africa took place in False Bay over 100 years ago, and over the next 60 years shark bites were sporadic with an average of one attack every six years (Wallett, 1978; Cliff, 2006). By the 1960s, reporting had improved and between 1960 and 2015, 29 shark bites, five of them fatal, took place in False Bay bringing the average up to one attack every two years (Cliff, 2006; Weltz et al., 2013). To address a growing public concern (Nel and Peschak, 2006), the City of Cape Town and partners have employed shark spotters at eight of its beaches to provide an early warning system for recreational water users (Kock et al., 2012), as well as a shark exclusion net at Fish Hoek (Kock and O'Riain, 2015). Research has demonstrated that this program is an effective way to reduce the spatial overlap between people and sharks in time and space, thus reducing the chance of negative encounters, which have the potential to affect the number of ocean users up to three months following a fatal incident (Engelbrecht et al., 2017).

5.5.3. Climate change vulnerability

Cape Town's coastline not only underpins its economy (by contributing ca. 10.7% to gross domestic product per year; Urban-Econ, 2017), but is also central to its identity, global desirability and sense of place. Paradoxically, due to its sheer length, dynamism, exposure to a high-energy wave climate and pressures driven by climate change, such as sea-level rise, the coastline presents a significant source of risk. Within False Bay and in the context of climate change, risk materializes most obviously in the form of shoreline regression and the subsequent damage to, or loss of, coastal infrastructure. The relatively flat profile of the northern coast of False Bay results in a disproportionate exposure to hazards of storm surges and sea-level rise (Brundrit, 2009). At the coastal resort of Monwabisi, for example, the coastline receded by an estimated

30 m between 2003 and 2014 (Fourie et al., 2015), resulting in service roads to the resort collapsing (**Figure 17A**). The exposure of infrastructure such as coastal resorts and transport routes to a receding coastline is not limited to Monwabisi but is increasingly evident throughout False Bay (**Figure 17B**).

The risks from the exposure of infrastructure to coastal erosion are not limited to financial impacts (e.g., through damage to or loss of property) but materialize in a variety of forms. Collapsing and unstable infrastructure presents a significant health and safety risk to the general public and detracts from the recreational and amenity value of False Bay's beaches (**Figure 17C**). Derelict and abandoned infrastructure along the coastline also attracts anti-social behavior, which in return becomes a burden to surrounding communities that such facilities were originally designed to service and benefit. These risks are anticipated to escalate as a consequence of climate change. The shift of mid-latitude cyclones to a more southerly latitude (Climate Systems Analysis Group, 2016; Section 2.2), as a consequence of a warming climate, is expected to generate waves with a more southerly, and hence more direct, approach into False Bay. This altered wave direction is expected to carry greater energy to the shoreline, thereby increasing the potential for coastal erosion and exposure of coastal infrastructure in False Bay. Southeasterly winds may also further increase in frequency and intensity (Climate Systems Analysis Group, 2016), generating persistent wind-driven wave chop and surge in False Bay (Section 2.5) thus further contributing to coastal erosion and exposure to coastal risk.

Figure 17: Examples of the coastal vulnerability of False Bay. Exposure of **(A)** infrastructure to erosion at Monwabisi, **(B)** the railway to erosion and wind-blown sand at Glencairn, and **(C)** broken infrastructure at the Macassar Beach coastal pubic resort creating an unsightly and unsafe environment (photo credits: B. Sutherland and D. Colenbrander). DOI: https://doi.org/10.1525/elementa.367.f17

The State is a key role player in managing coastal risk and vulnerability in the face of climate change. In South Africa, the state also needs to promote restorative and distributive justice, as a consequence of the country's past of exclusion and separation. While cities have adopted pro-growth and pro-poor strategies to counter the inequalities associated with the apartheid era, pro-growth strategies led by public-private partnerships have emerged as the dominant approach and are shaping how cities are being planned and built (Houghton, 2010). The dominance of the pro-growth strategy is particularly evident in False Bay, where numerous areas have been flagged for nodal development (City of Cape Town, 2009). As a consequence a distinctive dichotomy is beginning to surface within CoCT planning circles, i.e., maximizing of socio-economic upliftment through the conduit of coastal development while simultaneously ensuring that such development is risk averse and sustainable (Colenbrander and Sowman, 2015).

