NATURE'S *letters*



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Journal's focus and scope

Nature's Letters is a multi-disciplinary journal aimed at documenting, describing and critically reflecting on applied social (e.g. historical) and/or ecological research topics that contribute to understanding and conserving Nature's Valley and its surrounds.

The journal is published online and in print format by NVT Tsitsikamma, a not-for-profit company that focuses on conservation, conservation education, applied research and community engagement in the Western Cape, South Africa.

Manuscripts for review can be submitted by anyone working on or who has worked on any social and/or ecological topics in and around Nature's Valley within the past five years.

Guidelines for submissions are available at https://nvt.org.za/natures-letters/.

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FROM THE EDITOR'S DESK

As we delve deeper into the remarkable biodiversity of Nature's Valley, we uncover its increasingly fascinating and intricate ecological tapestry. Nature's Valley is integral to the Cape Floristic Region[1] and is situated within the UNESCO-designated Garden Route Biosphere Reserve, adjacent to the Tsitsikamma section of the Garden Route National Park. Many are surprised to learn that our region is endowed with several prestigious designations. Amongst others, it can boast being–

- One of only ten Whale Heritage Sites globally (World Cetacean Alliance);
- One of 11 prioritised strategic water source areas in South Africa (Department of Forestry, Fisheries and the Environment);
- One of 18 ecologically or biologically significant areas in South Africa (South African National Biodiversity Institute);
- One of 112 important bird and biodiversity areas in South Africa (BirdLife SA); and
- One of 165 Hope Spots (Mission Blue).

From an ecological research perspective, the area's diverse ecosystems render it a valuable site for scientific inquiry. The principal ecosystems include:

- Afrotemperate forests, constituting a significant portion of the largest remaining forest complex in southern Africa;
- Tsitsikamma fynbos which, within the Sout (Oos) River catchment, hosts unique fynbos types such as the vulnerable Tsitsikamma sandstone fynbos and South Outeniqua sandstone fynbos, as well as the endangered Garden Route shale fynbos[2];
- Unique rivers and estuaries which feature macroinvertebrate Gondwana relics[3,4];
- Coastal interfaces, encompassing dynamic dunes significantly impacted by human activity along with sandy and rocky shores; and
- A marine zone linking two marine protected areas, Robberg and Tsitsikamma, the latter being South Africa's oldest marine protected area.

In the past year, we have made significant progress in expanding our knowledge regarding key species (including primates, birds and larger forest mammals) that fulfil essential roles in the local ecology. In this issue of *Nature's Letters,* three newly published papers addressing these topics will be presented.

Since our inaugural issue, we have broadened our research focus via intern projects and research partnerships to include subjects previously neglected by NVT, such as sandy shore ecosystems, dung beetles, bats and otters. Moreover, we have contributed substantially to marine and

[1] It is noteworthy that this is the only hotspot worldwide encompassing an entire floral kingdom (fynbos) which includes five of South Africa's twelve endemic plant families and 160 endemic genera, hosting species found nowhere else on Earth.

[2] Apart from fynbos, it ought to be noted that the area is also home to various near-threatened, vulnerable and endangered species, including *Bartholina etheliae*, *Brunia nodiflora*, *Ceratandra grandiflora*, *Disa cernua*, *Disa cornuta*, *Disa hians*, *Disa sagialis*, *Erica onusta*, *Eulophia aculeata*, *Holothrix villosa*, *Satyrium acuminatum*, *Satyrium longicolle* and *Satyrium outeniquense*, all of which are adapted to the local temperate climate.

[3] A preliminary study conducted by de Moor and Bellingan in 2010 revealed three undescribed genera and 16 undescribed species of mayflies (Ephemeroptera) and caddisflies (Trichoptera).

[4] de Moor, F.C. & Bellingan, T.A. 2010. Evaluation of the conservation requirements of Trichoptera from the Tsitsikamma mountain streams in South Africa. *Water SA*, 36(1):1-8.

coastal research through the publication of a report analysing the drivers, pressures, conditions and impacts of human activities in Plettenberg Bay. This report proposes numerous strategies to mitigate such effects and we are collaborating with various stakeholder groups to develop a spatial and management plan for the bay.

I am pleased to announce that we are now officially co-champions of the Plettenberg Hope Spot, an initiative spearheaded globally by Dr Sylvia Earle through Mission Blue. In this role, we are working closely with the ORCA Foundation, contributing meaningfully to marine research efforts.

Additionally, we are advancing plans to establish a *Community Wellness and Sustainability Centre* in Kurland (with a satellite in Covie) intended to support future research endeavours and fortify community-based conservation initiatives. This centre is poised to enhance our contributions to social-ecological research.

I eagerly anticipate the visit from the Transdisciplinary International Learning Lab group in May 2025 who will collaborate with NVT and other key organisations such as SANParks and CapeNature. Our joint project aims to explore the potential use of traditional ecological knowledge related to medicinal plants, gardening and nature guiding as vehicles for self-employment opportunities. Given the pressing need for job creation in our area (Nell & Coetzee, 2024[5]), this initiative holds promise for positive community impact. Future editions of *Nature's Letters* may feature some of our joint findings.

In this issue, we also present insightful research contributions from Nature's Valley property owners John Blaine and Des Mahony: The one sketches the geological history of Nature's Valley and the other the extraordinary contribution of the young Swedish explorer, John Fredrik Victorin, who spent a mere 16 months in and around the valley back in the 1850s.

To conclude, akin to our inaugural issue, I will contextualise the findings presented here with a brief overview of their implications for our local conservation efforts.

I trust you will find this edition of *Nature's Letters* enlightening. As always, all feedback, insights and suggestions are most welcome.

Sincerely,



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[5] Nell, W. & Coetzee, H.C. 2024. *Community needs, assets, psycho-social well-being and environmental attitudes in Kurland and Covie, Western Cape, South Africa: Implications for interventions and community-based conservation.* (In NVT internal report). Available on request via https://naturesvalleytrust.co.za/applied-ecological-research/scientific-publications/

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SCHOLARLY PAPERS

To follow are seven papers submitted by former visiting post-graduate students and interns, as well as current and former staff and research partners. They explore a diverse array of topics ranging from birds, bushbuck and invertebrates to carbon dynamics.

Together, these papers contribute to our ever-increasing knowledge base related to nearly every habitat found in the valley – estuaries, forests, fynbos and rivers – along with the hitherto unexplored sandy shores.

To pique your interest, here's a brief overview of what you can expect to learn from each paper, organised by subject:

Birds

1. Who would have guessed that Nature's Valley village is home to at least 75 different bird species? The number of observable species fluctuates, with the highest species density found in Zone 2, located in the north-eastern corner of the valley between Forest Drive, Cineraria Street, St George's and Lagoon Drive. Kayla Webster, a former colleague now working with Birds & Bats Unlimited Environmental Consultants, authored a paper detailing the results of bird surveys we conducted in Nature's Valley over the past year. This research excites me and highlights the impactful, targeted interventions possible when one truly understands one's local area.
2. In another paper by Kayla Webster, she analyses a three-year project, funded by the Hans Hoheisen Charitable Trust, focusing on the white-fronted plover (*Anarhynchus marginatus*). Our study investigated the effectiveness of temporary nest enclosures designed to conserve this sensitive shore-breeding bird species. Many may be surprised to learn that the research indicates these enclosures do not significantly enhance the species' survival probability. In fact, they may have unintentionally drawn attention to nest sites but, nevertheless, may have had some positive effects by protecting the dunes. These findings have implications for NVT's interventions related to the conservation of coastal breeding birds and dune restoration.

Bushbuck

3. Giulia Baldini, a former NVT intern who recently completed her master's degree under Dr Dominic Wright at Linköping University, examined the perceived impacts of dogs and humans on the behaviour of bushbuck (*Tragelaphus scriptus*) in the Hebron Private Nature Reserve where NVT is conducting extensive forest research and restoration work. Her findings reveal that while bushbuck are not adversely affected by human presence, dogs negatively influence their behaviour, triggering more flight responses. Consequently, dogs are now prohibited in the Hebron Forest – a great example of how research can inform management decisions in protected areas.

Carbon dynamics in the Sout (Oos) River catchment

4. A paper by Micheal Powell and Nicholaus Huchzermeyer from Rhodes University, compiled by NVT intern Carla van Hasselt, builds on the project summary published in the first issue of *Nature's Letters*. It presents key findings on carbon stocks in various vegetation types in Nature's Valley, including Tsitsikamma Sandstone Fynbos and Southern Afrotemperate Forest. I had long suspected that invasive alien plants threaten these ecosystems and am relieved to learn that removing them and restoring degraded areas can enhance carbon sequestration. This work underscores the importance of addressing less obvious topics like carbon assessments to inform local conservation efforts and mitigate climate change in the long term.

Invertebrates

5. Being sensitive to changes in water quality and habitat conditions, macroinvertebrates serve as valuable bioindicators of freshwater health. Drs Wynand Vlok and Nick Riverse-Moore from Bioassets, again assisted by NVT intern Carla van Hasselt, explored the diversity and abundance of macroinvertebrates in the Sout (Oos) River. Their study, which sampled four sites, revealed spatial and seasonal trends influenced by human activities. Diversity was highest upstream (where impacts were minimal) and decreased downstream (where impacts were more evident). The findings highlight the role of macroinvertebrates in catchment management and biodiversity conservation, an aspect NVT already incorporated in its long-term monitoring plans.
6. In her paper, Dr Linda Harris from Nelson Mandela University reports on the biodiversity of sandy beach macrofauna between Nature's Valley and Plettenberg Bay. Nature's Valley was surveyed for the first time in 2024, while the five sites in Plettenberg Bay were last sampled in the 1980s. Unfortunately, overall species richness declined from 24 species in the 1980s to 18 species in 2024, with Plettenberg Bay experiencing a decline in both richness and abundance while Keurboomstrand showed stability or slight increases. Linda also discovered a new population of *Tylos capensis* (pill bug) at Nature's Valley and confirmed their presence at Keurboomstrand, though this species seems to have vanished from Plettenberg Bay. We are not entirely sure why this is happening, but it seems likely related to increased disturbance levels and clam wash-outs. Linda's research highlights the urgent need for interventions to alleviate human pressures on the bay's beaches.

Rivers and estuaries

7. The final paper in this issue of *Nature's Letters* presents a two-year source-to-sea project in the Sout (Oos) River catchment (funded by the Whitely Fund for Nature) aimed at developing a model for understanding, restoring and conserving rivers and catchments in South Africa. This approach incorporates the latest thinking on nature-based solutions and highlights the importance of multidisciplinary collaboration in conservation. It also illustrates how planned interventions, such as invasive alien plant removal, can improve ecosystem stability, enhance biodiversity and strengthen community participation in conservation efforts.

Birders paradise: An inventory of species in the village of Nature's Valley, South Africa

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Creating species inventories is becoming an increasingly important task with modern day global change (Stephenson & Stengel, 2020). Access to evidence of historic biodiversity provides a backstory of environmental change and is a requisite to effective conservation. Birds are one of the most valuable indicators of environmental change (Furness & Greenwood, 1993) and have been the subject of hundreds of conservation-themed studies (Stephenson & Stengel, 2020). The presence of birds (considering diversity, species richness and abundance) in an area can inform us about the condition of the local environment.

A co-benefit of creating species inventories, is that it can support eco-tourism for a particular area (Salvador *et al*., 2011). Experiencing new wildlife and landscapes is a foundation of eco-tourism and can play a large role in supporting conservation initiatives. This holds true for birds in particular as birding is a popular hobby across the world, attracting birders to many corners of the globe in search of species and birding-related experiences to add to their lists (Steven *et al*., 2015).

The bird diversity and abundance in Nature's Valley, South Africa has long been celebrated by residents and frequent visitors, with some accounts reaching up to 150 species for the area (Lucking, 2016). In fact, Nature's Valley was recently recognised by BirdLife South Africa as a birding hotspot and is now registered on their 'GoBirding' website, which lists hundreds of acclaimed birding sites across South Africa (BirdLife South Africa, s.a.).

The present study aimed at building an inventory of bird species that one is most likely to encounter in the village of Nature's Valley, South Africa (**Figure 1**). Additionally, it sets out to determine which sections of the village have the greatest species richness and are, hence, most rewarding for birding excursions. The village is a particularly unique urban area for three main reasons. Firstly, it is surrounded by an impressive variety of natural habitats within a relatively small area. Secondly, the village was designed to include stepping-stone habitats and corridors that connect the interior to the surrounding protected areas. Finally, the general ethos among permanent residents tends towards nature-oriented and sustainable practices (such as indigenous gardens), which is further encouraged and supported by their local urban conservancy. Given these favourable circumstances, species richness was expected to be well-represented within the Nature's Valley urban area. Zone 4 (**Figure 1**) in particular was expected to have the highest species richness due to its proximity to both coastal and estuary habitat.

Methods

Nature's Valley is a residential village situated on the southern Cape Coast of South Africa (**Figure 1**). The village, consisting of only 400 erven, is surrounded by the Tsitsikamma section of the Garden Route National Park. There are three main vegetation types in the area, including Tsitsikamma Sandstone Fynbos, Southern Afrotemperate Forest and Cape Seashore Vegetation (Rutherford & Mucina, 2006). The village and surrounds offer a broad range of habitat types for birds, with the Groot Rivier estuary to the east, Nature's Valley Beach to the south, forested hill slopes that plateau to dense fynbos to the west and north, and three green spaces in the centre of the village, including a small fynbos reserve patch, a forest reserve and a botanical garden (with fynbos, forest and thicket sections).

Bird species richness was surveyed once a month for one year, from January 2023 to February 2024, excluding December 2023 (February was surveyed again in 2024 to ensure a third summer month could be included in the study). The survey area, which encompassed the entirety of the 52-ha village, was divided into four zones along existing public roads (**Figure 1**).

Road transect surveys were conducted on foot at a moderately slow pace in the mornings between 8 am and 10 am when bird activity was high, with one or two observers (depending on skill level and capacity) per zone. Transects were completed along peripheral roads as well as interior roads, but zones were treated as mutually exclusive entities (i.e. when walking between Zones 1 and 3, the observer surveying for Zone 1 would only record birds that were within Zone 1). Additionally, birds were only recorded if they occurred within or flying above the zones outlined in **Figure 1** and not the neighbouring habitat. When a bird was observed (calls were not used to confirm presence), the observer would confirm the species using binoculars and record its presence if it had not yet been seen during the specific survey session. Presence was recorded along with the habitat it was seen in and its behaviour.

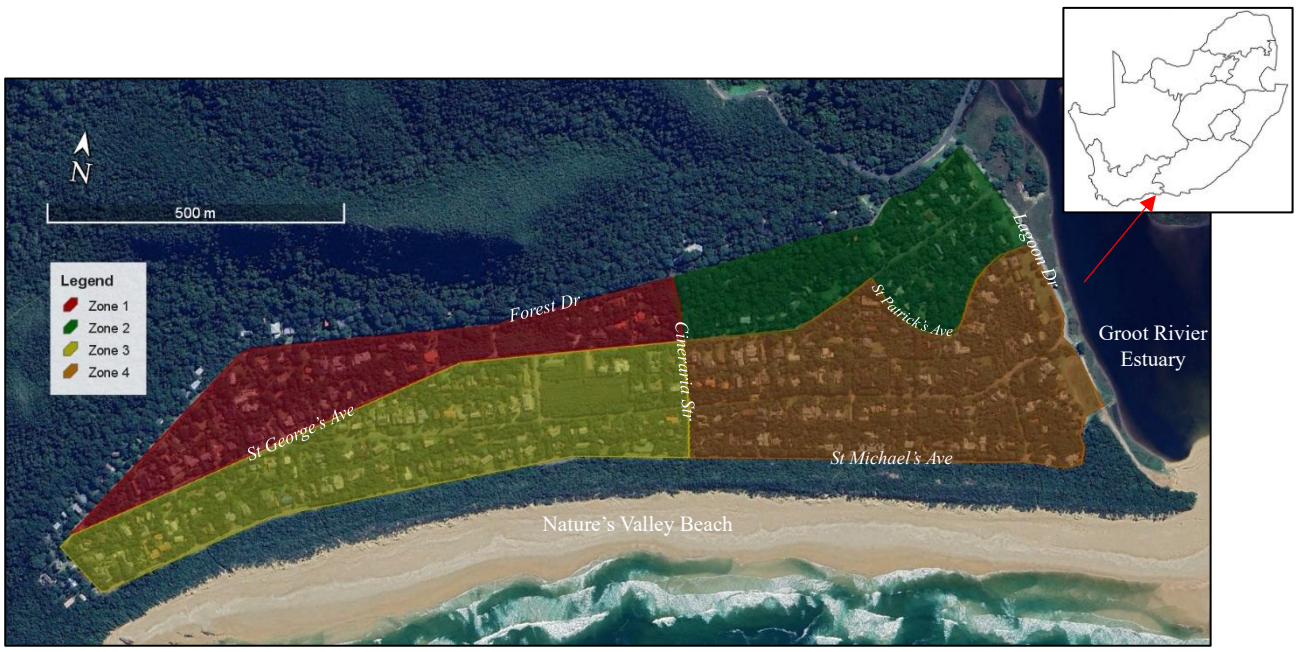


Figure 1: The Nature's Valley residential area with zonation of the survey area depicted in different colours

Results

A total of 75 bird species were detected in the Nature's Valley village throughout the survey period (see **Appendix A** for a full checklist). Of these, 53% were passerines (commonly known as songbirds, such as robins, sunbirds and canaries), 47% were non-passerines (such as raptors, swifts, doves and pigeons), of which 29% were aquatic (species that are normally associated with water, such as cormorants and egrets). Some of the most sighted species included Cape white-eye (*Zosterops virens*), sombre greenbul (*Andropadus importunus*), African dusky flycatcher (*Muscicapa adusta*) and Knysna turaco (*Tauraco corythaix*), while some of the rarer species included black-collared barbet (*Lybius torquatus*), blue crane (*Grus paradisea*), Cape longclaw (*Macronyx capensis*) and African hoopoe (*Upupa africana*).

The cumulative species richness curve indicates a typical sharp rise in number of species in the beginning of the study, but soon thereafter, a far more gradual increase is shown until the final survey in February 2024, which once again shows a sharp rise in species (**Figure 2**). The ability to extrapolate an estimate of total species richness for the area with any reliability was limited due to a relatively small sampling effort. The sudden increase in number of species in the last survey (February 2024) suggests that further surveying effort would be required to better represent the full species assemblage within Nature's Valley.

Some species were more common than others, with 35% occurring across all four zones, while 32% were recorded in only one of the respective zones (**Table A1, Appendix A**). The remaining species were found in two or three different zones. As expected, Zone 4, which contains the village botanical garden (the Phyl Martin Park) and neighbours the Groot River lagoon and coastal dune habitat, had the greatest number of species at a total of 56 (**Table 1**). This was followed by 50 species in Zone 3 which contains the small fynbos reserve and is surrounded by coastal dune and forest habitat, 44 species in Zone 2 which is surrounded by forest and marsh and lastly 39 species in Zone 1 which contains the forest reserve and is surrounded by forest habitat.

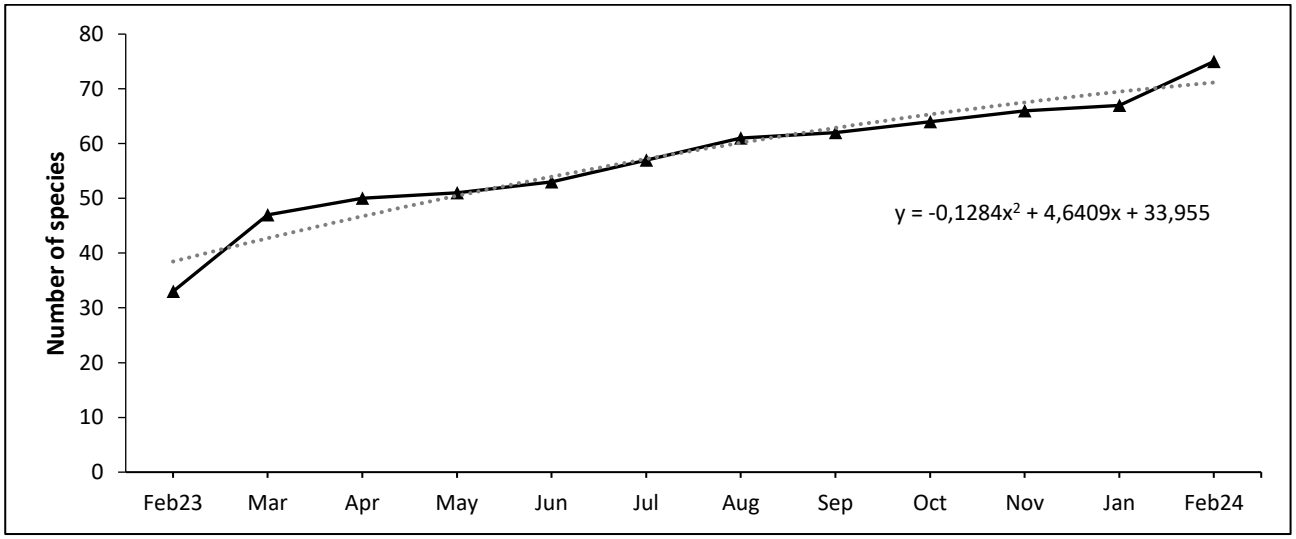


Figure 2: Cumulative species curve for bird species occurring in the Nature's Valley residential village

**One survey was conducted per month, for 12 months. The dotted line is the trendline, with the function equation below the curve*

However, taking the area of each zone into account, Zone 2 had the highest species density per 10 000 m^2 (49.6 spp/10 000 m^2) followed by Zone 1 (41.8 spp/10 000 m^2), Zone 3 (31.7 spp/10 000 m^2) and lastly Zone 4 (33.1 spp/10 000 m^2) (**Table 1**). Therefore, Zone 2, had the highest bird species density in the Nature's Valley residential area.

Seasonality of species richness varied throughout the year with the highest number of species present in March 2023 and February 2024, at 40 species each (**Figure 3**). The second highest peak was unexpectedly in winter, with August reaching up to 36 species present. This corresponds to the increase in the number of species detected between June and August in the species accumulation curve (**Figure 2**). The lowest was 28 species recorded in April. On average, a slightly greater number of species were present in summer months (35 species) than in winter months (33 species).