A key strategy employed by the CoCT in responding to escalating risks in False Bay from climate change is the rehabilitation and protection of 'green belts' along the coastline as buffers to climate-related pressures. Ecosystem-based adaptation, although recognized internationally as one of the most effective means to counter climate change impacts (Renaud et al., 2013), is not without its own challenges. Firstly, the rehabilitation and retention of green belts along the coast is construed by some communities in False Bay as anti-development and therefore obstructive to improving the livelihoods of previously marginalized communities. This argument is supported by the fact that intensive and sweeping coastal development has taken place in the past and continues to benefit predominantly white, affluent communities in other locations along Cape Town's coastline, and that such development should be replicated in poorer regions of the False Bay coast, where currently it is very limited. Further, a perception remains in False Bay, particularly in the Cape Flats region, that green belts harbor criminal elements and are thus viewed as undesirable spaces that should rather be developed (Renaud et al., 2013).

6. Discussion

6.1. Changes, gaps and opportunities

Over the past three decades, natural resource management has shifted from independently managed sectors towards a system-oriented approach, as adopted by the frameworks of ecosystem-based management and ICM. Like many other nations, South Africa has adopted these holistic management principles, and they are now entrenched in a number of laws and policies (Section 5.1). Knowledge-based decision-making in terms of ICM, involves the coordination between multiple role-players, including decision makers in the public and private sectors, social and natural scientists, resource owners, users and managers, non-governmental organizations and the general public. For its implementation, such a system-oriented approach requires the setting of overarching objectives and execution of comprehensive assessments. These assessments need to combine all aspects of the physical, biological and human dimensions of a management area into a single management framework.

In the context of False Bay, this integration has proven to be complex and difficult in practice because suitable processes and structures for implementing an integrated approach are often not in place (Celliers et al., 2015) and are hindered by bureaucratic governments (Colenbrander and Bavinck, 2017). A lack of integration between the multiple agencies that hold different parts of the sustainability mandate (Section 5.1) and the lack of knowledge transfer among different stakeholders and disciplines impede effective management for sustainable utilization. This review paper, by holistically synthesizing the most important changes that have occurred in the bay in the past 30 years and their impacts, is able to (a) identify key gaps and opportunities for research and monitoring towards a better understanding of the system and its dynamics, and (b) offers a starting point for a shared vision of the bay's management.

6.1.1. Oceanography

The ability to report on long-term trends and decadal shifts in the physical and chemical oceanography of False Bay is compromised severely by the scarcity of reliable time-series data for most of the key variables. At a much wider scale, a southward shift of the South Atlantic high-pressure system has been observed (Jarre et al., 2015; Vizy and Cook, 2016) coinciding with increased upwelling-favorable winds along the South African southwest and south coasts, inclusive of False Bay. This shift has resulted in cooling of sea temperatures in False Bay in the past 30 years while in contrast air temperatures have increased (Rouault et al., 2010). No data exist to infer long-term trends for nutrients or other chemical constituents of the bay, but increased upwelling along the southwest coastal region, including Cape Point and the Cape Hangklip upwelling cell (Blamey et al., 2012), has likely led to an increase in nutrients, especially on the southern side of the bay during summer. Concurrently, increased effluent discharges along the northern shores of the bay over the past 30 years have likely led to eutrophication and concentration of metals and other pollutants on the northern side of the bay (Section 3.2). Both of these assumptions and the relative importance of various processes, however, require confirmation from empirical evidence. Moreover, the variability in primary production and phytoplankton biomass in False Bay remains unknown (Section 3.3) despite its importance for the rest of the marine food web and implications for fisheries management. One of the few well-studied phenomena of False Bay is the regular occurrence of algal blooms ('red tides') and their effects on marine life and people. For example, significant inter-annual variability in the abundance of the toxin-producing *D. acuminata*, with no obvious long-term trend, has been revealed by daily water sampling and screening for harmful algae in the northeastern corner of the bay since 1992 (Section 3.4).