Table 1: Each zone's area as well as species richness and species density as surveyed from February 2023 until February 2024 (excluding December) in the residential area of Nature's Valley

Zone	Zone area (10 000 m^2)	Species richness	Species density/10 000 m^2
Zone 1	93.3	39	41.8
Zone 2	88.7	44	49.6
Zone 3	157.7	50	31.7
Zone 4	169.0	56	33.1
Total	**508.7**	**75**	**14.7**

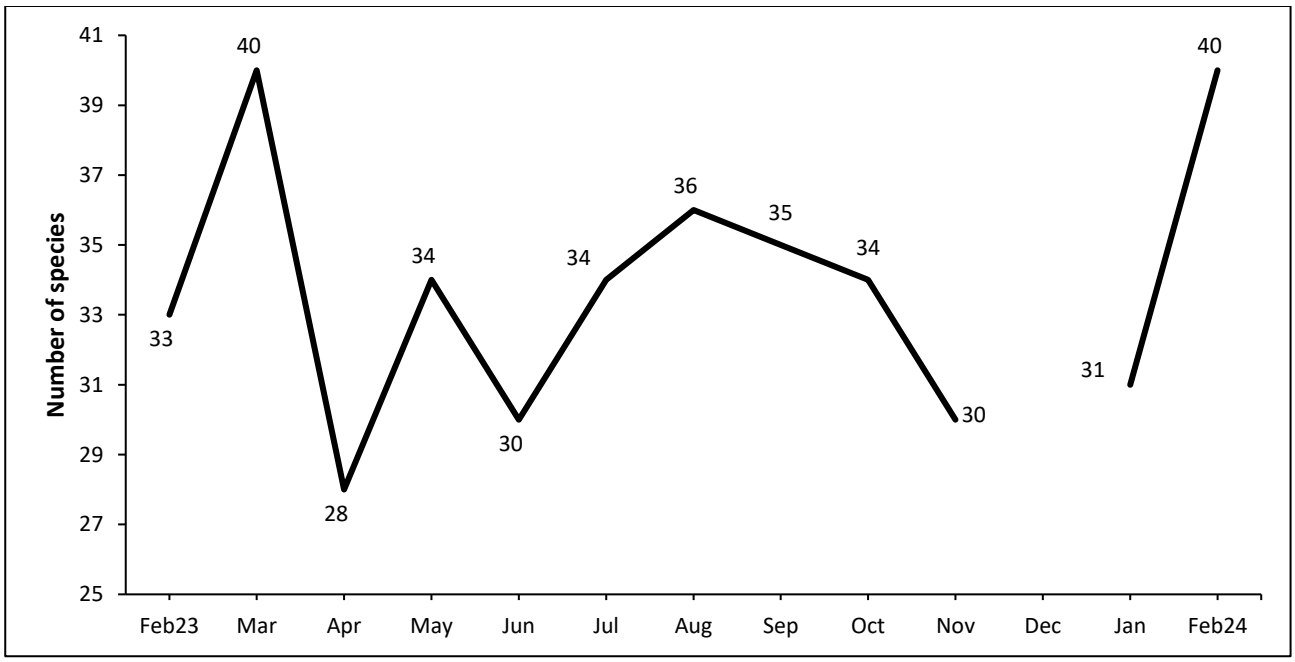


Figure 3: Species richness recorded each month over a year of surveying the four zones of the Nature's Valley residential area

**No survey was done in December 2023*

Discussion

The variation and proximity of natural vegetation surrounding urban areas can affect the abundance and diversity of birds found there (Chamberlain *et al*., 2004). Nature's Valley is completely surrounded by natural vegetation, most of which is protected area managed by SANParks. Additionally, indigenous vegetation is well-represented and preserved in the village, with two stepping-stone habitats, a forest corridor situated in the centre and 70% of homeowner properties displaying no sign of invasive alien plants, but are well vegetated with locally indigenous plants (Beveridge, 2024). Therefore, avian species richness was expected to be notably high for the area.

The cumulative species curve suggests that there are more than 75 bird species present in the 52-ha village of Nature's Valley. Further surveying would likely reveal a number of other species present in the area, particularly those that are more difficult to detect. Indeed, other species are known to occur in the extended area, such as the cryptic Narina trogon (*Apaloderma narina*), elusive white-starred robin-chat (*Pogonocichla stellata*) and the olive bush-shrike (*Chlorophoneus olivaceus*) (Arendse & Webster, 2024), which were not recorded in this study. A complete species list was also not the aim of this study. A longer-term study may bring the total species closer to 150 bird species, as was observed by Ben Lucking in 2016, reporting to have reached that number within just two weeks with concerted effort (Lucking, 2016).

Detection of elusive species is notoriously difficult in forests as the environment is often dark and dense vegetation can make bird movement difficult to detect. In a 6-year study by Brown (2006), a total of 188 forest-utilising bird species were recorded in a small block of Coastal Lowland Forest in Umdoni Park, KwaZulu-Natal. The study showed significant seasonal variance for forest-utilising and forest-specific species, with the former having peaks in summer and the latter having peaks in winter (Brown, 2006). Given the variance of species presence over different seasons and difficulty in detectability, Brown (2006) highlighted the importance of a longer-term study to obtain species richness in forest habitats.

Aquatic species represented 13% (10 species) of the total species count, which is a slight under-representation of the area's potential. The extended area of Nature's Valley is known to have more aquatic birds, given the coastal and Groot River lagoon/estuary habitat to the south and east of the village, respectively. Records of CWACs (Coordinated Waterbird Counts) between 1998 and 2024 have accumulated to a total of 41 waterbird species for the Groot River estuary and an average of 13 species per survey (CWAC, s.a.). CWACs are conducted on/at the relevant water body and count all aquatic birds associated with it. Although the technique of CWACs differ to the technique followed in the present study, it serves as an indicator as to the aquatic bird diversity one may find near Zone 4. The majority of the aquatic species were recorded in Zone 4, which neighbours the lagoon and coastal habitat and likely be the most rewarding zone for birdwatchers seeking aquatic species. Most of these aquatic sightings were fly-overs heading towards the Groot Rivier estuary and the coastline.

Zone 4 had the highest overall species count which was expected. However, when area was accounted for, in fact Zone 2 had the highest species density per unit area (49.6 species/10 000 m^2). This may be a result of there being more habitat diversity (and hence more resource availability and diversity) within the smaller Zone 2 than in Zone 4, allowing for a greater density of species in the

small area. While Zone 4 is neighboured by coastal vegetation, Zone 2 is neighboured by forest and both share a boundary to the lagoon on the east. The higher species richness per unit area seen in Zone 2 as compared to Zone 4 may be an indication that the forest habitat can support a greater number of bird species than the coastal dune habitat. Indeed, a similar result was found between the forested Zone 1 (41.8 species/10 000 m^2) and the coastal Zone 3 (31.7 species/10 000 m^2). Forest is the second most diverse biome is South Africa, after fynbos (Mucina & Geldenhuys, 2006). Southern Afrotemperate Forest has more vegetation diversity than Cape Seashore Vegetation and would hence have a greater variety of food resources to support different bird species.

Recommendations for birders

Planning a birding excursion to Nature's Valley

This data can be used to plan a birding excursion to Nature's Valley. One can visit different sections of the village, depending on the goal of the excursion. If one is seeking a general birding experience, the data suggests that Zone 2 would be best for seeing many different species in a shorter time period and without much effort as it has the highest species richness. However, if one is targeting a certain species, such as the Black-collared barbet, spending extra time in the particular zone it occurs in (Zone 2) could be more beneficial (refer to **Appendix A**).

Visiting during the summer months will be most rewarding. Between December and February, breeding activity is normally high and birds become more active and vocal, making detection easier. Additionally, some of the migratory birds, such as the red-chested cuckoo (*Cuculus solitarius*), will be present during this time.

Attracting birds to your garden

If you prefer watching birds from home, the best way to bring indigenous birds to your urban area, is by planting a locally indigenous garden. Creating a garden that is rich in local shrub and tree species with a small lawn and less tree cover invites more diverse and abundant bird visitation (Paker *et al*., 2014). Indigenous birds favour indigenous vegetation, whereas alien birds favour alien vegetation (Daniels & Kirkpatrick, 2006), so eliminating alien vegetation to plant indigenous vegetation will encourage visitation from birds that are naturally found in the area and create a more diverse, rewarding experience of birds in your garden.

The variation in garden characteristics can have a major influence on garden bird assemblages. By studying the influence of garden characteristics on birds in suburbia, Daniels and Kirkpatrick (2006) emphasise that simply through gardening, homeowners can contribute to the conservation of indigenous avifauna significantly.

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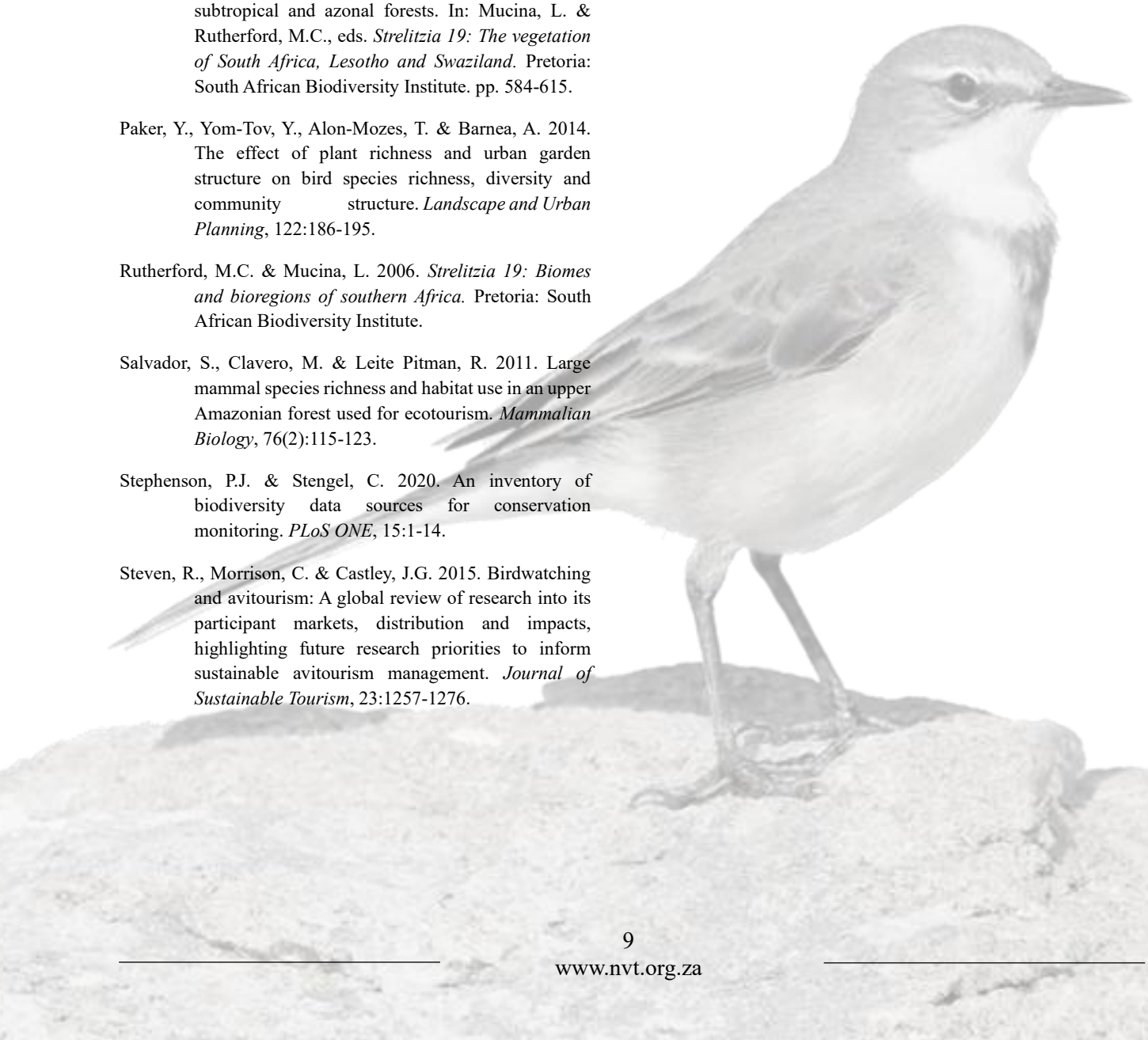
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Appendix A: Species checklist

Table A1. A species checklist for birds whose presence were recorded during the study. The 'occurrence' column refers to the specific zone/s in which the species was found.

Common name	Occurrence	✓	Common name	Occurrence	✓
African black swift	3 or 4		House sparrow	1 or 2	
African dusky flycatcher	1 or 3		Karoo prinia	3	
African emerald cuckoo	4		Kelp gull	4	
African hoopoe	4		Knysna turaco	1	
African olive pigeon	4		Laughing dove	2	
African paradise flycatcher	2		Levaillant's cisticola	4	
Alpine swift	1, 2 or 3		Little egret	4	
Amethyst sunbird	1		Olive thrush	2	
Bar-throated apalis	4		Olive woodpecker	4	
Black oystercatcher	1		Pied crow	3	
Black saw-wing	1		Pied kingfisher	2 or 4	
Black-backed puffback	1 or 4		Red-chested cuckoo	2 or 3	
Black-bellied starling	3 or 4		Red-eyed dove	2	
Black-collared barbet	2		Red-winged starling	3	
Black-headed oriole	1		Ring-necked dove	1	
Blue crane	4		Rock martin	1	
Blue-mantled crested flycatcher	3 or 4		Sombre greenbul	1	
Brimstone canary	3		Southern boubou	3	
Cape batis	4		Southern double-collared sunbird	1	
Cape cormorant	4		Southern fiscal	4	
Cape crow	1		Southern grey-headed sparrow	3	
Cape longclaw	4		Speckled mousebird	4	
Cape robin-chat	3		Speckled pigeon	3	
Cape sunbird	4		Spur-winged goose	4	
Cape wagtail	2		Streaky-headed seedeater	1	
Cape weaver	3		Swee waxbill	1 or 2	
Cape white-eye	1, 2 or 4		Tambourine dove	2	
Chorister robin-chat	4		Terrestrial brownbul	2	
Collared sunbird	1		Water thick-knee	3 or 4	
Egyptian goose	2		White-backed mousebird	3 or 4	
Fiscal flycatcher	2		White-breasted cormorant	3	
Forest canary	4		White-necked raven	1 or 3	
Fork-tailed drongo	3		White-rumped swift	3 or 4	
Greater double-collared sunbird	1		White-throated canary	3	
Greater striped swallow	3		Yellow-billed duck	2	
Green wood hoopoe	1		Yellow-throated woodland warbler	1	
Green-backed camaroptera	2				
Hadeda ibis	4				
Helmeted guineafowl	4				

Are temporary nest enclosures an effective conservation intervention for the white-fronted plover (*Anarhynchus marginatus*)?

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Abstract

Following the worldwide trend of shorebird populations, the regional population of white-fronted plovers (*Anarhynchus marginatus*) is in decline. As coastal areas attract further development, increasing human disturbance to nesting sites may reduce breeding success. An experimental approach was used to investigate whether a simple conservation intervention would improve nest survival on sandy beaches of the Garden Route, South Africa. An experimental group was subject to basic rope enclosures with signage, erected at a 30m x 30m distance around individual plover nests, which was compared against a control. A total of 133 nests were monitored over three breeding seasons. Mayfield and Kaplan-Meier estimates for a survival analysis revealed that survival probability was low (~30%) at both sites. An Accelerated Failure Time model confirmed that there was no statistically significant difference in survival probability between groups ($p = 0.27$), but that nests in the experimental group had a 21% shorter survival time than those in the control.

Introduction

Coastal areas are often economic hubs that support large human populations (Lotze *et al*., 2006). Extensive habitat modification and repetitive human disturbance are typical of urbanising coastal environments (Baudains & Lloyd, 2007; Lotze *et al*., 2006). Maintenance and enhancement of beaches for recreational use has overshadowed their value as critical habitat for a range of biota and has led to concern over the conservation of beach ecosystems (Jordan & Fröhle, 2022).

The Garden Route District has developed considerably over recent years due to a rise in economic opportunity, demand for real estate along the coast and tourism (Western Cape Government, 2023). The coastal Bitou Municipality is experiencing the highest rate of population growth and urbanisation in the district for its popularity as a beach holiday destination among South Africans (Western Cape Government, 2023). Consequentially, the seasonal influx of people in summer months adds significant disturbance pressure to beach habitat and biota, including many shore-breeding birds, such as the white-fronted plover (*Anarhynchus marginatus*).

White-fronted plovers are ground-nesting shorebirds whose population has been in decline along the coast of South Africa for over three decades (Lee, 2024; Ryan, 2013). As a coastal breeder, the species is experiencing increasing human-related disturbance that negatively affects their ability to breed successfully (Baudains & Lloyd, 2007; Weston & Elgar, 2005). Repetitive disturbance during

the nesting period displaces incubating birds which can affect nest attentiveness (Weston *et al*., 2011), exposing eggs to increased risk of predation and egg crushing (Weston *et al*., 2012), and potentially fatal fluctuations in egg temperature (Smith *et al*., 2012).

Repetitive non-lethal disturbance stimuli by humans can lead to white-fronted plovers becoming habituated, which can reduce some of the negative impacts of disturbance on breeding success (Baudains & Lloyd, 2007). For example, incubating plovers that are habituated allow a closer human approach before leaving the nest and will return to the nest sooner after disturbance (Baudains & Lloyd, 2007). By minimising the length of time that eggs are exposed, the extent of egg cooling or heating below or above tolerable physiological temperatures is reduced, leaving egg development uninterrupted (Smith *et al*., 2012). However, habituation is not so advantageous at the chick-rearing stage. Habituated chicks tend to allow a closer human approach and spend less time hiding or crouching after a disturbance (Baudains & Lloyd, 2007). This behaviour can be expected when disturbance is non-lethal as brooding and foraging activities can be resumed sooner without fatal consequence (Weston & Elgar, 2005). Most human disturbances are indeed non-lethal, but this is often not the case when humans are accompanied by (unleased) domestic dogs, which is very common at popular recreational beaches (Williams *et al*., 2009; Baudains & Lloyd, 2007). In fact, the disturbance and nest mortality caused by dogs has become so concerning, that they are recognised as a common predator of white-fronted plovers (Hockey *et al*., 2005) as well as many other ground-nesting shorebirds (Leseberg *et al*., 2000; Williams *et al*., 2009; Weston & Elgar, 2005). Other common predators of white-fronted plovers include mongooses, corvids, raptors, thick-knees, and gulls (Lloyd & Plagányi, 2002).

There are some examples of conservation interventions that address shorebird demise by preventing disturbance. Perhaps the most locally well-known shorebird conservation effort is the success story of the African black oystercatcher (*Haematopus moquini*). By raising public awareness and achieving a nation-wide ban for recreational use of 4x4 vehicles on beaches, among other interventions, the African black oystercatcher conservation campaign was pivotal in assigning conservation importance to sandy beaches in South Africa (Brown *et al*., 2019). Another intensive conservation intervention being used internationally includes erecting temporary beach closures/enclosures along with informative signage to limit disturbance to breeding shorebirds (Weston *et al*., 2012; Medeiros *et al*., 2007). The purpose is to provide a buffer zone between human activity and shorebirds to reduce the frequency or intensity of responses to disturbance during the breeding season.

Despite extensive documentation of the decline of the white-fronted plover and over a decade of research on the species, no studies have been published that reports the effectiveness of temporary nest enclosures in the conservation of the white-fronted plover. This study aimed to use an experimental approach to determine whether temporary nest enclosures are an effective conservation intervention for the white-fronted plover. This study tested the null hypothesis that the presence of nest enclosures would make no difference to egg and chick survival probabilities over time, and hence, no difference to the overall breeding success rate. Meanwhile, the alternative hypothesis was that the presence of nest enclosures would result in higher egg and chick survival probabilities over time, leading to a higher overall breeding

success rate as opposed to when the intervention is not used.

Methods

Study design

Permission for the study was granted by SANParks (AREN-B/2020-025) and its animal use and care committee (018-20). A ringing permit for the work was also issued by CapeNature (CN-28-15012). This study used an experimental approach where two experimental sites were subject to a conservation intervention and compared against a control over three breeding seasons (2021–2024). The conservation intervention involved setting up a simple rope enclosure around all white-fronted plover nests, 30 m away from the nest on all sides (**Figure 1**), to section them off from public disturbance. Along sections of beach where there was less 30 m distance between the nest and the high tide line, the rope and signage were set up a few meters above the high tide line to prevent equipment from being washed away, while still allowing space for beach walkers to pass by. Signage was used to inform a people that the area should be avoided in respect of breeding shorebirds and encouraged adherence to local dog regulations (referring to no-dog or leash areas at each beach entrance). No intervention was carried out on the control site.

A citizen science site at Keurbooms beach (7.1 km) was initially included in the study but later removed due to complex interactions with observer bias in the analyses. Regardless, incorporating a citizen science project as part of a conservation initiative can be an effective way to spread awareness amongst locals and can lighten the load of field work. However, it is imperative that all those involved receive in-depth monitoring training to ensure that breeding success is not in fact adversely affected by volunteer observers.

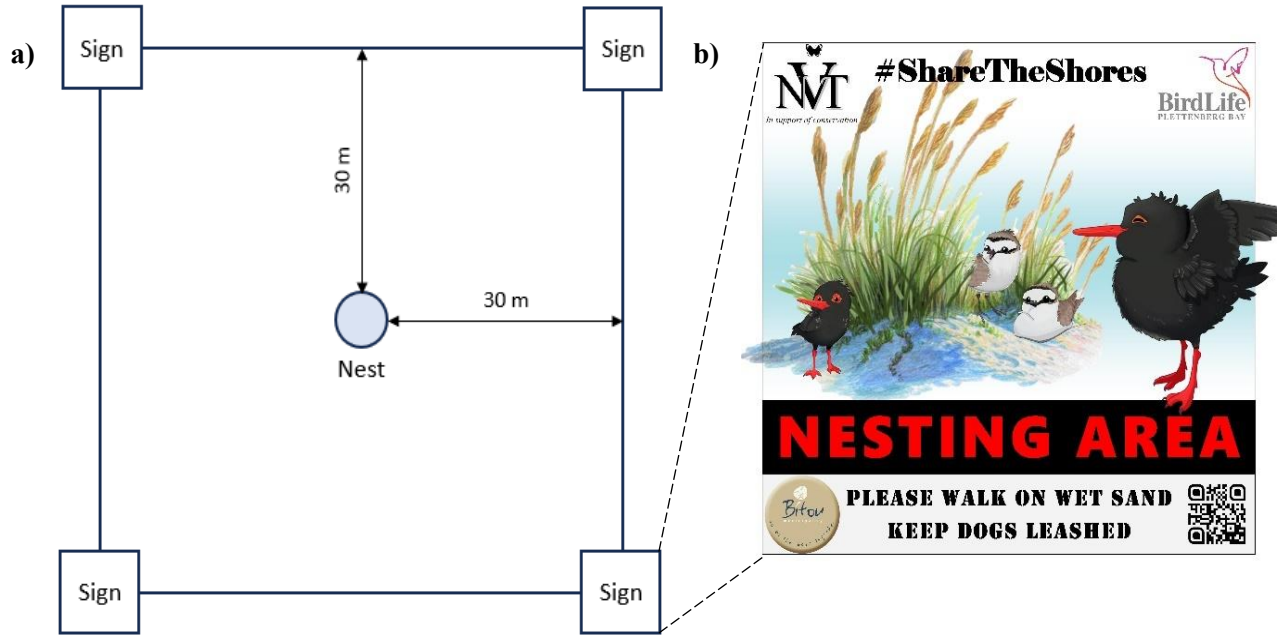


Figure 1: a) Schematic representation of the setup for white-fronted plover nest enclosures and **b)** the signage used at each corner of the enclosure

Study sites and species

The study was conducted across three open-access sandy beaches, accumulating to 8.7 km of coastline along the Bitou Municipality of the Garden Route District, South Africa. Lookout beach (1.4 km) and Nature's Valley beach (3 km) were experimental sites, subject to the conservation intervention and Robberg beach (4.3 km from Beacon Isle Hotel to Wreck Beach) was the control site (**Figure 2**). All three sites are characterised by stretches of sandy beaches with vegetated dunes, all classified as Cape Seashore Vegetation which stretches from the Cape Agulhas to East London (Mucina *et al*., 2006).

Nature's Valley is the most remote site, neighbouring a small holiday village, where most beach goers are visitors to the area, seasonal holiday makers and fishermen. Lookout and Robberg receive the significantly larger population of Plettenberg Bay. Robberg has no formal protection and receives the most visitor pressure, especially during the peak season of December and January. It is also the most built-up site, with large beach houses encroaching on the hind dunes. Lookout consists of a narrow hummock-dune field which is surrounded by the Keurbooms lagoon on the north-west and the coast on the south-east. The dunes, lagoon and estuary are formally protected and managed by CapeNature, but the beach is managed by the municipality. Lookout is also home to a large kelp gull (*Larus dominicanus*) colony in the grassy centre of the dune field whose breeding season overlaps with white-fronted plovers.



Figure 2: Location and layout of study sites along the Garden Route of South Africa: C = control site; E = experimental site; CS = citizen-science site

** The Keurbooms citizen-science site was not included in the study but is shown for context as this site remained an important part of the conservation initiative*

The white-fronted plover is a small, 35–60 g, plover that breeds on exposed sandy or rocky shores. They are monogamous and nest in solitude near the high-water mark or on the first, sparsely vegetated hummock dunes (Summers & Hockey, 1980). The breeding season extends from August to April, with peak egg laying occurring in summer, (November to February) coinciding with a peak in human recreational use of beaches. Clutch sizes range from 1–3 eggs (mode = 2) which are laid in a shallow scrape in the sand. Eggs are laid at intervals of 2–7 days (mean = 3 days), the incubation period is 27–29 days (mean = 28 days) after clutch completion (Lloyd & Plagányi, 2002). Both parent birds share incubation duties during the day, while mostly males incubate during the night (Hockey *et al*., 2005). Chicks begin to fly 28 – 35 days after hatching, fledging shortly thereafter (Hockey *et al*., 2005).

Nest monitoring

From August to March, sites were visited once a week to locate new nests and check on the status of known ones. If weather conditions were not suitable, monitoring did not occur so as not to disturb nests in unfavourable conditions, which included wind exceeding 5 m/s (wind speed that causes sand to move), extreme heat or cold, or heavy rain. New nests were found by watching adult birds' behaviour and following converging tracks in the sand. GPS coordinates of new nests and unique ring numbers of adult plovers were recorded on the Google Earth mobile app for easy relocation/identification on following site visits. Most adult plovers had been ringed before the start of this study to help identify individuals and distinguish between different broods and ring numbers could be confirmed from a distance using binoculars and/or a camera. Eggs of newly found nests were floated to determine the approximate laying date and estimate the hatching date (Liebezeit *et al*., 2007), which was assumed to take place by the 30th day of incubation. When a new nest was found at experimental sites, the eggs were shaded with a hat while enclosures were set up to minimise temperature fluctuations.

Nest sites were visited soon after the hatching date to confirm whether hatching was successful. This was done by firstly checking whether the nest was still active with an incubating parent. If no incubating parent was seen from afar, the nest was approached to check for eggs buried in the sand. In the absence of eggs at the nest site, chicks and if the known parents were not displaying chick-rearing behaviour the nest was assumed to be a failure. If the chicks were found, they were ringed at a young age while easy to capture. No measurements were taken of chicks during the ringing process to minimise stress, rings were used for identification only. Chicks were aged based on their known hatching date or a combination of the estimated hatching date and physical appearance.

If there was no sign of a known nest in a subsequent visit, it was considered a failure as a result of flooding, depredation, abandonment, wind or trampling. A nest was determined to be successful when at least one chick from the brood reached flying age (28 days after hatching).

Statistical analyses

Survival rates were calculated for each nest based on the Mayfield -40% method (Johnson, 1979). White-fronted plovers produce a relatively small clutch size, so calculations were done at the broader level of 'nest success', where partial losses of eggs or chicks was ignored (Mayfield, 1975). In light of the Mayfield -40% method, the following rules

were used to calculate nest-days: 1) if chicks could not be found from a confirmed nest, hatching could not be confirmed so nest-days were counted between the last visit that the nest was confirmed active, and the hatch date; 2) nest-days for chicks were not counted unless evidence of chicks or chick-rearing behaviour was recorded; 3) unless the hatch date was certain, 30 days were used as the length of the incubation period, which included the laying period (this is the maximum exposure period, following Mayfield 1975); 4) chicks were assumed successful fledglings if they survived 28 days (maximum exposure period for the hatchling period) after hatching as they begin to fly at this age and are more likely to escape predators. The Mayfield method assumes that all nests are subject to the same constant daily mortality rate from the day the first egg is laid until the nest either fails completely or has at least one success. All nests that had an unknown outcome, which was sometimes the case if chicks could not be found after hatching, were discarded from analyses (5 nests in total). Hatching success was calculated as the number of hatchlings divided by the number of eggs laid and hatchling success was calculated as the number of fledglings divided by the number of hatchlings.

To determine which variables apart from treatment group to include in the survival time analysis, a Generalized Linear Mixed Model (GLMM) was generated using R version 4.4.1 (R Development Core Team, 2024) to ascertain which variables had a significant effect on nesting success. The variables included in the model were "group" (experimental/control), "eggs" (number of eggs laid), "month" (referring to the month in which the nest was initiated) and "season" (referring to the specific year of monitoring). Specifying a binomial distribution, the outcome of breeding attempts (success or failure) was set as the response variable and "date" (e.g. "season1_January") was included as a random effect owing to nests being clustered within months and monitoring seasons. Pairwise comparisons of group means were conducted using estimated marginal means derived from the GLMM using the *emmeans* package (Lenth *et al*., 2024).

A survival time analysis was also employed to quantify the statistical difference in survival probabilities between experimental and control groups using the *survival* package (Therneau, 2024). The Kaplan-Meier estimator was used to estimate survival functions, which were plotted to visualise the survival probabilities for treatment groups. The log-rank test was used to assess statistical differences in survival between groups for the entire nesting period and the incubation and hatchling periods separately. Following the Kaplan-Meier analysis, the proportional hazards assumption in the Cox proportional hazards model were found to be violated when a proportionality test was conducted and visualised ($p < 0.05$; **Fig. 4b**) and after checking Schoenfeld residuals (Schoenfeld, 1982). Therefore, an Accelerated Failure Time (AFT) model, which models time-to-event, was fitted to further investigate the effects of the intervention on survival time. The response variable was the total number of nest days and the predictor variable was treatment group, specifying a log-normal distribution. The acceleration factor (AF) was calculated as $AF = e^x$, where e is the base of the natural logarithm, and x is the AFT model coefficient.

Results

A total of 133 white-fronted plover nesting attempts were monitored over three breeding seasons, with 31 at Robberg, 56 at Lookout and 46 at Nature's Valley. Locations of all nests can be seen in **Figure 3**. Of these, 26% and 30% of nests were successful at the control and

experimental sites, respectfully, where a successful nest is one that produced at least one fledgling. Hatching success, i.e. the percentage of eggs that hatched successfully, was similar between the control and experimental groups (**Table 1**), however, there was a large difference in chick success, i.e. the percentage of chicks that fledged successfully, between the two groups. Overall breeding success was very similar between groups, at 30% for the experimental group and 29% for the control group.

Results of the GLMM indicated that treatment group did not have a significant effect on the outcome of nests, but that the month of December and the second year of monitoring (2022/2023) did have a significant effect on nest success (**Table 2**). The pairwise comparison between groups indicated that the likelihood of nest success was slightly higher in the experimental group, but confirmed no significant difference between groups (estimate = -0.266, p-value = 0.637).

Mayfield and Kaplan-Meier estimates for daily survival rate, survival probability for the laying/incubation and hatchling periods, and overall survival probability (across both periods) are presented in **Table 3** and Kaplan-Meier survival functions for groups are shown in **Figure 4a**. Except for the hatchling period, Mayfield estimates of survival probability were slightly greater for the control than for the experimental group, while all Kaplan-Meier estimates for the experimental group were greater than the control. Taking the average between Mayfield and Kaplan-Meier estimates, the overall breeding success 30.7% for the experimental group (n = 102) and 31.3% for the control (n = 31).

Table 1: Summary of white-fronted plover nest success for experimental and control sites over three breeding seasons (2021 – 2024)

	Experimental	**Control**
No. of nests (*n*)	102	31
No. of eggs	183	59
Hatching success	35%	34%
Chick success	59%	45%
No. of nest-days (exposure)	3076.7	1059.7
No. failures	71	22
No. of successes	31	9



Figure 3: Map of the sites used to monitor white-fronted plover breeding success over three breeding seasons (2021–2024), including **a)** the control site, Robberg and two experimental sites, **b)** Lookout and **c)** Nature's Valley

**Successful nests were those that produced at least one fledgeling*

Table 2: Outcome of the Generalised Linear Mixed Model for the effect of treatment group (experimental vs. control), number of eggs laid, month and monitoring season (2021/22, 2022/23, 2023/24) on the outcome of white-fronted plover nests

*The model estimates (β) of predictor variables are shown with their corresponding standard errors (SE), z-values (z) and p-values (p). Highly significant predictors are shown in bold

	Model output			
Predictor variables	**β**	**SE**	***z***	***p***
(Intercept)	**-3.839**	**1.707**	**- 2.248**	**0.025**
Group (experimental)	0.266	0.565	0.472	0.637
Eggs	0.587	0.572	1.026	0.305
Month (December)	**2.423**	**1.217**	**1.991**	**0.047**
Month (February)	0.459	1.708	0.269	0.788
Month (January)	2.087	1.204	1.733	0.083
Month (March)	-22.240	1.202×10^5	0.000	0.999
Month (November)	-0.132	1.264	- 0.104	0.917
Month (October)	0.354	1.204	0.294	0.769
Month (September)	0.121	1.342	0.090	0.929
Season2 (2022/2023)	**1.508**	**0.633**	**2.382**	**0.017**
Season3 (2023/2024)	0.605	0.575	1.053	0.292

Table 3: Mayfield and Kaplan-Meier estimates of survival probability for white-fronted plovers on experimental and control sites on the Garden Route

**95% confidence intervals (CIs) are given in brackets*

	Mayfield estimate		**Kaplan-Meier estimate**	
	Experimental (95% CI)	**Control (95% CI)**	**Experimental (95% CI)**	**Control (95% CI)**
Daily survival rate	0.977 (0.972–0.982)	0.979 (0.970–0.988)	0.980 (0.975–0.985)	0.979 (0.970–0.988)
Survival probability for laying/incubation period	0.411 (0.409–0.413)	0.473 (0.469–0.477)	0.402 (0.317–0.509)	0.367 (0.229–0.587)
Survival probability for hatchling period	0.752 (0.748–0.756)	0.710 (0.703–0.717)	0.756 (0.635–0.900)	0.692 (0.482–0.995)
Overall survival probability*	0.309 (0.307–0.311)	0.336 (0.333–0.340)	0.304 (0.227–0.408)	0.290 (0.167–0.503)

**Also referred to as 'breeding success'*

The log-rank test comparing overall survival between the experimental and control groups indicated that there was no significant difference between groups, with a chi-squared statistic of 0.4 (df = 1) and a p-value of 0.50. The Kaplan-Meier group-specific survival curves (**Figure 4a**) showed some distinction during the incubation period, where the experimental site had more fatalities in a shorter period of time, but tapered just before the hatchling period at approximately day 27 where it began to overlap with the control. Upon deeper examination, there were no significant differences between groups during the incubation (chi-squared = 0.7; df = 1; p-value = 0.4) or hatchling (chi-squared = 0.1; df = 1; p-value = 0.7) periods when tested separately. This is reiterated in the cumulative hazard curves (**Figure 4c**) which overlap multiple times and meet at the end of the nesting period.

The AFT model (**Figure 4d**) for the entire nesting period produced an estimated coefficient of -0.239 for the experimental group and an acceleration factor of 0.787, indicating that nests at experimental sites had a 21% shorter survival time than those at the control. However, the difference in survival time between the experimental and control groups was not statistically significant (p = 0.27), which is confirmed in the AFT survival curves (**Figure 4d**). The curves quickly diverged, the experimental curve declining slightly faster, and then paralleled just after day 20. The AFT model curves largely reflect the results of the Kaplan-Meier analysis.

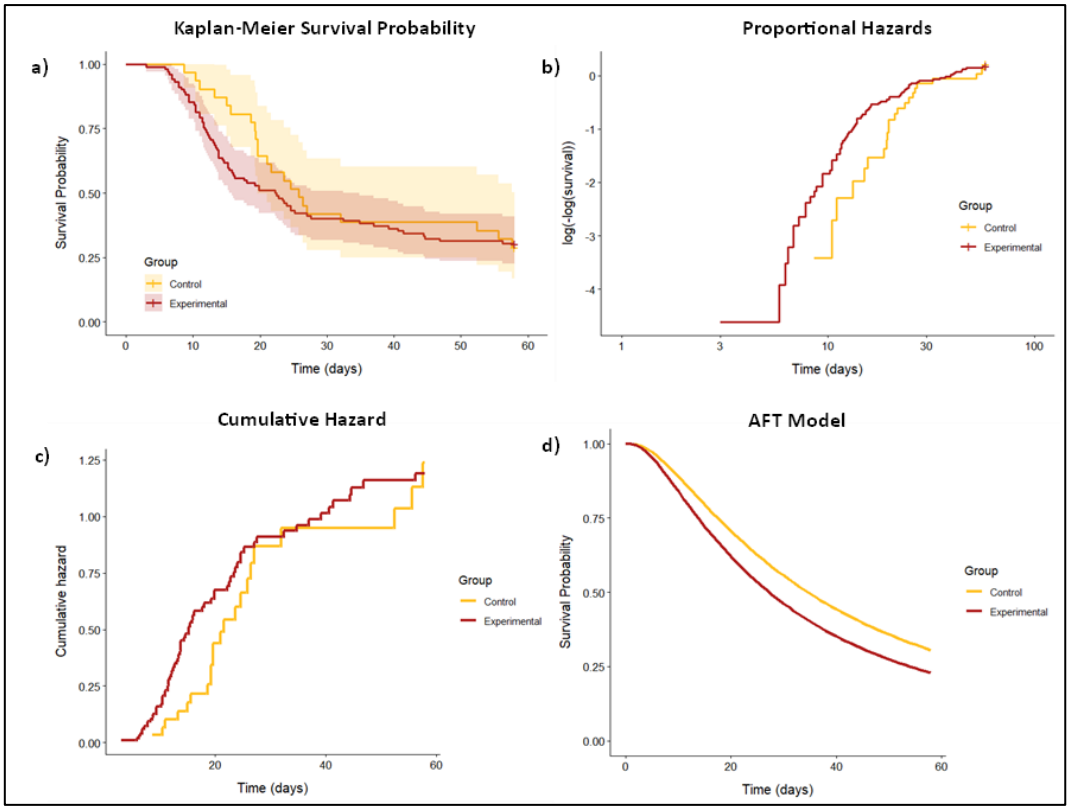


Figure 4: Comparison of survival functions for white-fronted plover nests on experimental and control sites, showing **a)** the Kaplan-Meier survival probability against time with 95% confidence intervals displayed the transparent shaded area around the curves; **b)** violation of the proportional hazards assumption specifying a complementary log-log distribution; **c)** the cumulative hazard against time; and **d)** results of the Accelerated Failure Time (AFT) model showing survival probability against time using the log-normal survival function

Discussion

Ryan (2012) observed an alarming 40% population decline between surveys carried out in 1980/81 and 2010/2011, which covered about 10% of South Africa's coastline (Ryan, 2013). A more recent survey in 2020/21 revealed that the population had once again risen by 43% overall, but that the "recovery" was lowest on the Cape Peninsula which still suffered a 42% population reduction since the 1980/81 survey (Lee, 2024). What caused the initial population decline is still unknown and could be attributed to either genuine population fluctuations or movement patterns related to environmental conditions (Van der Merwe *et al*., 1994). The permanent decline observed on the Peninsula between the 1980/81 and 2020/21 surveys could be a result of intense urbanisation and associated increase in human disturbance in and around Cape Town. The similar trend of development on the Garden Route warranted investigation into potential conservation measures for white-fronted plovers.

A survival time analysis was used to determine whether erecting simple rope and signage enclosures around individual white-fronted plover nests would improve their breeding success by minimising exposure to human-related disturbance. It was found that the null hypothesis could not be rejected because the presence of enclosures made no significant difference to the survival of eggs in the incubation period, chicks in the brooding period, or the nesting period as a whole. Despite this, the intervention may still hold value in minimising disturbance to breeding plovers, particularly over the busy months of December and January. Results of the GLMM indicated that the months of December and January had more influence on nest success than other months. This suggests two things, either the nest enclosures were most effective in reducing disturbance during the two months that have the highest human visitation rates of the year, or that these months are the most ideal for breeding successfully in terms of environmental conditions.

The GLMM also showed that the experimental group had a slightly higher chance of being successful, which was supported by Kaplan-Meier estimates. This differs to estimates of the Mayfield method, which indicated that the experimental group had a lower survival probability at all stages except for the hatchling period. However, survival time analyses have been shown to be a more advantageous and statistically sophisticated compared to the Mayfield method (Nur *et al*., 2004). Both methods were retained in this study for comparability, however Kaplan-Meier estimates were favoured in making final conclusions.

Overall breeding success (including incubation and hatchling periods) was low and was very similar between treatment groups, at 30.4% for the experimental group (n = 102) and 29.0% for the control (n = 31). Most studies of white-fronted plover breeding success only report on success of the incubation period which ranges from 3.8–48.0% (Lloyd & Plagányi, 2002; Tulp, 1998). Comparatively, incubation success observed in this study was within the upper end of this range at 40.2% for the experimental group and 36.7% for the control. However, according to the AFT model, nests at experimental sites had a 21% shorter survival time than those at the control. Although AFT models are robust against disproportionate hazards, there may be certain external, site-specific hazards that caused the experiment to accelerate towards failure faster than the control. These include observer effects, level of disturbance and habituation of individuals at different sites, local environmental conditions and predation (Smith *et al*., 2012; Baudains & Lloyd, 2007; Lloyd & Plagányi, 2002; Tulp, 1998;). Lloyd

and Plagányi (2002) conducted a study on observer effects by modelling breeding success across four beaches with varying levels of human use (low impact to high impact). They found that the busiest beach had a negligible observer effect on breeding success which they attributed to human presence warding off small predatory mammals, while the two least busy beaches had more significant observer effects which they attributed to higher rates of avian and small mammal predation in the lesser disturbed areas. Five years later, Baudains and Lloyd (2007) published their research on how habituation can moderate the impacts of human disturbance on breeding performance at busier locations and compared those results to a control ara within a significantly less busy protected area. The results explained and confimed the results of the 2002 study.

Although an assessment of predation was beyond the scope of this study, it is important to consider the effect of predation on survival probabilities. More disturbed sites have been shown to have lower predation rates than less disturbed sites, likely due to there being fewer natural predators in disturbed areas (St Clair *et al*., 2010; Baudains & Lloyd, 2007; Lloyd & Plagányi, 2002). Disturbance typically drives out some variety of natural predators, particularly those more sensitive to habitat degradation associated with increased human activity (St Clair *et al*., 2010). As a result the more tolerant, generalist predator species, such as alien corvids, are the main predators at disturbed sites (Lloyd & Plagányi, 2002). Therefore, the 21% shorter survival time experienced by the experimental group could be partially explained by higher rates of predation on experimental sites than on the control site. Lookout hosts the largest kelp gull colony in South Africa (see gull territory in **Figure 3b**) (Whittington *et al*., 2016) which likely adds significant predation pressure to the plover population. Meanwhile, the Nature's Valley site is surrounded by protected area and the beach itself has an intact, well-vegetated dune system on the anterior which provides refuge and support for an array of predators. Some of these included mongooses, otters, kelp gulls, thick-knees, kestrels and corvids, all of which were observed showing predatory behaviour or whose tracks were present at a nest site when nest contents were discovered to be missing.

There were signs of habituation among adult birds on Robberg and Nature's Valley beaches, where an incubating bird would not leave the nest even when an observer approached within 5 m to float eggs of a newly found nest (**Figure 4)**. However, at Lookout where the dune field provides more refuge from human activity, incubating birds were more easily disturbed off the nest and parents displayed quicker protective tactics than those at Robberg or Nature's Valley. It should also be noted that different pairs showed differing levels of habituation. Pairs who maintained territory closer to beach entrances or on very narrow strips of beach (as on the west end of Nature's Valley) were observed to be more habituated than those further removed from frequent disturbance.

Many local people became familiar with the campaign to conserve breeding shorebirds and were helpful in confronting unaware beach-goers. However, in some cases the enclosures were reported to have attracted the attention of beach-goers, who would approach the boundary of a nest enclosure curiously looking for eggs or chicks. On less habituated pairs this often displaced the nervous parent, disturbing incubation. Additionally, the enclosures were not designed to exclude any predators, so unleashed/ unattended dogs were still able to enter the sectioned-off breeding areas and were suspected of being an important cause of nest mortality – a very common struggle among

shorebird conservation efforts (Williams *et al*., 2009). Throughout the study there were numerous observations and reports of dogs wandering the dunes off-leash, which is often the case at Robberg and Nature's Valley, while Lookout receives fewer dogs due to the strict no-dog policy as a CapeNature protected area. In one particular case, there was a report of a dog chasing and attacking a young chick on Nature's Valley beach and the chick did not survive.

Despite the intervention having no significant effect on nest survival of white-fronted plovers, it did have an effect on human behaviour and awareness, such as avoiding the upper beach area and dunes or keeping dogs on leashes. Indeed, Weston *et al*. (2012) studied the effectiveness of different configurations of temporary beach closures (including signage, fencing and wardens) and public compliance with the intervention for the hooded plover (*Thinornis cucullatus*). They concluded that any configuration of closure was worthwhile in terms of altering human behaviour, which would in turn reduce the destruction of nest contents. Avoidance of the upper beach and dune areas could also benefit a range of other species that make use of this habitat, allowing them to use the resources more freely. This may include small mammals and insects as well as plants, which also play an important role in stabilising dunes and creating a more resilient beach environment (Sigren *et al*., 2014).

a)  **b)** 

Figure 4: Two habituated female white-fronted plovers at **a)** a beach entrance at Robberg; and **b)** a narrow strip of beach at Nature's Valley that allowed an approach within 5 m before stopping incubation to leave their nests

**Photo b was taken with a cell phone camera to emphasise proximity*

Conclusions and recommendations

This study suggests that erecting nest enclosures as a conservation intervention to increase breeding success in white-fronted plovers is not significantly effective, therefore the null hypothesis could not be rejected. The white-fronted plover population does not require urgent attention, however, as this species continues to fluctuate around an overall decline, it remains an important task to keep track of their ability to cope with increasing levels of disturbance and overall breeding success. Conserving habitat and building public campaigns, education and awareness remain imperative parts of shorebird conservation and should be prioritised. A major theme within this should

be mitigation against disturbance, particularly in developing coastal areas. A simple signage intervention has been proven effective in this way (Medeiros *et al*., 2007), but should be followed up with community engagement by local conservation groups to promote public education and awareness. Considerable effort should be given to conserving breeding habitat. If the quality of sandy beaches – particularly the foredune habitat – is not maintained, the conditions required for white-fronted plovers to breed successfully will likely be progressively lost. This is likely to be exacerbated by increasing human disturbance, which also affects their ability to select the best breeding sites (Erwin, 1980).