Routine, publicly available in-situ measurements are currently recorded for wind, coastal temperature, rainfall, evaporation, river flow and water quality indicators. These measurements are all very near shore, however, and other variables have only been measured during shorter-term projects, and are often not published or made accessible. Where time series of in-situ data do exist, they are typically limited to one or few locations such that assessments of spatial variability have been speculative. This limitation also applies to the National Centers for Environmental Prediction Climate Forecast System Reanalysis product that was used for this synthesis. Satellite time series offer an alternative for in situ observations, and some products are available at relatively high spatial resolution (e.g., 1 km for MODIS-TERRA; 4 km for Pathfinder), having allowed for characterization of spatial differences in the seasonality of SST in False Bay and linkages with the ENSO cycle (Dufois and Rouault, 2012). However, issues with algorithm accuracy close to the coast are known to cause unreliable results (Schlegel and Smit, 2016), while different satellite products yield conflicting results when investigating long-term trends. For example, Pathfinder version 4 shows a cooling trend for SST in False Bay at an annual scale, whereas when using Pathfinder this trend is only evident for late summer (Dufois and Rouault, 2012). In the absence of observations, models have been developed to resolve the circulation of the bay (Section 2.3), its thermal structure and wave parameters, but few of these studies have been published to date (Section 2.5). Nonetheless, in situ measurements are needed to inform and verify models, and at this stage there is a clear deficiency in oceanographic observations for False Bay. To address this issue, the South African Environmental Observation Network is currently planning to deploy an intensive observations array, consisting of in situ and remote sensing instruments in the near future. This initiative will undoubtedly contribute immensely to the study of the False Bay system, especially if the project takes into consideration the data requirements to address broader multi-disciplinary research questions, as recommended in this review (Section 6.3).

6.1.2. Biology

False Bay is highly productive and diverse in marine life, given its location at the interface between the cold-temperate west-coast upwelling region and the influence of the warm Agulhas current to its east. Over the past 30 years, kelp has expanded along the rocky western and eastern shores (Section 4.1.3), transforming nearshore ecosystems into dense kelp forests and likely facilitating the expansion of a suite of associated species. A shift in the relative abundance of the west coast rock lobster from the west to the southwest coast has resulted in an increase in its population size to the east of False Bay. This shift is likely a response to environmental change in conjunction with reduced predation pressure associated with the decline of reef fish as a result of over-fishing (Cockcroft et al., 2008; Blamey et al., 2014). However, the impacts of anthropogenic pressures on ecological interactions, such as those triggering trophic cascades, have seldom been researched explicitly in False Bay and surrounds.

By the 1990s, all of the most sought-after line-fish in False Bay had undergone stock declines due to overexploitation by commercial and recreational fisheries in the bay and countrywide. Since then, despite prohibitions on particularly destructive fishing gear such as purse-seining, and a reduction in beach-seine effort of 80%, most stocks in False Bay have continued to decline, some to critical levels. This decline might be attributed to the relatively unchanged overall effort in shore-angling and boat-based line fisheries (Section 5.2.1). The one exception is yellowtail, which has successfully recovered from collapse following the closure of the purse-seine fishery in the early 1980s. Diminishing returns in the commercial line-fishery have been exacerbated by an increase in storminess and a drop in the number of days that the fleet can fish (Augustyn et al., 2017). To partly compensate for declining yields and accommodate demand for participation in commercial fisheries, new resources are currently being explored, e.g., through an experimental octopus fishery.

Due to their dependence on the shifting distributions of pelagic fish or rock lobster as food source, numbers of several seabird species have increased along the South African south coast at the expense of the west coast (Section 4.3). These include the endangered African penguin, which established a new breeding colony in False Bay in 1985. Breeding at this colony has remained stable in recent years in contrast to several colonies in the Western Cape Province, which have shown critical declines. Efforts to protect and boost this colony, e.g., through protection from predators, human disturbance and pollution events, are essential not only for the long-term survival of the species in this province, but for sustaining the important direct and indirect benefits of tourism at this colony to the local economy. This case provides a useful example of the type of synergistic solutions that are needed for the sustainable management of False Bay.

Penguins (Section 4.3), whales, dolphins, seals and sharks (Section 4.4) constitute the so-called "marine big 5", which together are the basis for considerable generation of revenue for the bay from tourism. Whereas seal and whale populations in the bay have shown recovery from past over-exploitation, recent, as yet unexplained, reductions in the numbers of southern right whales and white sharks have occurred along the southern Cape coast including False Bay. Given the iconic status of the white shark, its protected status, and its value for tourism, debate regarding the causes of the population change is robust and will likely inspire fresh research on the species. The changes in this top predator population also provide opportunity to gain greater insight into their role in structuring the communities in the bay, i.e., by assessing the changes in other species that follow the reduction in white shark numbers. In general, the role of top predators, including white sharks and seals, in ecosystem function in the bay is currently a major gap in research. Another gap is the lack of understanding of other cetacean species that are commonly or occasionally observed in the bay, in terms of their population structure, distribution, abundance and trends. This data shortage may be because of the challenges of studying highly mobile and/or elusive species such as Bryde's whales and dolphin species. Especially given the unknown population size and structure of Bryde's whales and the unexplained population level changes regarding southern right whales (Section 4.4.3), monitoring of incidences of entanglement (e.g., in fishing gear for rock lobster or octopus) of these and other species, and reducing and mitigating such interactions, are a priority. Citizen involvement in reporting entanglement incidence is essential for both monitoring and mitigation.