In future studies, I recommend implementing randomised placement of nest enclosures across sites rather than designating site-specific experimental and control groups. This approach will help mitigate the influence of environmental variability, habituation, predation, and human disturbance, which may have confounded the results of this study.

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The influence of humans and dogs on bushbuck (*Tragelaphus scriptus*) behaviour

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Abstract

The loss of natural habitats and biodiversity due to human activities is a pressing global issue. Continuous land transformation significantly affects wildlife and their behaviours. While outdoor activities can benefit humans, they often adversely impact wildlife, leading to stress and heightened flight responses. Not only humans disrupt wildlife. Domestic animals like dogs and cats also present considerable challenges. Researching the influence of dogs' presence on wildlife can provide valuable insights into the distribution of species. This study was conducted in the Hebron Private Nature Reserve in South Africa, focusing on the bushbuck (*Tragelaphus scriptus*). Despite the importance of understanding bushbuck behaviour in relation to human and dog presence, there is a notable lack of existing studies. The aim of this research was to determine whether human and dog presence impacts six specific behaviours of bushbuck. The findings indicated no significant effect from human presence. However, the 'running' behaviour of bushbuck showed statistically significant changes, with an increased flight response observed when dogs were present. Consequently, it is essential to consider and implement management measures to mitigate these impacts, including public awareness campaigns, enforcing leash regulations for dogs and designating specific areas for dog use to minimise negative effects on wildlife.

Introduction

The loss of natural habitats and biodiversity due to human activities is a significant global concern (Yang *et al.*, 2023; Skowno *et al.*, 2021; Newbold *et al.*, 2015; Lowry *et al.*, 2013; Sponsel, 2013). This decline is primarily driven by various human actions, with agriculture being the leading cause of habitat loss (Prakash *et al.*, 2022). Other contributing factors include overexploitation of natural resources, climate change, pollution and the introduction of invasive species (Prakash *et al.*, 2022; Hudson *et al.*, 2014; Tittensor *et al.*, 2014).

Land fragmentation is viewed as a major driver of ecosystem disturbance, resulting in decreased biodiversity (Yang *et al.*, 2023; Prakash *et al.*, 2022; Hopping *et al.*, 2004) and increased deforestation, which adversely affects the availability of natural resources and habitat space (Prakash *et al.*, 2022). As a result, isolated forest patches are at risk of further decline, potentially leading to

their complete disappearance. The rapid pace of deforestation today suggests that many forests, along with their associated plant and animal species, may vanish in the future (Bodo *et al.*, 2021).

In recent years, deforestation has accelerated, largely due to agricultural expansion, particularly in cattle farming (Bodo *et al.*, 2021). Fortunately, there is a growing awareness of the need for environmental preservation, which has spurred efforts in biodiversity conservation (Frost *et al.*, 2016) and habitat restoration (Bodnaruk *et al.*, 2017).

Beyond habitat destruction, human activities impact wildlife in various ways, including through outdoor recreation. Over the centuries, outdoor activities and tourism have increased, allowing access to previously untouched areas (Balmford *et al*., 2009). While outdoor recreation can benefit humans and promote conservation efforts (Larson *et al.*, 2016), it can also negatively affect ecosystems, leading to increased flight responses (Naylor *et al.*, 2009), altered habitat use (Rogala *et al.*, 2011) and stress among wildlife (Banks & Bryant, 2007). Animals respond differently to human disturbances based on the latter's frequency and nature, exhibiting varied behaviours (Lowry *et al.*, 2013). For instance, ungulates often display flight responses in the presence of humans, while some species may view humans as a resource (i.e. food waste) or indicative of reduced predator presence (Nickel *et al.*, 2020).

Domestic animals, particularly dogs and cats, also pose significant threats to wildlife (Hughes & McDonald, 2013). As two of the most widely distributed domestic species globally (Ferreira *et al.*, 2011), dogs and cats can negatively impact wildlife through predation and by spreading diseases (Young *et al.*, 2011). Studies have consistently shown that dogs disturb wildlife (Dos Santos *et al.*, 2018; Weston & Stankowich, 2013; Hughes & McDonald, 2013; Lacerda *et al.*, 2009; Stankowich, 2008). For example, Holderness-Roddam and McQuillan (2014) highlighted the severity of dog attacks on wildlife in urban natural areas, while Young *et al.* (2011) noted disturbances to Mongolian herbivores caused by dogs.

Research on the relationship between dogs and wildlife in natural environments indicates that dog presence can help elucidate the distribution of species. Dos Santos *et al.* (2018) found that dogs negatively affect wildlife distribution, limiting opportunities for wild carnivores to prey in certain areas. With an estimated global dog population of around 700 million, free-roaming dogs are particularly disruptive to ecosystems (Hughes & McDonald, 2013).

To mitigate the stress that dogs may cause wildlife, management measures should be implemented (Weston & Stankowich, 2013). Strategies such as restricting dog access to certain areas or implementing time-based restrictions (Gilmartin, 1983) have proven effective. Additionally, creating designated 'dog areas' where dogs can roam off-leash (Williams *et al.*, 2009) can balance human recreation with wildlife protection. Even with these measures, keeping dogs on a leash can enhance management since it keeps them from roaming freely (Weston & Elgar, 2007).

Ultimately, understanding how animals behave in the presence of humans and dogs is crucial in determining whether these interactions are beneficial or detrimental to wildlife.

Aim

Several studies have explored how ungulates respond to human presence and the effects of human activities on their behaviour (Jha &

Isvaran, 2022; Marion *et al.,* 2022; Eldegard *et al.*, 2012; Anderson *et al.,* 2010). However, research specifically on bushbuck (*Tragelaphus scriptus*) behaviour is notably lacking. For instance, Jha and Isvaran (2022) documented a negative impact of human activities on the behaviour of blackbuck (*Antilope cervicapra*). In contrast, in their study, Marion *et al.* (2022) found no significant behavioural changes related to high levels of hiking activity. In fact, they observed red deer (*Cervus elaphus*) to be less active in the absence of humans.

Given the absence of studies examining bushbuck behaviour in relation to human and dog presence, one of the primary objectives of this research was to assess how the presence of these entities affects bushbuck behaviours. Additionally, this study aimed to identify which behaviours are most frequently exhibited by bushbuck during different times of day. We hypothesised that the presence of humans and dogs will influence bushbuck behaviour, resulting in changes to their activity patterns.

Materials and methods

Study area

The research was conducted at the Hebron Private Nature Reserve (HPNR) from 12 November 2022 to 6 December 2023. HPNR spans 14.5 hectares and is situated on a coastal platform above Nature's Valley, along the eastern border of the Western Cape, South Africa (**Figure 1**). This study site consists of a relatively undisturbed Southern Afrotemperate Forest, serving as a vital wildlife corridor to the greater Tsitsikamma forest complex (Wilson *et al.*, 2022)

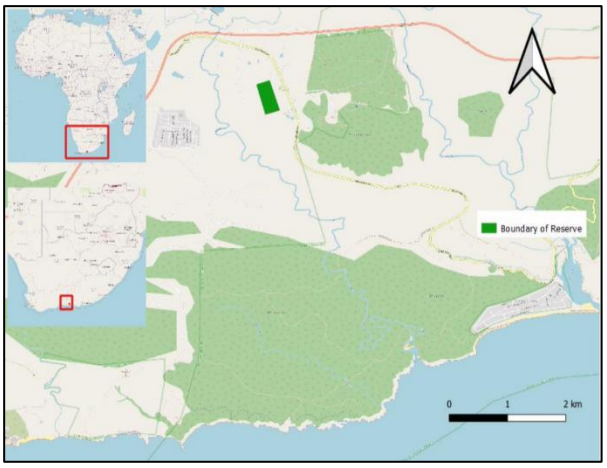


Figure 1: Location of the Hebron Nature Reserve, Western Cape, South Africa

Study species

Bushbuck are medium-sized antelopes, with males weighing between 29 and 52 kg (averaging around 42 kg), while females typically weigh between 24 and 38 kg (averaging 28 kg). Both sexes are generally less than one metre in height. Their coloration and markings can vary among individuals and between sexes. In South Africa, male bushbuck exhibit a darker brown coat with white markings on the thighs and flanks and a distinctive white spot on the throat, accompanied by a white band around the neck (**Figure 2a**). Only males possess twisted, corkscrew-shaped horns that rise just behind their eyes. In contrast, females have a lighter coloration and unique white spots that vary individually (**Figure 2b**) (Apps, 2012).

Various populations across Africa have been studied, revealing important information about bushbuck activity patterns (Wubie & Mesele, 2018; Wronski *et al.*, 2006; Dankwa-Wiredu & Euler, 2002; Simbotwe & Sichone, 1989). Research indicates that bushbuck are primarily active during the evenings, at night and in the early mornings (Wronski *et al.*, 2006; Dankwa-Wiredu & Euler, 2002; Simbotwe & Sichone, 1989).



Figure 2a: Male bushbuck (source: Bob Adams)
Figure 2b: Female bushbuck (source: Bernard Dupont)

Camera traps

Conservation is crucial for preserving animal species, and understanding animal behaviour can enhance the effectiveness of conservation efforts. Camera traps are valuable tools for recording and identifying various animal behaviours, providing images and videos along with critical data such as location, time and date (Caravaggi *et al.*, 2017). These devices are particularly relevant for estimating mammal populations, analysing the impacts of habitat fragmentation and studying behavioural patterns, including activity levels (Brassine & Parker, 2015).

While the use of camera traps offers both advantages and disadvantages, as noted in various studies (Caravaggi *et al.*, 2020; Caravaggi *et al.*, 2017; Meek *et al.*, 2015; Hamel *et al.*, 2013), they come with limitations such as storage capacity, backup issues (Hamel *et al.*, 2013) and the time required for image processing (Harris *et al.*, 2010). Nevertheless, the benefits of this method are significant (Caravaggi *et al.*, 2017; Newey *et al.*, 2015;Hamel *et al.*, 2013). Camera traps enable researchers to monitor animal behaviour non-invasively, minimising interference with wildlife habitats and ensuring more reliable results (Caravaggi *et al.*, 2017; Brassine & Parker, 2015).

Monitoring mammals can be particularly challenging due to their nocturnal habits or tendency to avoid human presence, making camera traps an invaluable resource (Forrester *et al.,* 2016). For instance, thanks to camera traps, a study by Tan *et al.* (2013) revealed that the primate *Rhinopithecus brelichi* exhibited not only diurnal activity but also significant activity at dusk and during the night. These devices are cost-effective and can be deployed continuously over extended periods, enduring various weather conditions (Gaidet-Drapier *et al.*, 2006) and demonstrating impressive battery life (Harris *et al.*, 2010).

Understanding the impact of human activities on animal behaviour and predicting population-level responses is essential for developing effective conservation and management strategies (Caravaggi *et al.*, 2017). Factors such as habitat fragmentation and human disturbance can significantly alter animal behaviour and the proximity of humans can influence activity patterns. As highlighted in previous studies, land transformation has led to numerous ecological challenges (Prakash *et al.*, 2022; Klopper, 2010), resulting in potential behavioural changes (Caravaggi *et al.*, 2017). For example, research has demonstrated that habitat fragmentation has affected the activity patterns of specific forest mammals (Norris *et al.*, 2010).

Therefore, implementing a long-term monitoring plan using camera traps can

provide valuable insights into habitat dynamics and the effects of human activities, ultimately aiding in the preservation of ecosystems and their resident species.

Procedure

Surrounding the HPNR are residential areas, farms and other human establishments, some of which have domestic dogs that roam freely in the forest. Additionally, vehicles frequently enter and exit the area, and people (including tourists) walk through the reserve at their leisure. Camera traps were employed to monitor human presence within the reserve and to observe the various behaviours exhibited by bushbuck.

A total of 86 camera-trap sites were established around the reserve, strategically positioned along 52 sites along man-made trails and 34 sites along natural trails where human activity is typically observed (**Figure 3**). For the purpose of this study, use was made of Num'axes cameras (Model PIE1046) and a Bushnell camera (Model 119476). Each camera was mounted on sturdy trees at a height of one metre, angled to capture images of the trails. The cameras were configured to take multiple photos in quick succession (set to capture three, five or eight photos with no delay between shots), while video recordings were limited to 20-30 seconds in length. Due to a limited number of cameras (four in total), one was randomly designated for video recording.

The selection of camera-trap locations was occasionally influenced by external factors (e.g. the risk of theft), and although the data-collection period was initially scheduled for two weeks per site, this timeframe was affected by weather conditions and battery life. Consequently, the cameras were deployed for a minimum of six days and a maximum of twenty days at a time.

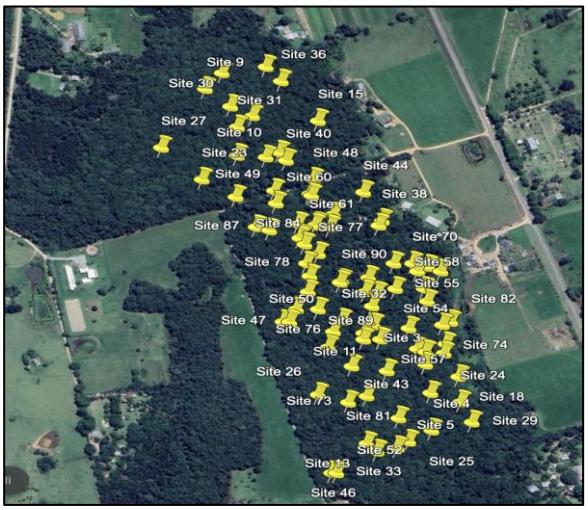


Figure 3: GPS coordinates of the different sites around Hebron Nature Reserve

Data gathering

The photos and videos were processed manually to analyse the presence of humans and dogs, as well as the behaviours exhibited by the bushbuck. This study utilised the behavioural categories established by Marion *et al.* (2022), with some modifications. Six specific behaviours were identified for each photo: walking, feeding, sniffing, standing still, being vigilant (head up) and running (see **Table 1**).

The observation timeline was divided into four periods: morning (6:00-12:00), afternoon (12:00-18:00), evening (18:00-24:00) and night (24:00-6:00). All behaviours, along with the presence of humans and dogs, were counted manually. For each recorded behaviour, observations were conducted for a maximum of 30 minutes before and after to capture any interactions involving dogs or humans.

Data analysis

The data was analysed using R Studio, specifically R version 4.2.1 (R Development Core Team, 2022). To assess the normality of the data distribution, the Shapiro-Wilk test (Royston, 1995) was conducted. The "tidy" package (Wickham *et al.*, 2023) was employed to combine the behavioural data. A bar chart was created using the "ggplot2" package to visualise the frequency of behaviours performed and to identify which ones represented the most activity throughout the day.

To determine the impact of human and dog presence on bushbuck behaviours, linear mixed models were utilised, with the "lmerTest" package providing visualisations of p-values and accounting for 'site' as a random effect. The "visreg" package was used to further visualise the results of these calculations.

Results

Descriptive statistics

Walking was the most frequently observed behaviour (recorded 241 times), while all other behaviours were documented significantly less frequently. The behaviour that occurred the least was feeding, with only 27 observations (**Figure 4**).

The analysis of bushbuck activity throughout the day revealed that they were most active during the evening (18:00-24:00), with activity levels only marginally differing from those observed in the afternoon and morning (**Figure 5**). In contrast, the bushbuck exhibited the least activity during the night (24:00-6:00).

The analysis of behaviours performed throughout the day indicated that walking was the dominant activity during the morning, afternoon, evening and night. Sniffing emerged as the second most common behaviour in the afternoon (**Figure 6 a-d**).

Table 1: All behaviours observed during the study

Behaviour	Description
Walking	When one or more legs moved
Feeding	When food is in mouth
Sniffing	With head down and nose on the ground or near leaves
Standing still	No movement performed
Vigilant	Head held high up, with ears pointed and head swivelling
Running	Rapid repeated leg movement

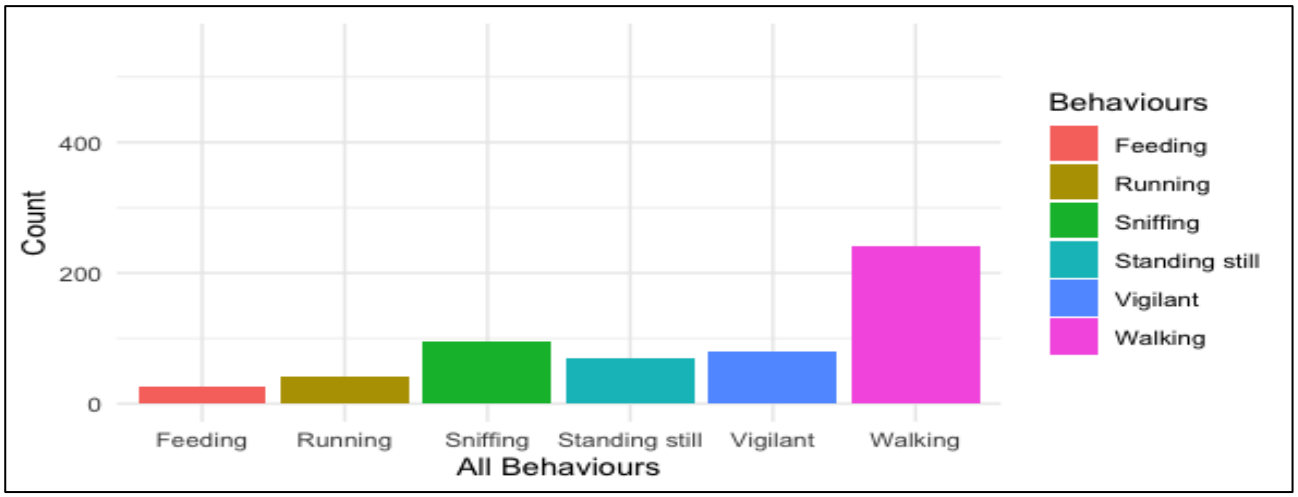


Figure 4: Total count of all the behaviours performed by the observed bushbuck in the Hebron Private Nature Reserve

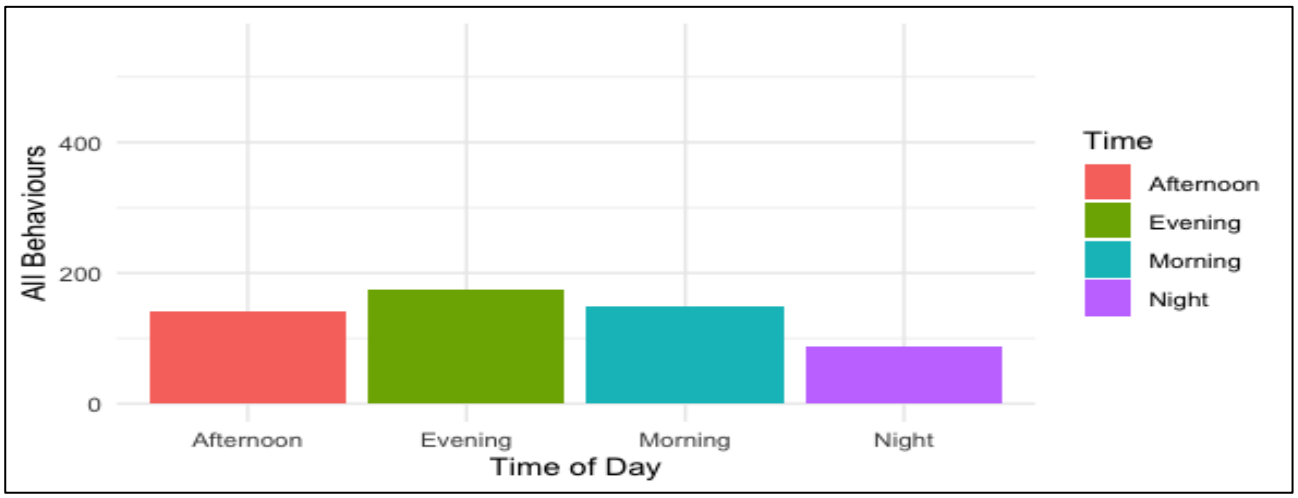


Figure 5: All behaviours performed by the time of day

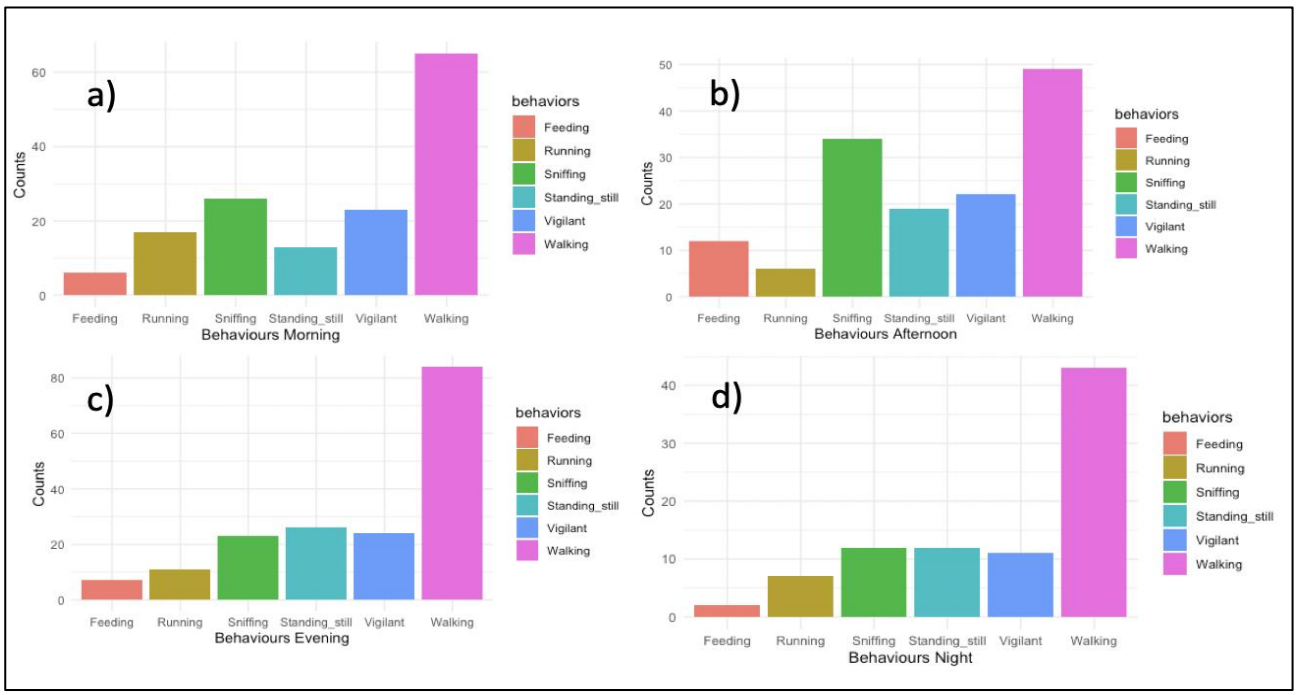


Figure 6 a-d: Total count of all the behaviours performed during the day

Anthropogenic influence

The potential effect of human presence on bushbuck behaviour was analysed, with one instance of human presence compared to 193 instances of human absence. Due to this disparity, it was not feasible to conduct a statistical test.

In contrast, the presence of dogs significantly influenced the running behaviour of the bushbuck (Chisq, $p < 0.01$). The results indicated that bushbuck exhibited more running behaviour when dogs were present (15 instances of dog presence compared to 179 instances of dog absence) (**Figure 7**).

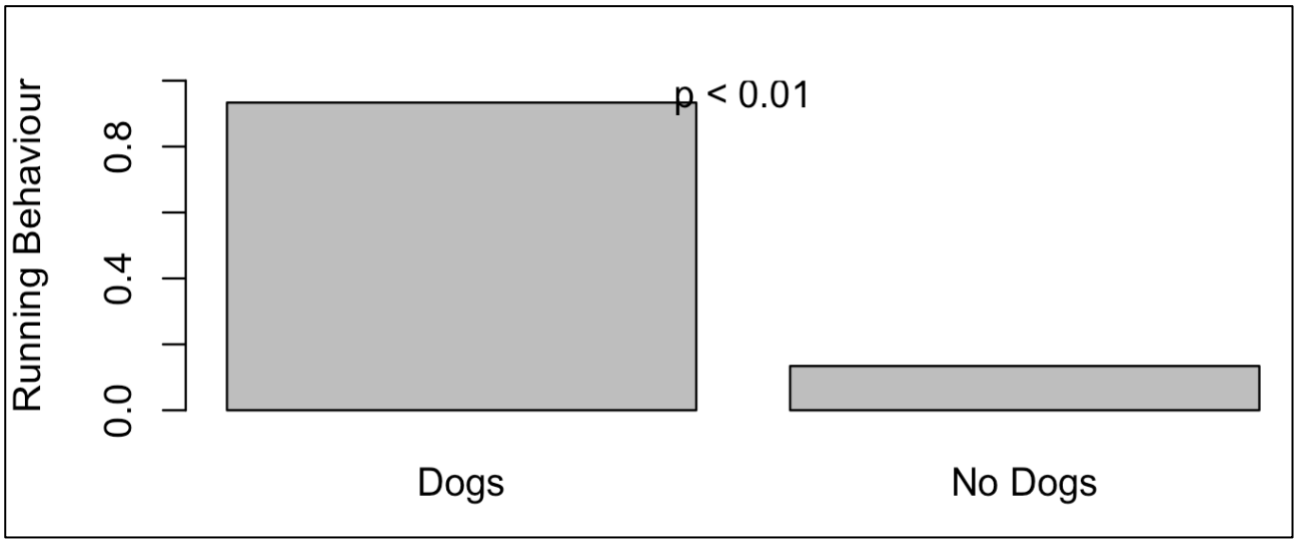


Figure 7: The proportion of running behaviour in the presence or absence of dogs ($p < 0.01$)

Discussion

Bushbuck were found to be most active during the evening, followed by morning and afternoon activity, with night time exhibiting the lowest recorded behavioural activity. This finding aligns with previous studies indicating that bushbuck are primarily active during the morning and evening (Apps, 2012; Wronski *et al.*, 2006). Interestingly, the observed afternoon activity is noteworthy, as it typically represents a resting period for these animals (Wronski *et al.*, 2006).

Lewis *et al.* (2021) suggest that animals may alter their activity patterns in response to disturbances. For instance, research on other antelope species, such as the mountain nyala (*Tragelaphus buxtoni*), indicates that they shift their feeding activities from day to night due to increased human activity (Worku *et al.*, 2021). This could potentially explain the heightened activity recorded in the afternoon. However, further research is necessary to explore this phenomenon and to gain insight into behavioural changes prompted by human presence or other factors.

In this study, human presence did not appear to influence bushbuck behaviours. However, it was noted that bushbuck exhibited increased running behaviour in the presence of dogs, supporting the hypothesis that dogs impact bushbuck behaviour.

Numerous studies have identified dogs as a threat to wildlife (Home *et al.*, 2018; Zapata-Ríos & Branch, 2016; Marzano & Dandy, 2012; Young *et al.*, 2011; Lenth *et al.*, 2008), leading to increased stress levels (Young *et al.*, 2011; Lenth *et al.*, 2008) and heightened alertness and flight responses (Marzano & Dandy, 2012). For example, Young *et al.* (2011) highlighted that various

ungulates are adversely affected by dog attacks and disturbances, resulting in increased displacement and contributing to their endangered status. Additionally, Taylor and Knight (2003) demonstrated that the presence of dogs influenced alert behaviour in mule deer (*Odocoileus hemionus*).

This study, conducted in a private nature reserve, showed that dogs often enter protected areas, increasing the risk of disturbance and negatively impacting local wildlife. The surrounding environment, particularly areas with farming, also influences dog presence within protected regions (Home *et al.,* 2018). As noted in multiple studies (Home *et al.,* 2018; Doherty *et al.*, 2017; Bellard *et al.*, 2016), dogs are considered an invasive species responsible for significant ecological consequences. Doherty *et al.* (2017) reported that dogs were the primary cause of extinction for 11 vertebrate species and pose a risk to many others. Furthermore, research indicates that recreational activities can disturb wildlife, with both humans and dogs affecting animal behaviours (Marzano & Dandy, 2012). Importantly, the threat posed by dogs in particular must be acknowledged and managed to protect and preserve wildlife.

To mitigate potential disturbances caused by dogs, it is crucial to implement effective management measures. Public awareness campaigns are essential since such measures are often met with resistance from the community. These campaigns should emphasise the risks associated with dog-wildlife interactions and outline preventive measures, such as prohibiting dogs in protected areas or restricting their roaming at night (Young *et al.*, 2011). Another strategy could involve mandating that dogs should be leashed, which would limit their movement in certain areas and reduce their impact on wildlife (Weston & Stankowich, 2013; Lenth *et al.*, 2008). Additionally, implementing restricted access for dogs in protected areas, particularly during specific times, is vital (Van Eeden *et al.*, 2022). However, the success of these measures relies on dog owners' willingness to comply with regulations, a challenge highlighted in Van Eeden *et al.*'s study. While most owners agreed that leashing and restricted access are beneficial, they also expressed concerns about their dogs needing access to natural areas. Nonetheless, establishing designated dog areas could help balance the needs of dogs and wildlife (Van Eeden *et al.*, 2022; Weston & Stankowich, 2013).

In conclusion, implementing management measures can significantly reduce dog presence in natural areas, thereby decreasing dogs' negative impact on wildlife and their behaviours.

Limitations

Camera traps are an invaluable tool for observing wildlife in a non-invasive manner. However, this study encountered several limitations. Ideally, multiple cameras should be deployed for more comprehensive data collection. Unfortunately, only four cameras were available due to budget constraints. While quality camera traps can be expensive initially, they offer durability over time. Despite their long battery life, performance can be affected by challenging weather conditions, necessitating more frequent battery checks (Newey *et al.,* 2015). This issue was evident in our study, where batteries required regular monitoring. Consequently, utilising more cameras and faster image-detection technology would likely have enhanced data collection and improved the overall results of this study.

Conclusion

Despite the study's limitations, several noteworthy results were obtained: Bushbuck displayed a heightened flight response in the presence of dogs, indicating that canine presence significantly affects their behaviour. However, additional research utilising more cameras and higher-quality equipment would provide clearer insights and further validate these findings.

Social and ethical considerations

The inability of camera traps to differentiate between animals and humans allows for their use in legal contexts (Blake *et al.*, 2017; Oberosler *et al.*, 2017). However, Butler and Meek (2013) highlight challenges that arise when humans are captured on camera. Researchers face a significant dilemma: While recording human presence can provide crucial evidence in cases of trespassing, it also raises important privacy concerns that, if overlooked, could have legal repercussions. The conundrum, as Sandbrook *et al.* (2018) pointed out, is that even though researchers might consider removing images of humans from wildlife monitoring, retaining those images could well be beneficial for research purposes. The key, according to Sharma *et al.*, (2020), is to obtain permission prior to conducting camera-trap monitoring. In this study, camera traps were deployed in a private nature reserve with the owner's consent, and local residents were informed that cameras will be used and they granted their permission to do so.

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Carbon dynamics in the Sout (Oos) River catchment: Implications for regional conservation strategies

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Abstract

The Sout (Oos) River catchment in Nature's Valley, South Africa, represents a significant area for understanding carbon stocks and sequestration potential within the Cape Floristic Region. This study used high-resolution landcover mapping and carbon quantification techniques to assess above-ground and below-ground carbon stocks across diverse vegetation types, including Tsitsikamma Sandstone Fynbos and Southern Afrotemperate Forest. The findings highlight the carbon storage capacity of natural vegetation, the risks posed by alien invasive plants and the potential for enhanced carbon sequestration through targeted restoration and management strategies. This work underscores the importance of localised carbon assessments in informing conservation planning and climate-change mitigation efforts.

Introduction

The critical role of ecosystems in sequestering carbon to mitigate climate change has gained global attention, particularly in biodiversity hotspots like South Africa's Cape Floristic Region (CFR). Characterised by its extraordinary plant diversity and unique ecological processes, the CFR has been increasingly affected by anthropogenic pressures such as habitat transformation, invasive species and climate change (Van Wilgen & Richardson, 2014; Cowling *et al.*, 1996). Within this context, localised carbon stock assessments are vital for developing targeted conservation and restoration strategies. This study focuses on the Sout (Oos) River catchment in the Western Cape Province, an ecologically significant area that spans from the Tsitsikamma mountains to the estuarine zone of the Sout River.

The Sout River catchment encompasses diverse vegetation types, including Tsitsikamma Sandstone Fynbos and Southern Afrotemperate Forest, both of which play key roles in carbon storage (Pool-Stanvliet *et al.*, 2017). Based on the South African National Vegetation Map, fynbos dominates approximately 61% of the catchment, while forests cover about 37% (Mucina *et al.,* 2006). Additional vegetation variants such as riverine systems, thickets and perennial streams contribute to the region's ecological heterogeneity. Mapping conducted by Vlok *et al.* in 2008 for the Garden Route Initiative (GRI) highlights the importance of these vegetation types for carbon sequestration and biodiversity conservation (Van Wilgen *et al.*, 2008). However, a growing concern in the region is the widespread occurrence of alien invasive plants (AIPs), particularly in protected areas such as the Garden Route

National Park where they have been shown to alter vegetation structure and threaten ecosystem functioning (Baard & Kraaij, 2014).

Carbon storage in ecosystems is influenced by landcover changes, degradation and management practices. The presence of invasive species such as *Acacia mearnsii* (black wattle) has significantly altered the landscape, contributing to carbon stock variations, water resource depletion and ecological imbalance (Le Maitre *et al.*, 2011; Le Maitre *et al.*, 2002). For instance, woody invasive plants can initially increase above-ground biomass but often degrade soil organic carbon and suppress native vegetation, resulting in long-term carbon sequestration deficits (Van Wilgen & Richardson, 2014). Soil carbon levels, in particular, have been shown to vary substantially across biomes and land uses in South Africa, with degradation linked to marked declines in soil organic carbon (Mills & Fey, 2004). The region also experiences periodic fires which influence the dynamics of above-ground biomass and soil carbon storage (Van Wilgen, 2009). These factors underscore the need for high-resolution spatial data to accurately quantify carbon stocks and evaluate opportunities to enhance long-term average carbon storage through practices that increase biomass and soil carbon or reduce carbon losses over time, even in the face of natural disturbances such as fire.

The overarching aim of this study was to establish a fine-scale carbon baseline for the Sout River catchment to inform land management strategies and climate mitigation efforts. Specifically, the objectives include quantifying carbon stocks across the principal vegetation types, assessing the impacts of landcover changes and identifying opportunities for both carbon sequestration and emission mitigation. By providing localised data, this work addresses gaps in regional carbon assessments, which often fail to capture the fine-scale heterogeneity of carbon dynamics in complex landscapes like the Sout River catchment.

The need for localised carbon stock assessments has become increasingly urgent as global climate change continues to threaten biodiversity and ecosystem services. By focusing on high-resolution spatial mapping and targeted carbon quantification, this study exemplifies the integration of ecological science and practical conservation planning. The findings aim to inform strategies that enhance carbon sequestration while supporting the ecological integrity and resilience of this globally significant region.

Methods

Study area

The Sout River catchment spans an area of approximately 5 549 hectares (uncorrected for slope) and is in the Western Cape Province of South Africa. The catchment extends from the foothills of the Tsitsikamma mountains to the permanently open estuary of the Sout (Oos) River. It encompasses diverse vegetation types, including Tsitsikamma Sandstone Fynbos, Southern Afrotemperate Forest and agricultural lands (**Figure 1**).

Landcover mapping

High-resolution landcover mapping was conducted using Sentinel-2 satellite imagery (DFFE, 2021), incorporating both the Dynamic World and South African National Land-Cover (SANLC) datasets for 2020. Brown et al. (2022) reported that the Dynamic World dataset employs advanced machine learning algorithms to generate near real-time landcover classifications with a spatial resolution of 10 metres. This dataset is particularly effective in capturing temporal

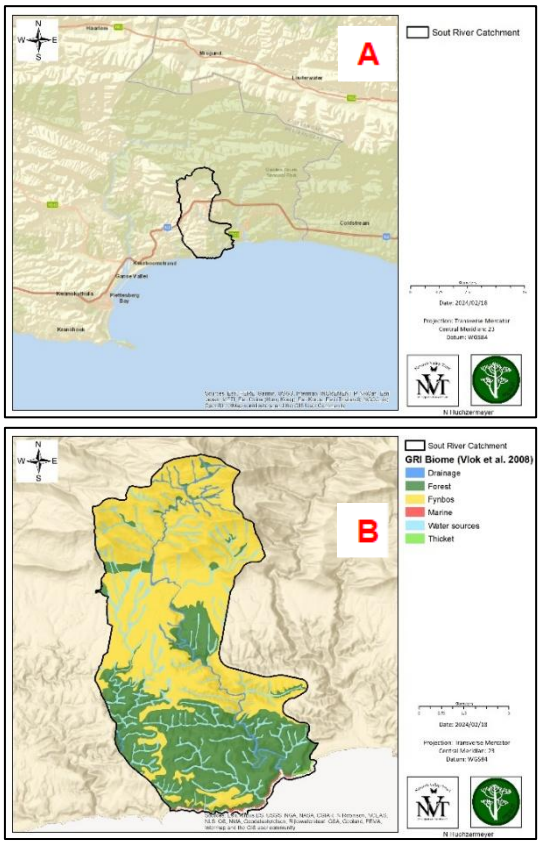


Figure 1: (**A**) Locality map of study area; (**B**) High order classification of the vegetation as biomes (Vlok *et al.* 2008)

changes in vegetation cover and in distinguishing between vegetation types that are otherwise challenging to classify using traditional remote sensing methods. Complementing this, the 2020 SANLC dataset (DFFE, 2021) provided additional classifications specific to South African vegetation types, anthropogenic influences and ecological gradients. The finer-scale mapping as prepared by Vlok *et al.* in 2008 for the GRI and the most recent National Vegetation Map (SANBI, 2018) were also integrated to ensure regionally relevant classifications.

Before field validation, desktop GIS analysis was performed to delineate the various landcover classes across the catchment. Ground-truthing was conducted in October 2023 over five days, during which the catchment was surveyed extensively on foot and by vehicle. Ground-truthing involved comparing satellite-derived classifications with direct field observations to ensure the accuracy of mapped landcover types. Particular attention was paid to validating vegetation variants from Vlok *et al.'s* (2008) mapping and documenting of the spatial extent of alien invasive plants. Time constraints precluded detailed assessments of age and density classes for invasive species.

Carbon stock quantification

Five key carbon pools were quantified: above-ground biomass (AGC), below-ground biomass (BGC), soil organic carbon (SC), litter carbon (LC) and deadwood carbon (DWC). Due to the project's budgetary and temporal constraints, published carbon stock estimates tailored to South African vegetation types were employed to estimate carbon stocks. Rather than relying on generic IPCC lookup tables, values were sourced from a range of regionally relevant studies to reflect the ecological characteristics of the study area better. For above-ground biomass, vegetation-specific allometric equations were used, correlating structural attributes like canopy cover and plant height to biomass (Mensah *et al*., 2017). Below-ground biomass was calculated using root:shoot ratios calibrated for fynbos and forest ecosystems from relevant literature. Soil organic carbon was estimated using published data for soil carbon densities within the Cape Floristic Region (Venter *et al*., 2021). Carbon values for litter and deadwood were derived using the tools proposed by the United Nations Framework Convention on Climate Change (UNFCC) and additional South African studies (**Table 1**). Broader guidance on default carbon pool values and national estimates also drew from the national terrestrial carbon sinks assessment (DFFE, 2020), which provided important benchmarks for carbon accounting within local landcover classes.

Table 1: The carbon figures employed for the various vegetation classes based on Vlok *et al.* (2008)

Vegetation class	SC (t C/ha)	RC (t C/ha)	LC (t C/ha)	DWC (t C/ha)	AGC (t C/ha)	TCS (t C/ha)	Source / Notes
Herolds Bay littoral vegetation	6.0	2.0	0.0	0.0	1.0	9.0	Mills *et al.* (2005b) – using Nama Karoo as proxy
Tsitsikamma littoral vegetation	6.0	2.0	0.0	0.0	1.0	9.0	Mills *et al.* (2005b) – using Nama Karoo as proxy
St Francis strandveld	28.0	5.0	0.0	0.0	1.8	34.8	Glenday (2007) for AGC/RC; Mills *et al.* (2005b) for SC
Hartenbos primary dune	0.0	0.0	0.0	0.0	0.0	0.0	Minimal vegetation cover; negligible carbon stock
Garden Route estuary	0.0	0.0	0.0	0.0	0.0	0.0	Small area and low vegetative cover
Tsitsikamma dune forest	72.0	13.0	4.5	2.6	41.8	133.9	Glenday (2007) – using coastal dune forest as proxy
Tsitsikamma River and floodplain	117.0	19.0	1.7	0.0	30.7	168.4	Mangwale & Shackleton (2018)
Keurbooms thicket forest	168.0	25.0	0.0	0.0	52.0	245.0	Mills *et al.* (2005a; b)
Stormsrivier thicket forest	168.0	25.0	0.0	0.0	52.0	245.0	Mills *et al.* (2005a; b)
Tsitsikamma perennial stream	64.0	12.5	1.9	5.3	40.0	123.7	Average of proteoid fynbos and mountain forest
Tsitsikamma forest fynbos	33.6	8.4	0.0	0.0	15.6	57.6	Mills *et al.* (2005b), adjusted +20%
Tsitsikamma ericaceous fynbos	28.0	7.0	0.0	0.0	13.0	48.0	Mills *et al.* (2005b), conservative estimate
Covie coastal proteoid fynbos	66.0	13.0	3.4	0.0	9.3	91.7	Mills *et al.* (2012) for AGC/RC; Mills *et al*. (2005b) for SC

Tsitsikamma mountain proteoid	28.0	7.0	0.0	0.0	13.0	48.0	Mills *et al.* (2005b), conservative estimate
Tsitsikamma fynbos forest	80.0	14.4	3.0	8.5	53.6	159.4	Mangwale & Shackleton (2018), adjusted -20%
Tsitsikamma mountain forest	100.0	18.0	3.7	10.6	67.0	199.3	Mangwale & Shackleton (2018)
Tsitsikamma riverine forest	100.0	18.0	3.7	10.6	67.0	199.3	Mangwale & Shackleton (2018)
Tsitsikamma plateau forest	100.0	18.0	3.7	10.6	67.0	199.3	Mangwale & Shackleton (2018)
Alien invasive plant stands (AIPS)	56.0	12.0	3.1	3.3	46.7	121.1	Glenday (2007) – using "feral plantation" as proxy

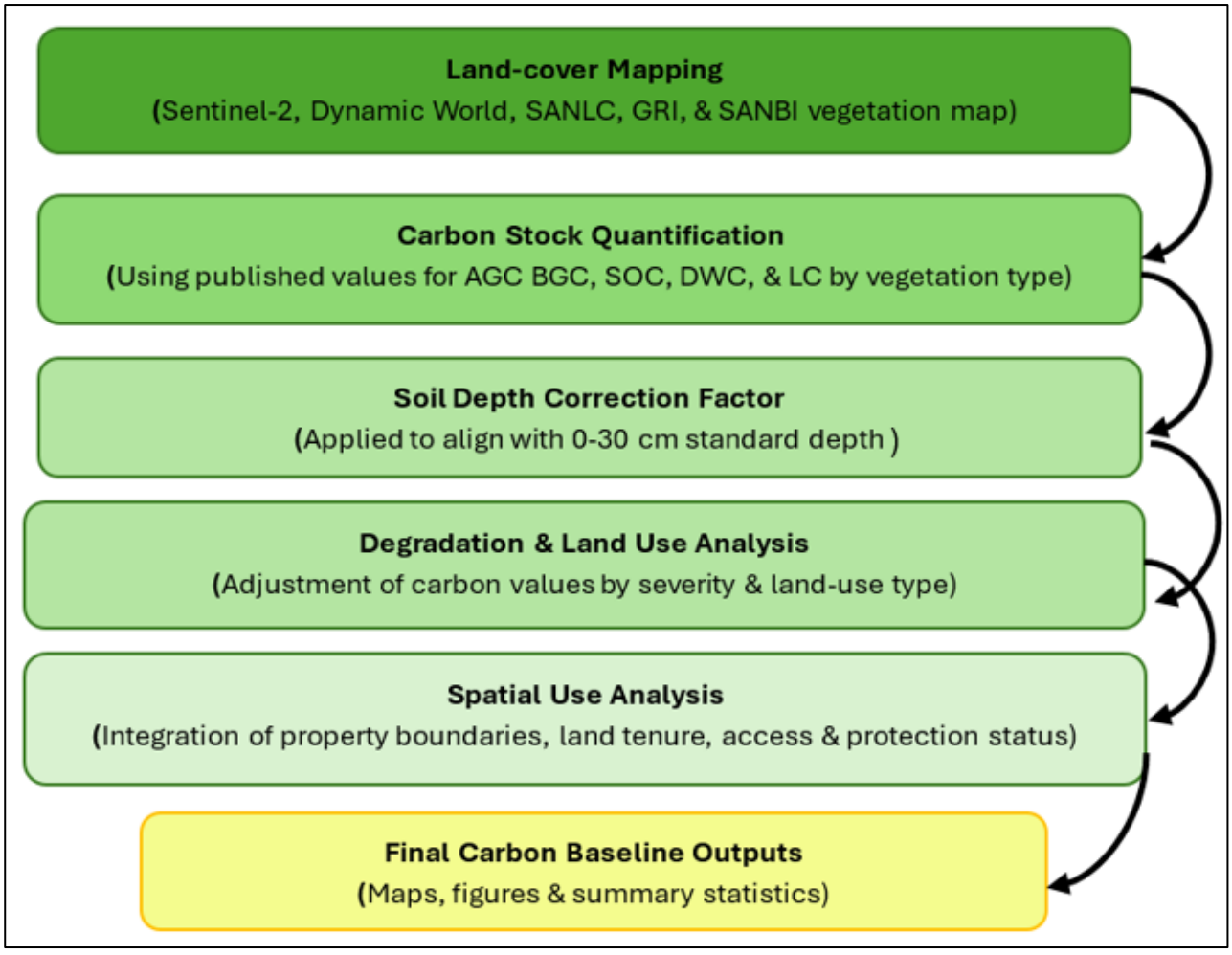


Figure 2: Overview of the methods utilised to generate carbon baseline outputs

As shown in **Figure 2**, following the landcover classification described above, the next step in calibrating the total carbon stock (TCS) for the catchment and for the various carbon sub-pools was to use the SANBI vegetation classes with carbon values for the different carbon pools from the local literature. Specific adjustments were made for forest and fynbos vegetation types. The following forest classes were grouped together, due to the lack of vegetation-specific carbon stocks in the literature: Tsitsikamma plateau forest; Tsitsikamma riverine forest; Tsitsikamma mountain forest; Tsitsikamma fynbos forest. For these forest classes, carbon stock values from Mangwale and Shackleton (2018) were applied, with a 20% adjusted reduction for the Tsitsikamma fynbos forest forest-to-fynbos transition that includes areas with lower carbon stocks.