Various introduced species that thrive in cooling waters have invaded the bay (Section 4.2), while some indigenous warm-water species have retracted. Furthermore, in a survey of all major ports in South Africa the most alien species were found to occur in Simon's Town Harbor in False Bay, and yachts were identified as the most likely vector for their introduction (Peters et al., 2017). To avoid new invasions and the dramatic effects they have on ecosystems, there is an urgent need to monitor harbors and marinas, as well as natural ecosystems in their vicinity for the occurrence of known problem species. Under consideration are the involvement of local port authorities and yacht owners in hull cleaning and monitoring initiatives, the establishment of eco-certificates for ports that participate in the eradication of alien and invasive species, and the introduction of an anti-fouling levy.

Waste and effluent management has not kept pace with the rapid growth of Cape Town's population, especially to the north of the bay. Consequently, pollution levels in the form of nutrients, metals and fecal coliforms, as well as litter, have increased in the bay. While existing monitoring efforts show episodic emergence of plastic litter with winter storms, the magnitude of the litter submerged and retained in the bay and its ecological impacts, is a matter of speculation. Pollution has also negatively impacted the ecological integrity of most estuaries, which have incurred flow, habitat and mouth modifications, alien invasions, overfishing and, in the case of estuaries that receive large volumes of treated effluent, freshening (Section 4.1.1). Assessments of pollution in unconsolidated (soft-bottom) substrates suggest that localized impacts have most likely increased at least in the northern part of the bay (Section 3.2), but until now little research has focused on biotic communities associated with these sediments, representing a gap for further research. At the time of this paper, development of multiple coastal desalination plants and re-use of treated effluent are being planned by the City of

Cape Town as a response to prolonged drought. Of these, the latter might address issues such as estuarine freshening. However, discharges of brine into the bay from the former are likely to be a future reality, which will require careful monitoring of the effects of hypersaline plumes on the receiving environment.

6.1.3. Human dimensions

The vast economic value of False Bay is evident through tourism-generated revenue and coastal property values that are significantly higher than outside the bay area (Section 5.3). Among the factors that are most unfavorable for tourism is coastal pollution in the form of litter, because it considerably undermines the aesthetic value of the coast (Figure S3). Litter also poses a direct threat to marine life through ingestion and entanglements. The issue of marine litter is thus receiving increasing attention internationally and locally, and numerous awareness-raising campaigns and coastal cleanup programs involving public participation have been initiated in the past decade. Furthermore, various environmental education and citizen science initiatives have been launched at local and national scales in South Africa, addressing the need to foster public awareness of environmental issues, which is in turn widely recognized as a prerequisite for achieving effective integrated coastal management (Sowman and Malan, 2018). These initiatives include programs such as Coastwatch, Working for the Coast, and the Blue Flag beach campaign, all of which aim to instill in the public a sense of ownership of the coast and responsibility for it (Taljaard et al., 2012). These programs also aim to address poverty alleviation by offering employment opportunities to impoverished communities or unemployed graduates, and are thus considered to have overall positive impacts on coastal communities (Sowman and Malan, 2018). Expanding such programs to further contribute to environmental monitoring, coastal cleanups, guiding local tourism, and patrolling the coasts to improve safety and security and generate jobs, are all being explored.

The governance of coastlines worldwide remains a challenge, primarily due to their complexity and multiple converging pressures (Cicin-Sain et al., 1998; Chuenpagdee et al., 2008; Fukuyama, 2013; Glavovic, 2013). In False Bay, the escalating risks associated with climate impacts, increasing developmental pressures and the divergent perspectives between governance actors within the coastal space, warrants a re-appraisal of governance approaches. The eight principles developed by Lockwood (2010) — legitimacy, transparency, accountability, inclusiveness, fairness, integration, capability, and adaptability — provide normative guidance for the establishment of good-practice multilevel governance of socio-ecological systems under change. In this context, the management of False Bay would benefit from a transition in governance, moving away from the conventional top-down, state-centric and regulatory approach, to a more inclusive and responsive mode defined by state-society interactions. A fundamental step towards achieving this transition is the establishment of institutional structures that facilitate legitimate and authentic engagement between the State and civil society, and thus move towards 'co-governance' of the bay.