Fynbos classes (i.e. Tsitsikamma mountain proteoid fynbos, Covie coastal proteoid fynbos, Tsitsikamma ericaceous fynbos and Tsitsikamma forest fynbos) were also grouped together due to lack of vegetation-specific carbon stocks in the literature. Carbon values were calibrated using Mills *et al.* (2012; 2005b), with conservative estimates applied to ensure robustness. Although there is a more recent publication from Mills *et al.* (2012) for carbon stocks in fynbos, we have opted to retain the Mills *et al.* 2005b figures (50% more conservative). The exception, though, is Covie coastal proteoid fynbos. Given that this is a tall, dense vegetation type with similar carbon density to thickets, the Mills *et al.* (2012) carbon values were applied.

Soil carbon calibration using a 3D-model approach

Estimated carbon stocks were further adjusted for soil depth since applying fixed-depth SOC values across heterogeneous terrain can lead to overestimation, as shown in prior studies (Mills *et al.,* 2005a; b). A slope-based correction was applied using a digital elevation model (DEM) derived from 5-metre contour data (CDNGI; https://www.cdngiportal.co.za/). A slope map was generated in GIS, and soil depth correction factors (SDCF) were applied across eight slope classes, reflecting the general decline in soil depth with increasing slope. This method, adapted from prior carbon baseline work in the Albany thicket biome (ATB), enabled more accurate, terrain-sensitive estimates of soil carbon across the catchment.

Degradation and land use analysis

The extent of degradation was assessed using a combination of international (Global Forest Watch, Dynamic World and the Normalized Difference Vegetation Index [NDVI]) as well as regional datasets, including the GRI's vegetation mapping (GFW, 2024; Brown *et al.*, 2022; Vlok *et al.*, 2008). Landcover classes from the 2023 dataset were converted into land-use categories for further analysis. These included classifications such as natural (wetlands, fynbos, forest), degraded (bare soil, AIPs) and agricultural (croplands, orchards, pastures). Summary statistics for total spatial extent in hectares and proportional catchment coverage were calculated for each category.

Spatial analysis and validation

All spatial datasets were clipped to the study area boundary within GIS software, and summary statistics were generated for the total area and extent of each landcover and vegetation class. Carbon stock values were identified for each of the landcover classifications to understand the spatial distribution of terrestrial carbon, including

areas with high-carbon stocks (e.g. intact forests) and degraded areas requiring restoration interventions. This integration was crucial for understanding the relationship between landcover, carbon storage and degradation across the catchment (Van Wilgen *et al.*, 2008).

Results

The study grouped landcover into the broad-level classes listed in **Figure 3**. More than two-thirds of the catchment is natural vegetation in the form of fynbos and forest. Dominant natural vegetation types include Tsitsikamma Sandstone Fynbos and Southern Afro-temperate Forest, adjacent to degraded areas influenced by alien invasive species and agricultural lands.

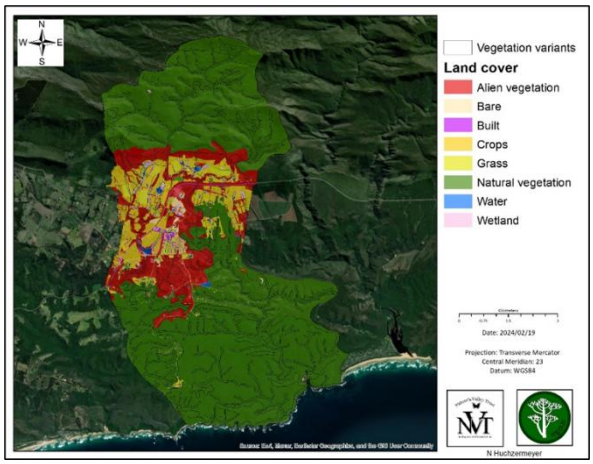


Figure 3: Broad-level landcover classes for the study area

Figure 4 illustrates the spatial distribution of current land-use types defined in this paper. It must be emphasised that the land-use classes employed in this study are basic since a thorough assessment would take a considerable amount of time, but such a study will, nonetheless, provide the finer resolution needed. The methodology would remain the same; however, further consideration of starting classes is required if the ability to identify long-term trends is to be enhanced.

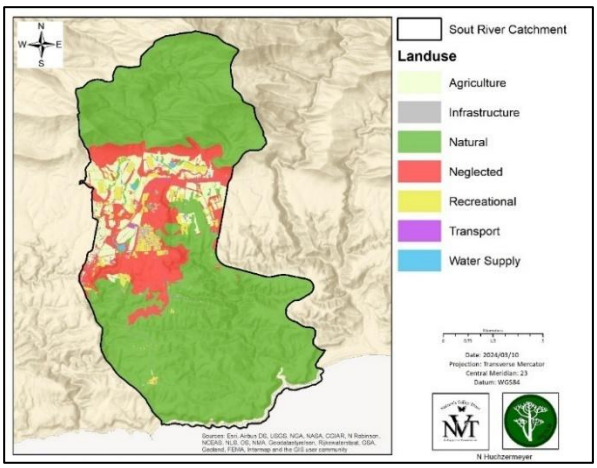


Figure 4: Land use in the Sout River catchment

The benefit of the more detailed GRI vegetation mapping by Vlok *et al.* (2008) is evident in the carbon stocks illustrated in **Figure 5** (approximately 630 000 t C in the catchment). In contrast, previous mapping in which the entire study area was pristine Afromontane or coastal forest, the comparative figure (without a soil-depth correction factor) would report approximately 1.7 million t C. **Figure 5** shows the relatively small roles that LC and DWC play (all vegetation types pooled). The key carbon stocks are RC (10.8%), AGC (29.2) and SC (55.0%).

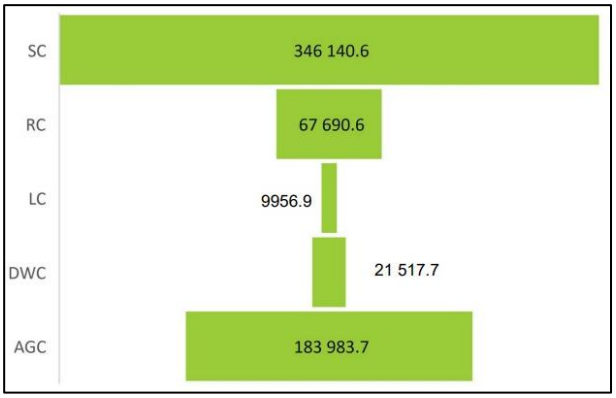


Figure 5: The contribution of each carbon pool to total carbon stocks using GRI Vegetation Mapping (Vlok et al., 2008)

The combined carbon stocks in Tsitsikamma plateau forest, Tsitsikamma riverine forest and Tsitsikamma perennial streams (pristine) account for 53% of the total carbon stocks in the study area. The addition of pristine Tsitsikamma mountain proteoid fynbos and pristine Covie coastal proteoid fynbos, together with Covie coastal proteoid fynbos-AIPs, Tsitsikamma plateau proteoid fynbos-AIPs and Tsitsikamma plateau proteoid fynbos and pastures accounts for 75% of the TCS in the catchment.

Southern Afrotemperate Forest exhibited the highest carbon density among the landcover types studied. Above-ground biomass contributed significantly to its carbon stocks, with substantial soil organic carbon stocks as well. This highlights the importance of forest patches within the catchment as critical carbon reservoirs. Tsitsikamma Sandstone Fynbos, while having lower above-ground biomass due to its shrub-dominated structure, demonstrated notable carbon storage potential through its below-ground biomass and soil organic carbon.

The outputs from the landcover dataset, intersected with the GRI vegetation layer and adjusted for soil depth, provide an improved estimate of carbon stocks in the Sout River catchment (**Table 2**). By including consideration of steep and variable topography as well as shallow soils in many sections of the catchment, estimated carbon stocks in the catchment are approximately 440 128 t. The improved understanding of the spatial heterogeneity and complexity of the carbon stocks created by this study is illustrated in **Figure 6B** (especially in comparison to other analyses illustrated in **Figure 6A** and **Figure 4**).

The spatial distribution of carbon stocks within the catchment revealed pronounced heterogeneity (**Figure 6B**). Mapping these variations provided key insights into areas requiring targeted restoration efforts and informed recommend-dations for conservation interventions.

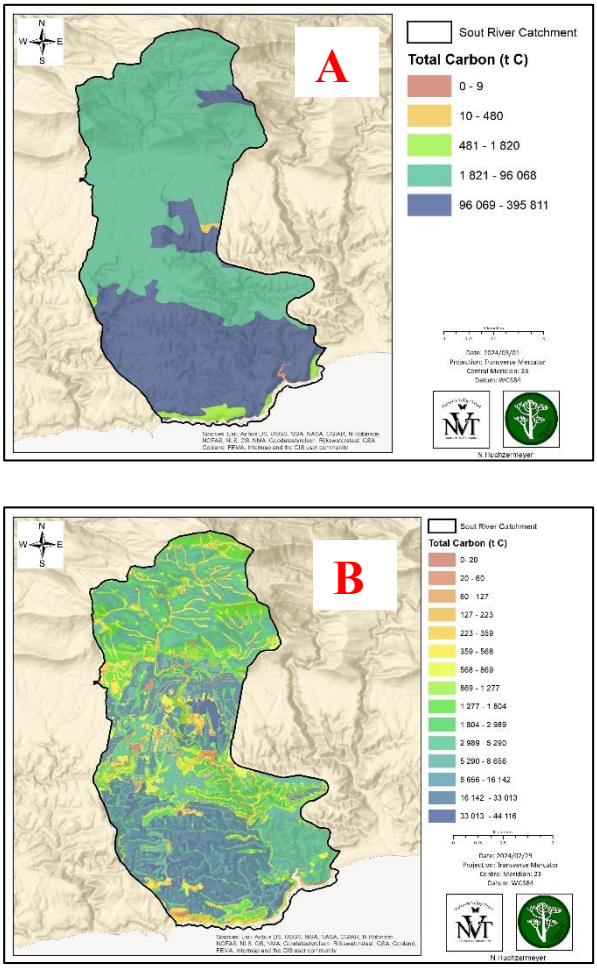


Figure 6: (**A**) The estimated carbon stocks per SANBI vegetation type (SANBI, 2018); (**B**) Total carbon for the Sout (Oos) River catchment based on outputs from the landcover dataset with GRI vegetation layers and adjusted for slope and soil depth

Table 2: Comparative table of estimated carbon stocks within the Sout River catchment based on different landcover or land-use classifications

Dataset	SC (t)	RC (t)	LC (t)	DWC (t)	AGC (t)	TCS (t)
SANLC	519 492	84 960	20 660	45 980	315 009	986 101
SANBI	297 802	60 528	7 956	21 879	179 180	567 345
Vlok 2008	346 141	67 691	9 957	21 518	183 984	629 290
Vlok landcover 2023	357 092	65 450	11 260	24 189	201 385	659 376
Vlok landcover 2023 and SDCF	174 027	29 669	11 242	24 138	201 052	440 128

AIPs occur in at least eight of the GRI vegetation classes. Of prime concern, especially from a biodiversity perspective, is the Tsitsikamma forest fynbos and Tsitsikamma plateau proteoid fynbos where the TCS contributed from AIPs is considerable (**Table 3**). Collectively, AIP stands contribute 14% of the TCS in the catchment, which may be an underestimate. Alien invasive species, particularly *Acacia mearnsii*, were identified as contributing significant above-ground biomass. However, these species negatively impact ecosystem functionality by displacing native vegetation, resulting in a lower overall contribution to long-term carbon sequestration. Agricultural lands, characterised by a lack of significant natural vegetation, had the lowest carbon density. Soil carbon stocks in these areas were further diminished by cultivation and land-use practices, underscoring the need for improved management strategies.

The AIPs in the catchment are reflected quite differently in various datasets (**Figure 7**): As mapped by GRI in **Figure 7A**, the "AIPs" are red and "Degraded" is grey. Closer analysis of "Degraded" as reflected on the vegetation map Vlok *et al*. (2008) compiled in support of the Garden Route Initiative in 2008 indicates that these areas are almost exclusively covered with AIPs at variable densities. The spatially more accurate reflection of AIPs in the Sout River catchment based on 2023 landcover data, which estimates the total area of AIPs from the GRI mapping to be 762 hectares, is presented in **Figure 7B**. A thorough and fine-scale AIP mapping exercise in the higher altitudes is likely to show that the AIP extent is well over 1 000 hectares and increasing rapidly.

Restoration potential was evident in degraded lands and areas impacted by invasive species. By restoring native vegetation, these areas could significantly increase their carbon storage capacity. For instance, based on Mills *et al.* (2005a; b), Glenday (2007) and Mangwale and Shackleton (2018), AIP stands such as mature *Acacia mearnsii* thickets have an estimated TCS of approximately 121.1 t C/ha, while indigenous thicket or forest vegetation in the region store significantly more, ranging from 199.3 to 245.0 t C/ha as shown in **Table 1**. These figures highlight the potential carbon gains that could be realised through invasive species removal and the re-establishment of indigenous plant communities. In agricultural lands, adopting agro-forestry and conservation tillage was identified as a viable strategy for enhancing soil carbon storage while maintaining productive land use.

Table 3: TCS linked to AIPs in the different GRI vegetation types

GRI vegetation class	TCS AIPs (t)	Veg TCS (t)	AIP TCS as proportion of veg C stocks (%)	AIP % of catchment TCS
Covie coastal proteoid fynbos	15 773.3	58 498.2	27.0%	2.4%
Tsitsikamma forest fynbos	4 442.0	7 869.3	56.4%	0.7%
Tsitsikamma fynbos forest	178.0	13 321.0	1.3%	0.0%
Tsitsikamma mountain proteoid fynbos	9 335.6	55 204.0	16.9%	1.4%
Tsitsikamma perennial stream	10 705.0	69 683.0	15.4%	1.6%
Tsitsikamma plateau forest	12 565.3	272 736.0	4.6%	1.9%
Tsitsikamma plateau proteoid fynbos	36 374.8	41 637.0	87.4%	5.5%
Tsitsikamma river and floodplain	2 658.1	24 897.0	10.7%	0.4%
TOTALS	**92 032.2**	**543 845.5**		

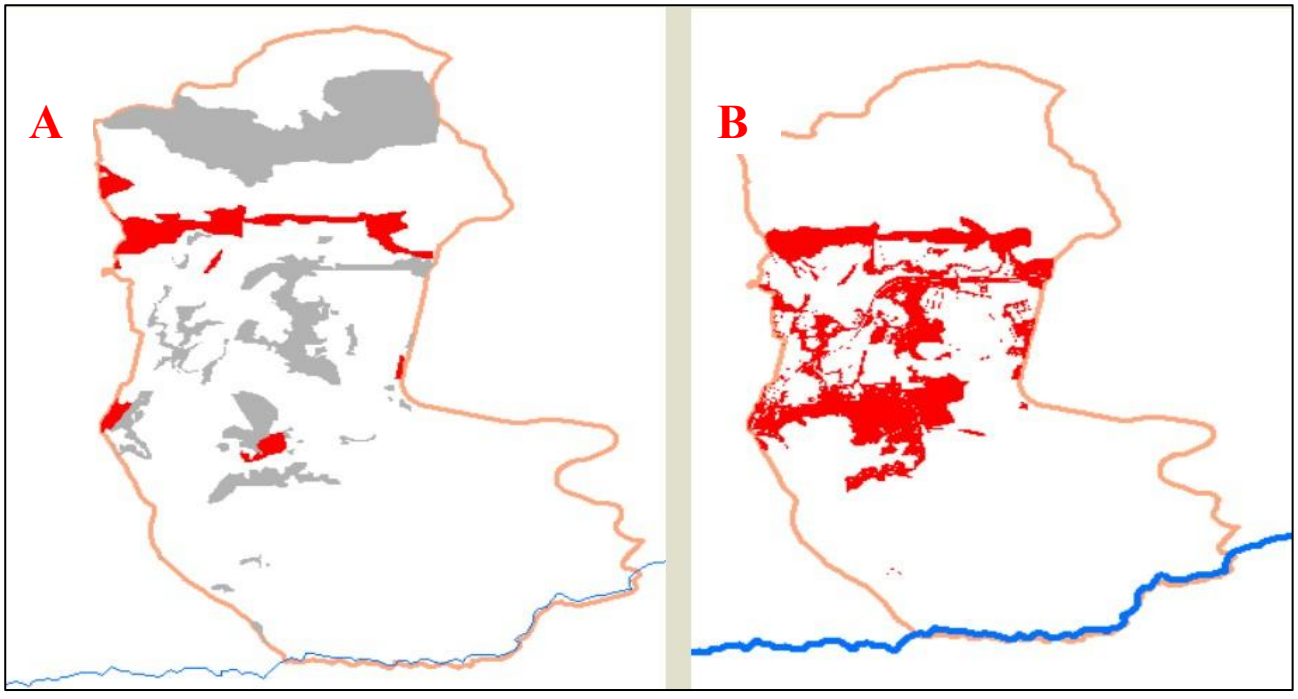


Figure 7: Comparative alien invasive plants (AIPs) mapping of the Sout (Oos) River catchment area: (**A**) GRI map, where "AIPs" are red and "Degraded" is shown in grey; (**B**) AIP spatial mapping using the 2023 landcover data

Discussion

The results of this study underscore the vital role of diverse vegetation types in carbon sequestration within the Sout River catchment. Southern Afrotemperate Forests emerged as critical carbon reservoirs, with their above-ground and soil carbon stocks far surpassing those of other landcover types. This aligns with previous findings that highlighted the high carbon density of indigenous forest systems (Mangwale & Shackleton, 2018). The intact Tsitsikamma Sandstone Fynbos also demonstrated moderate but significant carbon storage, particularly in below-ground biomass and soil carbon pools (Mills *et al.*, 2005b), reflecting the importance of preserving natural fynbos ecosystems.

Degraded areas and regions dominated by invasive species, such as those colonised by *Acacia mearnsii*, were identified as significant contributors to reduced carbon storage within the Sout River catchment. These findings echo those of Le Maitre *et al.* (2011), who emphasised the ecological and hydrological costs of invasive species in South African ecosystems. Furthermore, as pointed out by Richardson and Van Wilgen (2004), while these areas may initially appear to have increased above-ground biomass, the long-term impacts of invasive plants nevertheless include soil carbon depletion via soil erosion and diminished biodiversity, underscoring the need for targeted restoration efforts.

Restoration opportunities identified in this study include the removal of invasive species and the re-establishment of indigenous vegetation. The restoration of degraded fynbos and forest systems has the potential to enhance both biodiversity and carbon sequestration, as demonstrated in regional studies by Van Wilgen (2009) and Van Wilgen *et al.* (2008). However, successful restoration requires careful consideration of soil properties and vegetation dynamics to ensure long-term sustainability. For example, the carbon values assigned to Tsitsikamma forest fynbos and Covie coastal proteoid fynbos in this study were calibrated based on soil depth and vegetation structure, providing a nuanced understanding of carbon storage potential in these ecosystems.

It is important to note, however, that clearing tall AIP stands from fynbos systems may lead to a short-term reduction in carbon stocks due to the lower biomass of native vegetation. Nevertheless, preventing further spread of AIPs into uninvaded fynbos represents a critical conservation opportunity. Fynbos vegetation types in the Sout River catchment are highly susceptible to invasion, and further encroachment could result in substantial carbon emissions following fire events. For instance, full invasion of Covie coastal proteoid fynbos by AIPs would result in an estimated 92 000 tonnes of CO_2 equivalent being released after the fire, while similar scenarios for Tsitsikamma mountain and plateau proteoid fynbos would result in emissions of approximately 190 000 and 143 000 tonnes of CO_2 respectively. Across all vulnerable fynbos types in the catchment, potential emissions could total nearly 500 000 tonnes of CO_2. These figures highlight the significant mitigation value of proactive AIP control in safeguarding both biodiversity and long-term carbon stability.

Spatial analyses revealed significant heterogeneity in carbon storage across the catchment. Intact forests and well-preserved fynbos had relatively high carbon stocks, while degraded areas and agricultural lands exhibited significantly lower carbon densities. These findings emphasise the importance of maintaining landscape connectivity and minimising habitat fragmentation to preserve ecosystem functionality and carbon storage. The fine-scale mapping and validation

processes employed in this study offer a replicable framework for identifying carbon storage patterns in other biodiversity hotspots.

The study also highlights the role of land use in shaping carbon dynamics. Agricultural areas, while necessary for local livelihoods, exhibited reduced carbon stocks compared to natural vegetation. Implementing sustainable agricultural practices, such as agro-forestry and conservation tillage, could mitigate these losses and contribute to regional climate change mitigation strategies.

Conclusions and recommendations

This study underscores the vital role of the Sout River catchment as a key area for carbon sequestration and biodiversity conservation within the Cape Floristic Region. The findings highlight the significant carbon storage potential of intact vegetation types, such as Southern Afrotemperate Forests and Tsitsikamma Sandstone Fynbos. However, these ecosystems face growing threats from land-use changes, including commercial agriculture, urban expansion and the encroachment of AIPs. To address these challenges, targeted conservation and restoration strategies are essential.

The catchment contains unique pockets of intact vegetation that remain unprotected but are crucial for carbon storage. Expanding formal stewardship agreements with CapeNature and SANParks, as seen with contracted parks like Forest Hall, can secure habitats and mitigate development pressures. Securing ecological corridors to maintain connectivity between key biodiversity areas will ensure long-term ecological functioning and species conservation.

Restoration opportunities in the catchment are predominantly located in degraded areas outside protected zones. These areas, particularly those invaded by AIPs such as *Acacia mearnsii*, offer significant potential for carbon sequestration if restored. Systematic clearing of AIPs and re-establishing native vegetation in fynbos ecosystems can improve biodiversity and restore ecosystem functioning; however, this may lead to an initial reduction in carbon stocks. Restoration strategies should incorporate fire regimes where appropriate, as fire is critical for maintaining fynbos functionality. Bundling restoration projects into viable carbon offset programmes can attract financial incentives and encourage private landowner participation. Conducting a willingness assessment to identify suitable degraded lands for restoration could further enhance these efforts.

Accurate mapping and regular monitoring are essential to managing the catchment's carbon stocks effectively. The use of high-resolution landcover mapping, such as the integration of Dynamic World and SANLC datasets, provides detailed insights into vegetation types and land use. Ground-truthing and field validation are crucial for refining maps, particularly for areas dominated by AIPs or degraded lands. To improve monitoring, carbon stock assessments should be conducted every five years to track changes and trends. Developing fine-scale 3D terrain models and collecting soil-specific data would complement vegetation-specific carbon models and enhance overall assessments.

AIPs represent the single greatest threat to biodiversity, water resources and carbon stocks as well as livelihoods within the catchment. Comprehensive mapping of AIPs (including their density, age classes and spatial extent) is critical for developing targeted clearing plans. Preventative measures should prioritise areas with less than one percent AIP cover. Innovative biomass utilisation strategies (e.g. biochar production, wood vinegar and activated carbon) could reduce reliance on

subsidies and provide ecological and economic benefits.

The integration of these strategies into a broader, systems-thinking approach would ensure alignment among stakeholders, with the inclusion of local communities and government agencies. Establishing participatory monitoring and evaluation frameworks can enhance accountability and long-term project success. Protecting intact vegetation, restoring degraded lands and addressing invasive species are essential actions to preserve the region's ecological and carbon storage capacity. By aligning scientific research with practical conservation actions, the Sout River catchment can serve as a model for achieving ecological and climate resilience in the Cape Floristic Region.

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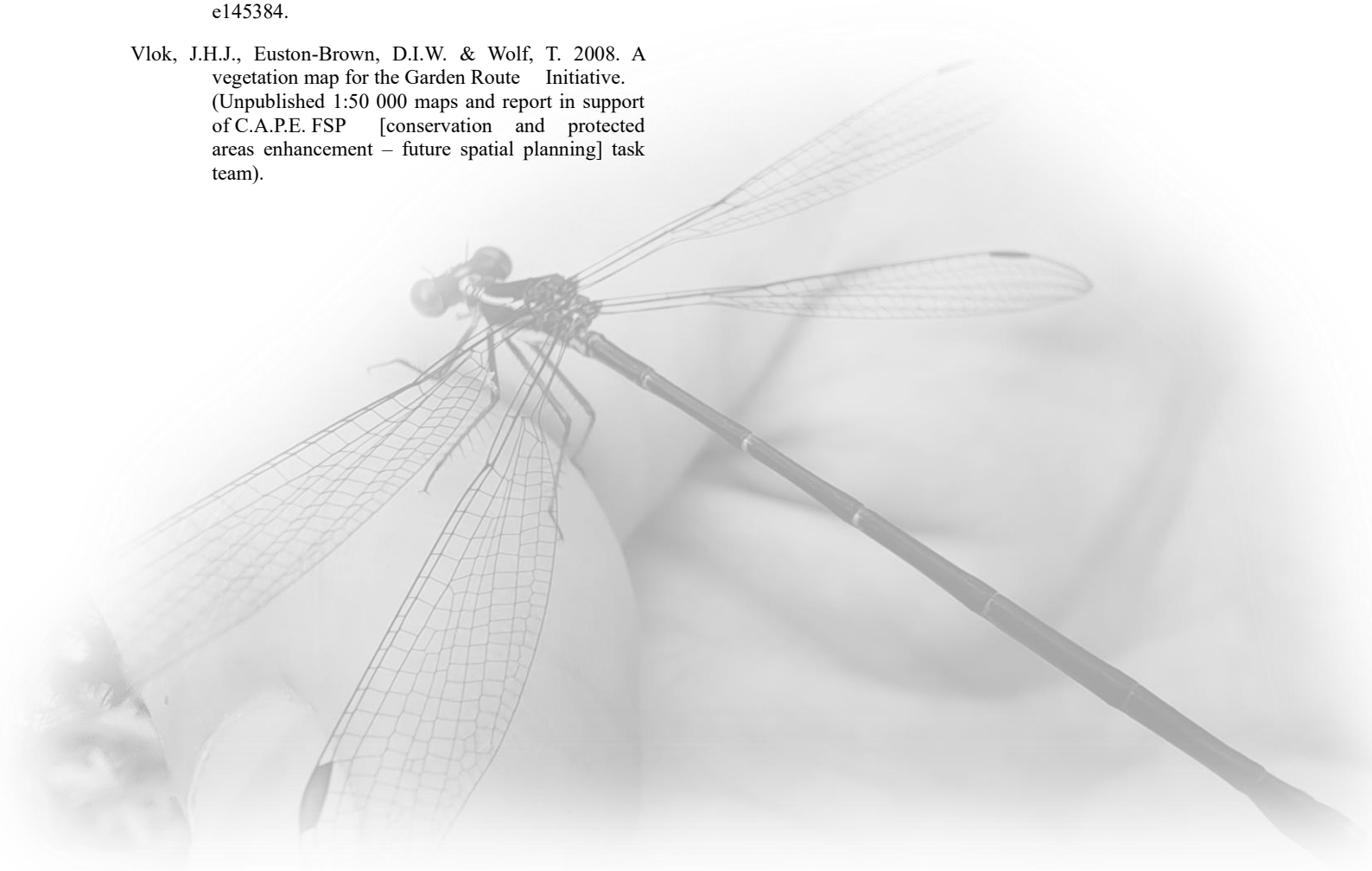
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The role of macroinvertebrates in assessing river health: A focus on the Sout (Oos) River

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Abstract

Macroinvertebrates are valuable bioindicators of freshwater health due to their sensitivity to changes in water quality and habitat conditions. This study investigates the diversity and abundance of macroinvertebrates in the Sout (Oos) River – a short, oligotrophic river system in South Africa's Garden Route region. Sampling at four sites revealed spatial and seasonal trends influenced by anthropogenic activities, with diversity highest upstream and declining downstream. Key taxa provided insights into ecological conditions, highlighting conservation priorities for Gondwana-relict species. These findings emphasise the role of macroinvertebrates in catchment management and biodiversity conservation.

Introduction

Freshwater ecosystems, among the most biodiverse habitats on Earth, are also among the most threatened (Sayer *et al.*, 2025). These ecosystems support a vast array of flora and fauna, many of which are directly dependent on the quality and stability of their aquatic environments. Macroinvertebrates, a diverse group of organisms that include insects, crustaceans and molluscs, are integral components of these ecosystems. They play critical ecological roles such as breaking down organic material and cycling nutrients, thereby serving as a vital link in the food web. Moreover, their sensitivity to environmental changes makes them valuable bioindicators for assessing freshwater health (Rivers-Moore, 2011).

The Sout (Oos) River (aka the Salt River) is a short and deeply incised river system in South Africa's Garden Route region which falls within the Cape Floristic Region (CFR), a global biodiversity hotspot well known for its high levels of plant endemism and diversity (Rust, 1998). Flowing from the Tsitsikamma mountains through the Bitou Local Municipality, its lower reaches pass through the Tsitsikamma (De Vasselot) section of the Garden Route National Park before entering the sea approximately three kilometres west of Nature's Valley (Morant & Bickerton, 1983). As a typical southern Cape mountain river, the Sout (Oos) River is shaped by seasonal flow variability, groundwater contribution and anthropogenic influences, similar to other river systems in the Garden Route region (Rivers-Moore *et al*., 2018). These factors make it a unique case study to explore the relationship between macroinvertebrate populations and river health.

Small mountain freshwater ecosystems, such as the Sout (Oos) River, function as unique ecological units shaped by biogeographical and environmental factors. Schael and King (2005) found that macroinvertebrate community differences between catchments resulted from fine-scale changes

within major taxonomic groups rather than the presence of unique species. These shifts were driven by environmental factors such as water chemistry, fish presence and historical drainage patterns, emphasising the need to consider each river as an ecologically distinct system. Studying the Sout (Oos) River's macroinvertebrate communities within this framework provides insight into its ecological distinctiveness and can contribute to broader conservation efforts for the many comparable systems in the Western Cape region.

The Sout (Oos) River is an oligotrophic system that flows through diverse landscapes, including fynbos, Afromontane forests and agricultural areas, each exerting varying degrees of influence on the river's ecological integrity. Despite its pristine appearance in certain sections, the Sout (Oos) River is highly vulnerable to anthropogenic pressures such as agricultural runoff, invasive vegetation and sedimentation. The upper reaches of the Sout (Oos) River remain relatively pristine, with de Moor and Belligan (2010) reporting acidic waters with a pH ranging from 4.5 to 4.9, low conductivity values between 60 and 90 μS/m and high dissolved oxygen levels, creating optimal conditions for sensitive macro-invertebrate species. However, downstream sections experience increasing anthropogenic impact. For example, agricultural activities upstream contribute to nutrient enrichment and sedimentation, while invasive species such as *Acacia mearnsii* alter the riparian zones, affecting habitat structure and water flow (Low & Rebello, 1996). Understanding how these changes influence macro-invertebrate communities is critical for the effective management and conservation of this unique river system. Macroinvertebrates serve as bioindicators of organic pollution and general river health because their diversity and abundance reflect cumulative environmental conditions. Monitoring both macroinvertebrate assemblages and physicochemical water-quality parameters provides a more comprehensive assessment of river health, since biological indices capture long-term ecosystem changes while water-quality data highlight real-time variations (Van Deventer *et al.*, 2022). Sensitive taxa such as Ephemeroptera (mayflies) and Plecoptera (stoneflies) are typically found in oxygen-rich, unpolluted waters, while more tolerant taxa like Chironomidae (non-biting midges) dominate degraded environments (Day & Davies, 2023). By studying macroinvertebrate assemblages, researchers can identify the specific stressors affecting freshwater ecosystems and develop targeted management strategies to mitigate pollution, restore habitat integrity and improve overall river health.

One of the Sout (Oos) River's most striking features is its role as a refuge for Gondwana-relict taxa – species that have persisted since the breakup of the ancient supercontinent (Chakona & Skelton, 2017). This holds significant evolutionary and conservation importance since these taxa provide a window into the evolutionary history of southern African river systems and underscore the importance of conserving this river's ecological integrity. However, the system's natural vulnerabilities (e.g. reduced acid-pH water moving towards more alkaline conditions and a loss in naturally event-driven, high-flow variability) combined with anthropogenic pressures heighten the urgency for conservation interventions (de Moor & Bellingan, 2010; Wishart *et al.*, 2002).

This study addresses two primary questions:

- What do macroinvertebrate populations reveal about the health of the Sout (Oos) River?
- How can these populations inform conservation and monitoring strategies?

By linking macroinvertebrate assemblages to environmental conditions, this study aims to provide a comprehensive overview of the Sout (Oos) River's health and to highlight

conservation priorities, particularly for Gondwana-relict species.

Methods

Study area

The Sout (Oos) River, located in South Africa's Garden Route region, is composed of distinct land-use types, including fynbos, Afromontane forests and agricultural areas, as indicated in **Figure 1**.

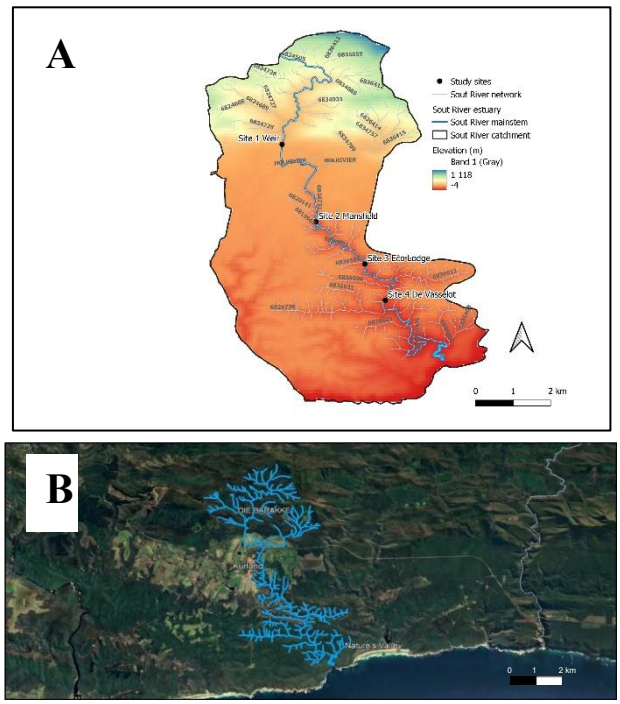


Figure 1: Maps of the study area: **(A)** Gradient map of the altitude range across the study area; **(B)** Map showing the rivers, streams and ephemeral drainage lines contributing water to the lower Sout (Oos) River and estuary ecosystem

Four sites were selected along the river to capture a gradient of anthropogenic impacts, the locations of which can be observed in the study site map in **Figure 2**. Site 1, situated upstream, represents pristine conditions with minimal human interference. Site 2, located downstream of Kurland village, reflects the effects of residential and agricultural activities. Site 3, located mid-reach in a forested ravine, shows signs of ecological recovery from upstream disturbances. Site 4, situated near the river's estuary, represents cumulative downstream impacts.

To answer the primary questions, macroinvertebrate diversity and abundance were assessed across four sites along the Sout (Oos) River, representing a gradient of anthropogenic impact. Sampling was conducted during summer and winter to capture seasonal variability, and the findings were analysed in relation to water-quality metrics such as pH, conductivity and dissolved oxygen. This observational study utilised a cross-sectional design to compare macro-invertebrate diversity and abundance across these sites. Sampling was conducted during the summer (December 2023) and winter (July 2024) seasons to account for seasonal variability. The study followed the South African scoring system (SASS5) methodology, a standardised approach for assessing river health through macro-invertebrate sampling (Dickens & Graham, 2002). This method targets three primary aquatic biotopes: stones in current, marginal vegetation and gravel/sand/mud substrate. At each site, substrates were systematically disturbed, and dislodged macroinvertebrates were collected using a fine mesh net. Samples were preserved in ethanol for subsequent identification in the laboratory.

Water-quality parameters (e.g. pH, conductivity, dissolved oxygen and temperature) were measured concurrently during field sampling. Historical water-quality data from prior assessments were also incorporated to provide additional context for the analysis.

Macroinvertebrates were identified to the family level using taxonomic keys under a stereo-microscope. Data collection focused on three key metrics: the SASS5 score (representing the cumulative sensitivity of macroinvertebrate families to environmental stressors), the number of taxa (reflecting overall biodiversity) and the average score per taxon (indicating the mean sensitivity of the

community). River-health categories were derived from the SASS5 scores using the Level I ecoregion guidelines as per Dallas (2007). The same team conducted all fieldwork and laboratory analyses to ensure consistency and to minimise observer bias.

Data analysis involved statistical techniques to detect spatial and seasonal patterns in macro-invertebrate metrics. The multivariate ordination technique of Bray-Curtis was used to show community similarity between sites. Correlation analyses were conducted to explore relationships between macroinvertebrate metrics and water-quality variables such as pH and conductivity. To visualise these patterns, box plots and scatter plots were generated for key variables, allowing for a comprehensive understanding of macroinvertebrate responses to environmental conditions.

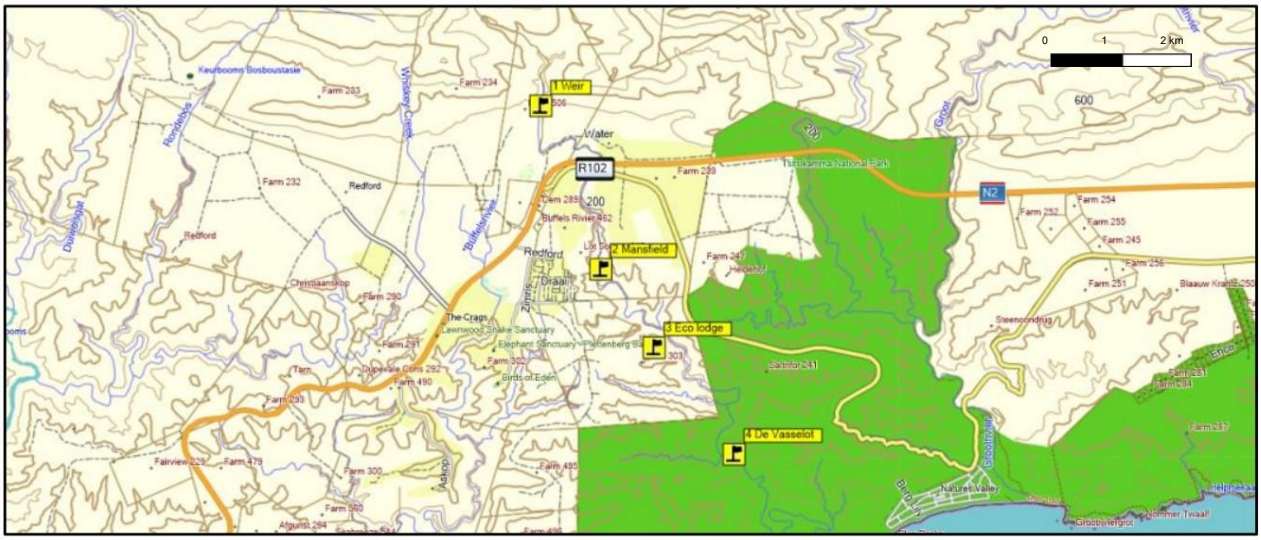


Figure 2: Map of the four selected sites for the study

Results

Macroinvertebrate diversity and taxon composition

A total of 43 macroinvertebrate taxa were recorded across the four study sites during the two sampling periods. Taxa richness varied along the river, reflecting the gradient of environmental conditions from upstream to downstream:

- Site 3 exhibited the highest diversity, with 20 taxa recorded in both summer and winter, suggesting stable habitat conditions and a diverse assemblage of macroinvertebrates.
- Site 1, representing the least disturbed conditions, had 19 taxa in summer and 13 in winter, indicating a seasonal decline in diversity.
- Site 4 showed moderate diversity, with 15 taxa in summer and 16 in winter.
- In contrast, Site 2 which is subjected to agricultural runoff and human settlements had the lowest diversity in summer (14 taxa) but showed a slight increase in winter (15 taxa).

These trends are illustrated in **Figure 3**, which highlights taxa richness across the four sites. Sensitive macroinvertebrate taxa, such as Ephemeroptera (mayflies) and Plecoptera (stoneflies), were still most prevalent at Site 1, indicating stable habitat conditions and relatively good water quality. Site 3, despite its higher diversity, exhibited a mix of sensitive and moderately tolerant taxa, suggesting that it

supports a broader ecological range. Pollution-tolerant taxa, such as Chironomidae (non-biting midges), were more abundant at Site 2, reflecting the impacts of organic pollution and sedimentation. Site 4 demonstrated an intermediate composition, with both sensitive and tolerant taxa present, which is indicative of partial ecological recovery.

SASS5 scores and ASPT trends

The SASS5 scores, which reflect the overall sensitivity of macroinvertebrate communities to environmental stressors, varied significantly among the four sites and between seasons. **Figure 4** provides a visual representation of the SASS5 scores and ASPT values across the sites, illustrating the spatial and seasonal trends:

- Site 1 recorded the highest SASS5 scores, with 130 in summer and 97 in winter, confirming its relatively pristine condition. The lower scores during winter likely reflect seasonal changes in water flow and habitat availability.
- In contrast, Site 2 exhibited the lowest SASS5 scores, with 84 in summer and 88 in winter, which is indicative of poor water quality caused by organic pollution and increased sediment loads.
- Sites 3 and 4 demonstrated intermediate SASS5 scores, with values ranging from 93 to 145 across the sampling periods. These sites showed signs of recovery, as indicated by the presence of moderately sensitive taxa alongside more tolerant species.

ASPT values, calculated as the average sensitivity score per taxon, mirrored the SASS5 trends as shown in **Figure 5**. Higher ASPT values were observed at Site 1 (6.8 and 7.46), while lower values at Site 2 (6.0 and 5.86) emphasised the degraded water quality downstream.

The Sørensen similarity index was calculated to compare the macroinvertebrate community composition between sites. The highest similarity was observed between Sites 3 and 4, with an index value of 0.39 in summer and 0.42 in winter, indicating that these sites share a moderate number of taxa despite their differing environmental conditions. In contrast, the lowest similarity was recorded between Sites 1 and 2, with values of 0.30 in summer and 0.22 in winter, reflecting the stark ecological differences between the relatively undisturbed upstream site and the impacted downstream site.

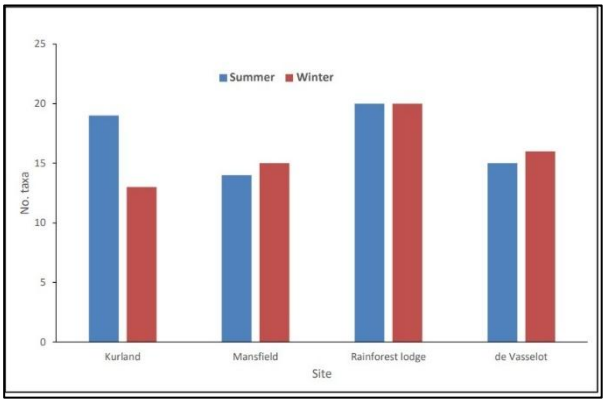


Figure 3: Number of taxa for summer and winter surveys of the four sites, arranged from upstream to downstream

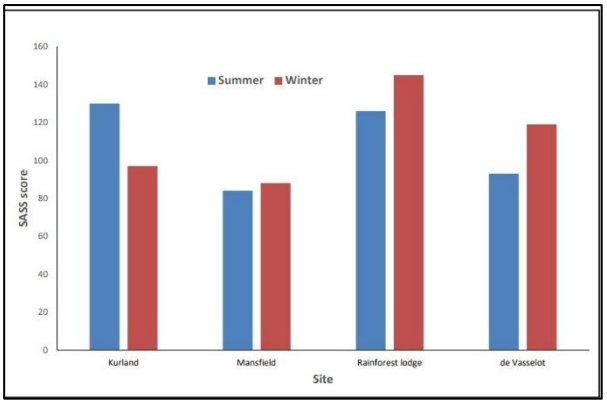


Figure 4: Taxon SASS5 scores for summer and winter surveys of the four sites, arranged from upstream to downstream

Overall, site-pair similarity based on Sørensen's similarity index showed that each site shared approximately 30% of its taxa at the

family level with other sites, meaning there was 70% uniqueness in macroinvertebrate composition at each site. These trends are summarised in **Table 1**, providing a clear overview of the spatial variation in macroinvertebrate assemblages.

A Bray-Curtis ordination analysis was performed to compare the SASS5 scores and associated taxa composition across the sites. The resulting biplot (**Figure 6**) highlights the clustering of macroinvertebrate assemblages based on their sensitivity and abundance. Site 1 is clearly separated from the other sites, reflecting its distinct community composition dominated by sensitive taxa. Sites 3 and 4 cluster closer together, indicating shared taxa and similar environmental conditions. Site 2 is isolated from the other groups, reflecting the dominance of tolerant species and the impact of anthropogenic activities. **Figure 6** further underscores the strong relationship between macroinvertebrate assemblages and enviro-nmental gradients showing that in addition to upstream-downstream species turnover, there was also high seasonal turnover in family-level taxa despite relatively stable SASS5 scores between seasons.