6.2. Synthesis

Since the last multi-disciplinary assessment of the bay was conducted in 1991, numerous important changes have occurred in its socio-ecological system and dynamics. False Bay has been noticeably altered by changes in climate regimes and associated ecosystem shifts, influenced by its location in the transition zone between cooler west coast and warmer south coast conditions. In particular, a change in the regional wind field has caused an eastward expansion of upwelling (Rouault et al., 2010; Blamey et al., 2012) and reduced rainfall in this region (Rouault and Richard, 2005). In concert, the distributions of key components of the marine ecosystem have shifted eastward, including kelp and rock lobster (Section 4.1.3), seabirds (Section 4.3), and pelagic fish species (Blamey et al., 2015), as well as several invasive alien species (Section 4.2). Moreover, the human population of Cape Town has more than doubled since the 1980s, mainly due to influx from impoverished rural areas (Statistics South Africa, 2016). This increase has led to intensified exploitation, coastal developments and pollution, largely as a result of poor servicing of sewage, solid waste and storm water, especially for the rapidly expanding informal and backyard settlements. Overfishing in various forms has led to alarming declines in the catches of many commercially and recreationally targeted fish (Section 5.2.1) and, while fishing regulations have shown some successes (such as for yellowtail), illegal fishing is rife (Brill and Raemaekers, 2013). It has become increasingly recognized that compliance would benefit from a more integrated and systems-oriented approach (e.g., ICM) whereby the bay is holistically managed (Section 5.1) by embracing both social and ecological goals.

For ICM to be effective, it has to provide for adaptive responses, e.g., in the form of guidelines, regulations or interventions, to inform multiple role players and decision makers when changes take place in the status of the socio-ecological system. Comprehensive socio-ecological monitoring programs need to be designed that track key societal goals, incorporate various stakeholders and appropriately integrate the ecological and the human dimensions within a single decision-making framework (Longo and Halpern, 2015). The data generated by appropriate monitoring will likely facilitate evidence-based communication between conflicting user groups and promote a more transparent decision-making process. Furthermore, there is a need for holistic, systems-oriented and collaborative approaches to the governance of coastal zones, and particularly for cases where the human developments and natural spaces intercept. The value and need to involve citizens in information sharing, monitoring and management is therefore essential, both for the provision of observations as well as the building of awareness of the need for sustainability and dependence on natural integrity.

6.3. Recommended priorities for future research and monitoring

Based on the knowledge gaps identified in this review, we make the following recommendations to guide overarching priorities of future multidisciplinary research and monitoring to support the integrated management of False Bay:

- Multidisciplinary integrated monitoring of socio-ecological systems requires a coordinated approach to data collection, including the integration, optimization and standardization of sampling protocols.
- Repeat observations are required to gain a better understanding of the dynamics and long-term trends in the physical, chemical and biological oceanography of the bay at various spatial and temporal scales. These include in-situ measurements of wind, currents, temperature, stratification, swell; measurements of nutrients from terrestrial and oceanic sources; monitoring of chemical pollutants in the water column and sediments and water quality indicators; evaluating the role of freshwater input; and monitoring chlorophyll *a*, as a proxy for primary production, and the occurrence of HABs and anoxia.
- Coherent monitoring of multiple variables, using automated systems where possible and linking measurements with simultaneously conducted observations of physical, chemical, biological and socio-economical parameters, which will enhance the understanding of interactions and feedback loops within the False Bay system.
- Complementary application of technologies, such as real-time mooring arrays, satellites, drones, and remotely operated vehicles will speed up data acquisition and provide spatio-temporal coverage relevant to various ecosystem components; the development of down-stream information technologies is required to process, integrate and manage vast quantities of data.
- Analytical frameworks for multidisciplinary research and monitoring will necessitate integration of large datasets, which will require state-of-the art data management systems and novel efficient analysis tools.
- Studies of the combined and interactive effects of multiple variables (particularly those derived from repeat observations) and of links between different aspects of the socio-ecological system need to be encouraged, as well as those that provide future projections and thereby inform mitigation and adaptation measures. Numerical models are effective tools to achieve such integration and prediction, and to integrate the physical, biological and human dimensions of the bay.
- Integrated biodiversity monitoring programs with standardized sampling protocols need to be developed for estuaries, intertidal and subtidal habitats; particular attention needs to given to areas in and close to marinas and harbors to detect and respond to introductions of alien and invasive species as rapidly as possible. These monitoring efforts can capitalize on mandated institutions (DEA, SanParks, Cape Nature, etc.) and local universities, who may coordinate initiatives.
- The roles of top predators in structuring communities (top-down) need to be assessed to be able to inform management actions regarding their extraction or protection levels.
- The sustainability of various fishing practices and their effects on ecosystem functioning and marine food webs need to be further explored.
- Avenues towards a more prolific and inclusive coastal economy need to be explored by appropriate research programs that identify new opportunities and ways to achieve equitable sharing of benefits. This exploration includes research regarding revenues of non-extractive uses of the bay, such as marine tourism, which are in line with a vision of sustainability of the bay.
- The sources, composition, extent and impacts of marine litter and micro-plastics on ecosystems and the economy need to be established, and appropriate policies and laws developed for their mitigation.
- A central database would be ideal to store and share data regarding the physical, biological and social aspects of the bay and facilitate interdisciplinary research. Routine observational data are not publicly available at this stage, and data-sharing agreements are not in place, which forms a major hurdle towards integrating disciplines.
- Knowledge-sharing forums, such as regular multidisciplinary workshops, courses, conferences and public events need to be fostered; facilitation of a lively stakeholder community through social media platforms and themed events will further enable inter-disciplinary collaborations and ICM.
- Job creation, capacity building and education are key societal goals for sustainable development that need to be built into all research and monitoring activities.
- Citizen science programs can multiply the sampling effort, while also contributing substantially to education and awareness building, especially where they involve people from all parts of society.

Supplemental files

The supplemental files for this article can be found as follows:

- **Figure S1. Geological map of False Bay and the Cape Peninsula.** Distinct differences exist between the western and eastern parts of the bay. Source: Council for Geoscience, South Africa. DOI: https://doi.org/10.1525/elementa.367.s1
- **Figure S2. Sea surface height at Simonstown, False Bay.** Observations (blue dots) and projection using a MIROC model rcp85 (green line) with trend line. The data show an approximate 5.7-cm rise in mean sea level over the past 30 years (0.19 cm yr^{-1}). DOI: https://doi.org/10.1525/elementa.367.s2
- **Figure S3. Factors affecting the tourism value of the Kogelberg coast, False Bay.** Estimated change from the status quo in terms of utility and expenditure, under different scenarios for the Kogelberg coast (adapted from Turpie and de Wet, 2007). DOI: https://doi.org/10.1525/elementa.367.s3
- **Table S1.** Overview of key ecological features of False Bay's estuaries: condition, biodiversity and conservation importance, major pressures, remedial actions required to improve health, and management and monitoring initiativesa. DOI: https://doi.org/10.1525/elementa.367.s4

Acknowledgements

We thank the multiple institutions and people that have made resources available to compile this review. Apart from listed affiliations, staff of the Nansen-Tutu Centre and the Research Demography Unit of the University of Cape Town have provided significant input. Janine Adams kindly reviewed the estuaries section, and Jordan Stander and Jaimie Poovan assisted with formatting of the manuscript. We are extremely grateful for the thorough editing and comments by George Branch and Tommy Bornman, which substantially improved this article.

Competing interests

The authors have no competing interests to declare.

Author contributions

Contributed to conception and design: MCP, RCL, SPK, SJPNR, JCH, LKB; Drafted and/or revised the article: all authors; Approved the submitted version for publication: all authors.

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How to cite this article: Pfaff, MC, Logston, RC, Raemaekers, SJPN, Hermes, JC, Blamey, LK, Cawthra, HC, Colenbrander, DR, Crawford, RJM, Day, E, du Plessis, N, Elwen, SH, Fawcett, SE, Jury, MR, Karenyi, N, Kerwath, SE, Kock, AA, Krug, M, Lamberth, SJ, Omardien, A, Pitcher, GC, Rautenbach, C, Robinson, TB, Rouault, M, Ryan, PG, Shillington, FA, Sowman, M, Sparks, CC, Turpie, JK, van Niekerk, L, Waldron, HN, Yeld, EM and Kirkman, SP. 2019. A synthesis of three decades of socio-ecological change in False Bay, South Africa: setting the scene for multidisciplinary research and management. *Elem Sci Anth,* 7: 32. DOI: https://doi.org/10.1525/elementa.367

Domain Editor-in-Chief: Jody W. Deming, School of Oceanography, University of Washington, US

Knowledge Domain: Ocean Science

Submitted: 29 November 2018 **Accepted:** 02 July 2019 **Published:** 08 August 2019

ELEMENTA
Science of the Anthropocene

Elem Sci Anth is a peer-reviewed open access
journal published by University of California Press.

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