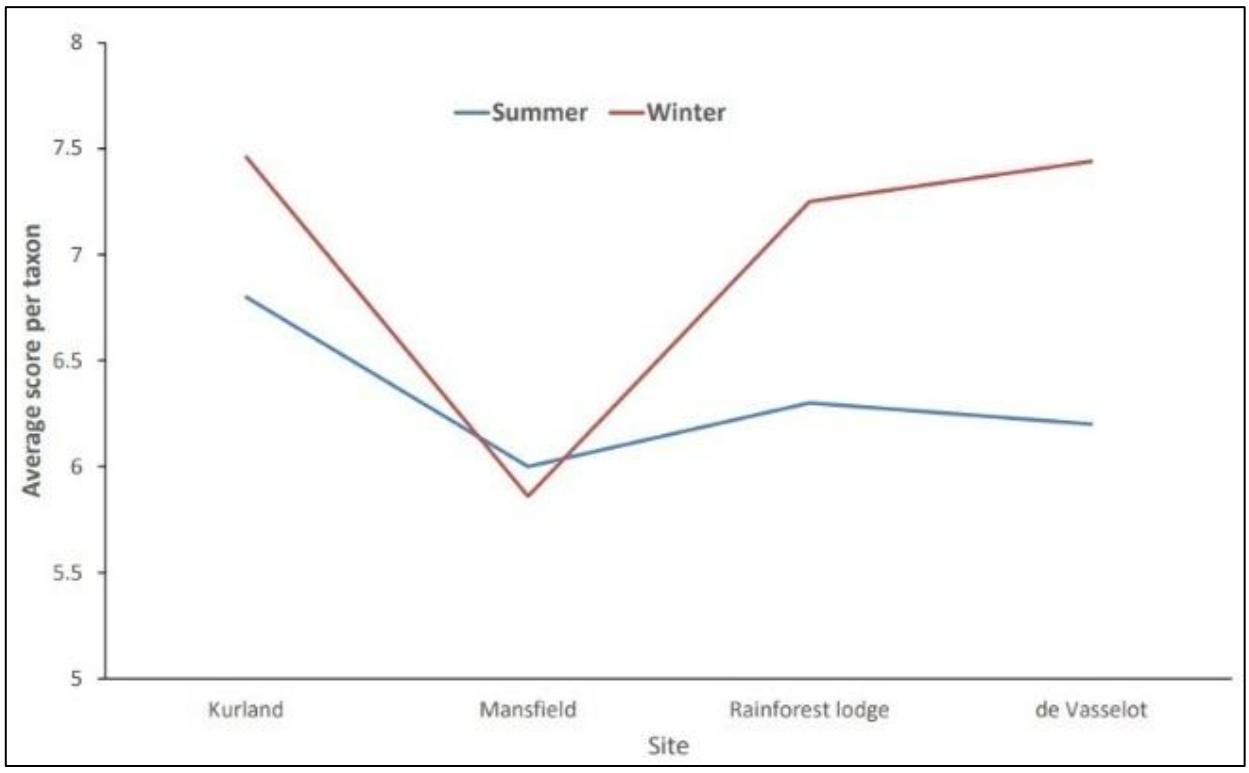


Figure 5: Average score per taxon (ASPT) for summer and winter surveys of the four sites, arranged from upstream to downstream

Table 1: Sørensen similarity index between site pairs for summer and winter samples based on SASS5 family-level data

	Summer				Winter			
	1	2	3	4	1	2	3	4
1	1.00				1.00			
2	0.30	1.00			0.22	1.00		
3	0.37	0.32	1.00		0.35	0.34	1.00	
4	0.38	0.36	0.39	1.00	0.29	0.34	0.42	1.00

Water-quality trends

In situ measurements of electrical conductivity (EC), dissolved oxygen (DO) and pH were recorded at the four sites (**Table 2**). Water-quality parameters measured during the study supported the macroinvertebrate data, highlighting the gradient of environmental conditions along the river. Acidity (pH) values ranged from 5.81 at Site 1 to 7.48 at Site 4 in winter, showing a gradual increase in alkalinity downstream. Conductivity followed a similar trend, increasing from 158 μS/cm at Site 1 to 320 μS/cm at Site 4 in winter, reflecting the cumulative effects of nutrient inputs and sedimentation. In summer, conductivity was highest at Site 1 (225 μS/cm), decreasing at Sites 2 and 3 (177 μS/cm) before rising again at Site 4 (320 μS/cm), reinforcing the pattern of increasing dissolved ions in downstream sections.

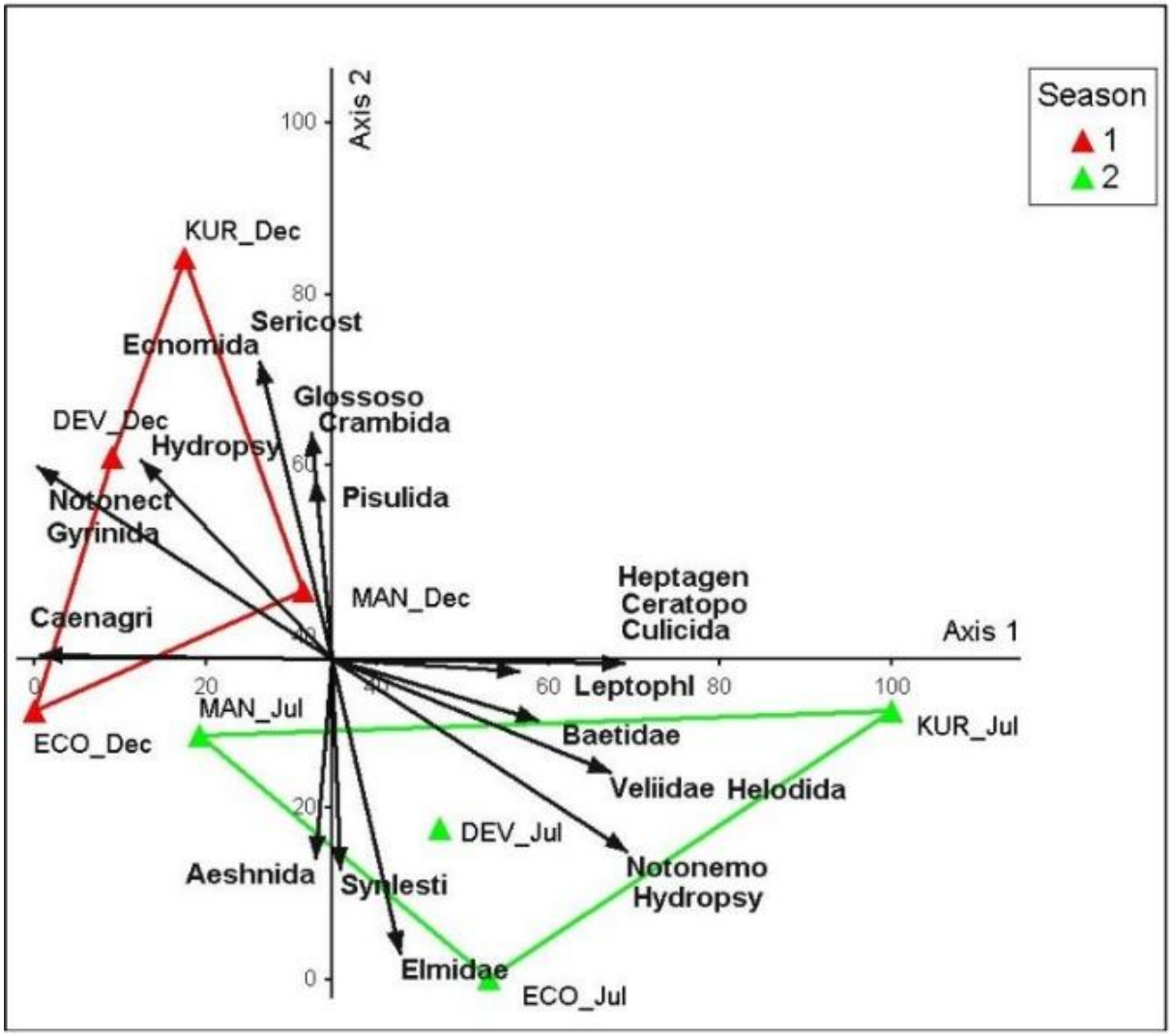


Figure 6: Bray-Curtis biplot of family-level SASS5 aquatic macroinvertebrates at sites 1-4 for summer (December 2023) and winter (July 2024) surveys

**Vector lines indicate aquatic macroinvertebrate taxa most strongly associated with sites. Convex hulls represent summer (1) and winter (2) surveys*

Table 2: Spot water-quality data from December 2023 and July 2024 surveys

Season	Parameter	Site 1	Site 2	Site 3	Site 4
Summer (December 2023)	pH	-		4.69	-
	Conductivity	225		177	
	DO (mg/L)	10.32		12.37	10.61
	Salinity (ppt)	0.12		0.08	
	Temperature °C	16.1		18.2	17.9
	Clarity (cm)	>100		69	>100
Winter (July 2024)	pH	5.81	8.19	7.84	7.48
	Conductivity	158	183	263	320
	DO (mg/L)	Null	Null	Null	Null
	Salinity (ppt)	Null	Null	Null	Null
	Temperature °C	13.6	13.3	12.4	11.9
	Clarity (cm)	>100	>100	>100	>100

Dissolved oxygen levels in summer showed notable variation, with the highest recorded at Site 3 (12.37 mg/L), while Sites 1 and 4 exhibited similar values (10.32 mg/L and 10.61 mg/L respectively). These results indicate well-oxygenated conditions across most sites, with slightly lower values at the upstream and downstream sites compared to mid-reach sections. Dissolved oxygen data were unavailable for the winter survey.

Water clarity remained high at most sites, exceeding 100 cm in both seasons, except at Site 3 in summer (69 cm) where reduced visibility suggests localised turbidity, likely associated with increased sedimentation. Salinity values remained low across sites, ranging from 0.08 ppt to 0.12 ppt in summer, while temperature showed expected seasonal variation with higher values recorded in summer compared to winter.

These trends align with observed shifts in macroinvertebrate diversity and community composition, reinforcing the influence of water-quality parameters on biotic assemblages along the Sout (Oos) River. The gradual downstream increase in conductivity and pH reflects cumulative anthropogenic influences, while localised changes in dissolved oxygen and clarity highlight site-specific environmental factors affecting river health.

Seasonal variability

Seasonal differences in macroinvertebrate diversity and abundance were evident but less pronounced compared to spatial variations. Taxa richness and SASS5 scores were generally higher during summer, likely due to increased habitat availability and stable flow conditions. Winter sampling showed a decline in sensitive taxa and an increase in tolerant species, particularly at Sites 2 and 4, reflecting the impact of seasonal flow fluctuations and reduced habitat stability.

Discussion

This study underscores the strong relationship between macroinvertebrate diversity and environmental conditions along the Sout (Oos) River, reinforcing the value of macroinvertebrates as bioindicators of freshwater health. The highest taxon richness was recorded at Site 3 (reflecting stable habitat conditions), while Site 1, despite being

relatively undisturbed, exhibited seasonal variability in species composition. Sensitive taxa such as Ephemeroptera and Plecoptera were most dominant in these sites, supporting previous studies that associate these taxa with high water quality (Rivers-Moore, 2011; Dallas, 2007). By contrast, Site 2 exhibited the lowest diversity and SASS5 scores, with macroinvertebrate assemblages dominated by pollution-tolerant taxa. This site is heavily influenced by agricultural runoff and residential waste, leading to degraded water-quality conditions. These patterns emphasise the need for pollution mitigation strategies (e.g. improved land-use practices and riparian restoration) to enhance downstream water quality and ecological health.

Sites 3 and 4 showed intermediate diversity and ecological conditions with overlapping macroinvertebrate assemblages, suggesting that these sites share similar environmental characteristics despite their geographical differences. The Sørensen similarity index confirmed this, while also highlighting the stark ecological contrast between Sites 1 and 2 where habitat quality differences were most pronounced. These findings suggest that conservation and restoration efforts in upstream areas could improve ecological conditions downstream, reinforcing the importance of a catchment-scale management approach.

Seasonal variability also played a key role in shaping macroinvertebrate ass-emblages. The summer survey reflected higher taxon richness and SASS5 scores, likely due to stable flow conditions and increased habitat availability. In winter, habitat instability and higher flow variability fav-oured pollution-tolerant taxa, particularly at degraded sites, demonstrating the influence of hydrological fluctuations on community composition. These seasonal trends highlight the importance of long-term monitoring to capture ecosystem dynamics and assess temporal shifts in river health (Wishart *et al.*, 2002). Previous research in South African river systems has shown that when analysed alongside water-quality trends, macro-invertebrate community responses can reveal subtle shifts in ecosystem health that may not be immediately evident through physico-chemical data alone (Van Deventer *et al.*, 2022). This underscores the need for integrated monitoring approaches that can assess biological and environmental variables in tandem to improve freshwater management strategies.

The Bray-Curtis biplot further highlighted spatial patterns in macro-invertebrate assemblages: Site 1 was clearly separated from the others, reflecting its distinct community dominated by sensitive taxa. Sites 3 and 4 clustered closely together, indicating shared environmental conditions, while Site 2 was isolated, emphasising the strong influence of anthropogenic stressors. These spatial trends illustrate the utility of ordination analyses in identifying ecological gradients and conservation priorities.

The observed macroinvertebrate trends closely mirrored the measured water-quality parameters. Acidity (pH) and conductivity followed a downstream increasing trend, aligning with the cumulative effects of anthropogenic inputs. Dissolved oxygen levels varied across sites, with the highest levels recorded in the mid-reaches, while turbidity was more pronounced in localised areas, particularly where sedimentation was evident. These findings further demonstrate the relationship between water quality and macroinvertebrate composition, reinforcing the need for integrated water resource management.

The presence of Gondwana-relict taxa at Site 1 further emphasises the ecological importance of preserving relatively un-disturbed upstream habitats. Targeted conservation efforts (e.g. restoring riparian vegetation, reducing sedimentation and mitigating nutrient inputs) will be crucial for maintaining biodiversity and supporting

ecological resilience. The observed spatial and seasonal trends highlight the need for integrated catchment management strategies to mitigate human impacts and sustain freshwater ecosystems.

Conclusion and recommendations

This study highlights the critical role of macroinvertebrates as bioindicators for assessing the ecological health of the Sout (Oos) River. Spatial and seasonal patterns in diversity and SASS5 scores demonstrated the sensitivity of these communities to environmental conditions and anthropogenic impacts. Site 3 exhibited the highest overall diversity, indicating stable habitat conditions, while Site 1, despite its relatively undisturbed status, showed seasonal variation in taxa richness. In contrast, Site 2 with macroinvertebrate assemblages dominated by pollution-tolerant taxa reflected the cumulative impacts of agricultural runoff and sedimentation. Intermediate conditions at Sites 3 and 4 suggest partial recovery, though the continued presence of tolerant taxa highlights the need for ongoing management interventions to address upstream disturbances.

The significance of this research extends beyond the Sout (Oos) River, offering insights applicable to similar river systems in South Africa and globally. Freshwater ecosystems worldwide are facing unprecedented pressures from climate change, land-use changes and pollution, making it imperative to develop robust monitoring tools. Macroinvertebrate-based assessments are cost-effective and scientifically reliable, providing an effective means to track changes in river health over time (Dallas, 2007; King & Schael, 2001). By integrating these assessments into catchment management, conservation practitioners can protect freshwater biodiversity better and ensure the long-term sustainability of these ecosystems. Given the demonstrated value of combining biological and water-quality assessments in freshwater monitoring (Van Deventer *et al.*, 2022), future conservation efforts in the Sout (Oos) River should adopt a multi-metric approach. This would enhance the detection of emerging ecological stressors and guide adaptive management strategies to mitigate Anthropogenic impacts.

Protecting the Sout (Oos) River's ecological health requires a holistic approach that integrates pollution mitigation, habitat restoration and long-term monitoring. Establishing riparian buffer zones along impacted areas, particularly near Site 2, is essential for reducing nutrient runoff and sedimentation while stabilising riverbanks and enhancing biodiversity. The removal of invasive vegetation and the reestablishment of native riparian plants will further improve habitat quality and water retention. Sustainable land-use practices, including erosion control and improved agricultural techniques, are also necessary to reduce both point and non-point pollution sources across the catchment.

The conservation significance of the Sout (Oos) River is further underscored by the presence of Gondwana-relict taxa at Site 1 which represent ancient evolutionary lineages. Prioritising the protection of this site through conservation designations and habitat management strategies will help safeguard these globally important taxa while preserving the ecological and evolutionary value of the river system. Community engagement through education and collaborative stewardship programmes can foster local investment in conservation efforts, ensuring long-term sustainability.

In conclusion, this study contributes to the growing body of knowledge on freshwater biodiversity conservation and underscores the importance of integrating macroinvertebrate monitoring into broader environmental management frameworks. The findings will

serve as a baseline for future research and management efforts, ensuring the long-term protection of the Sout (Oos) River and its unique biodiversity. This study also illustrates the need for targeted conservation and restoration efforts to protect the Sout (Oos) River's ecological integrity.

By addressing pollution, restoring riparian habitats and implementing adaptive management strategies that account for seasonal variability and climate change impacts, stakeholders can enhance the resilience of this freshwater ecosystem. These measures will not only secure the health of the Sout (Oos) River but will also serve as a model for managing similar river systems regionally and beyond.

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Biodiversity survey of sandy beach invertebrates between Plettenberg Bay and Nature's Valley: Changes since the 1980s

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Abstract

A biodiversity survey of sandy beach macrofauna was undertaken between Plettenberg Bay and Nature's Valley to survey some beaches for the first time (Nature's Valley) and to resample sites last sampled in the 1980s (Plettenberg Bay, Keurboomstrand) to assess changes in the communities. Seven beaches were sampled in 2024 following standard techniques and baited pitfall traps left in the beach overnight to target nocturnal supralittoral pill bugs (*Tylos capensis*). Overall, species richness declined from 24 species in the 1980s to 18 species in 2024, with species richness and abundance declining at Plettenberg Bay and increasing or remaining the same at Keurboomstrand. A population of *T. capensis* was recorded at Nature's Valley for the first time, continued presence was confirmed for Keurboomstrand, and it appears that pill bugs have been lost from Plettenberg Bay. Higher levels of disturbance and clam wash-outs are suspected to be driving the beach macrofauna declines in Plettenberg Bay.

Introduction

Sandy beaches are important coastal ecosystems that provide a substantial number of ecosystem services, many of which enhance human health and wellbeing (Harris & Defeo, 2022). Although beaches are best known as 'sea, sand and sun' (Defeo & Elliott, 2021), they are also home to unique biota (McLachlan & Defeo, 2018; Harris *et al.*, 2014;Campbell, 1996) that are mostly buried in the sand and thus are unnoticed by people. The dynamic nature of the water through tides and wave action, and ever-shifting sand, creates very harsh environments for the resident biota. Consequently, the macrofauna (invertebrates > 1 mm) living on beaches respond more to the physical environment than each other, such that there is stronger abiotic than biotic control of the communities, *sensu* the autecological hypothesis (Noy-Meir, 1979). Beach animals need to be able to burrow faster than the time between waves and swashes to avoid being washed away, and the sand needs to be a grain size that they can burrow into relatively easily (Nel, 1995). This means that beaches with steep slopes, coarse sand and heavy wave action that breaks directly onto the beach face (reflective beaches) support fewer animals than beaches with flat slopes, fine sand and waves that expend most of their energy in wide surf zones (i.e. dissipative beaches) (McLachlan & Defeo, 2018), *sensu* the swash exclusion hypothesis (McLachlan *et al.*, 1993). Beaches are thus classified by their morphodynamic types (broadly either reflective, intermediate or dissipative) based on their tides, waves and sand (McLachlan & Defeo, 2018; Wright & Short, 1984;Wright & Short, 1983). The resident fauna are well adapted to surviving these conditions, for example through excellent burrowing abilities,

endogenous activity rhythms that are linked to tidal cycles and orientation on the beach using the sun as a compass (McLachlan & Defeo, 2018).

South African beaches are among the best-studied beaches in the world (Nel *et al.*, 2014). Sandy beach research has been taking place in the country primarily since the 1970s, and particularly after the first International Sandy Beach Symposium, held in South Africa in 1983 (McLachlan & Erasmus, 1983). It was during the 1980s that the beaches in the Plettenberg Bay area were first surveyed, with McLachlan *et al.* (1981) sampling one site at Keurboomstrand (approximately 3 km east of the Keurbooms Estuary) and Wooldridge (1988) sampling four sites at increasing distances from the base of Robberg and one site at Keurboomstrand. Nature's Valley beach had never been sampled.

Given that two-thirds of South Africa's beach macrofauna species are endemic and found only in southern or South Africa (Harris *et al.*, 2014), the global responsibility for conserving and sustainably managing these species lies largely with us. This means it is important to keep track of our populations of beach invertebrates, especially because they provide food for higher vertebrates, such as shorebirds and fish; contribute to water filtration and nutrient cycling, thereby maintaining coastal water quality; and provide food and bait to people (Harris & Defeo, 2022).

The aim of this study was to undertake the first baseline biodiversity survey of beach invertebrates at Nature's Valley and to resample the sites sampled in the 1980s at Keurboomstrand and Plettenberg Bay to determine if there has been any notable change in the macrofaunal communities at those sites since the 1980s. A second aim was to survey for the presence of the pill bug (*Tylos capensis*), which is not well captured in intertidal sampling because it lives in the supralittoral habitat and comes onto the beach to forage at night. Specifically, the objectives were to collect beach invertebrates by excavation and pitfall trapping, to identify all specimens to the lowest possible taxonomic level, to determine species richness and abundance, and to compare the intertidal invertebrate communities with those sampled in the 1980s.

Methods

Study area and permissions

The study area extended from Plettenberg Bay to Nature's Valley in the Western Cape (**Figure 1**), with seven sites sampled in June and October 2024, five of which sites were sampled previously (**Table 1**). An additional eighth site was included in the analysis that was sampled only in the 1980s. Sampling in 2024 was conducted with ethical clearance from Nelson Mandela University (A23-SCI-ZOO-002) and permission to collect invertebrates from the Department of Forestry, Fisheries and the Environment (RES2024-50) and from CapeNature (CN44-87-30705).

Data collection

Sampling followed standard protocols for collecting beach macrofauna (Schlacher *et al.*, 2008b). At each site, a standard suite of physical parameters was measured at low tide to determine the beach morphodynamic type, including beach slope (measuring the change in elevation with distance along the central transect [**Figure 1c**]), wave height (average of ten waves) and wave period and swash period (average of three waves or swashes, averaged over ten replicates). To determine sand grain size, sand samples were taken at the high

shore, midshore and low-shore stations along the central transect (respectively stations 1, 5 and 10). The sand samples were mixed per site and washed through a 63 µm sieve to remove salt, oven dried at 80°C for 24 hours and sieved through a stack of sieves in phi intervals using a SMC mini-sifter sieve shaker. The weight of sand retained in each phi sieve was weighed and mean grain size calculated using GRADISTAT (Blott & Pye, 2001).

The intertidal beach width was measured and divided into one transect comprising ten equidistant stations, with three transects laid out that were spaced 10 m apart along the shore (**Figure 1c**). At each station, one 0.1 m^2 core of sand was excavated to a depth of 30 cm and the sand sieved through a 1-mm mesh bag. The animals were elutriated out of any remaining sediment using filtered seawater, preserved in absolute ethanol and identified under a microscope. Species that were very large and easy to identify in the field (i.e. *Donax serra, Latona sordida, Bullia rhodostoma*) were measured for shell length and released alive, with a few kept as reference specimens. Ten pitfall traps were also deployed at sunset per site and were retrieved the next morning. The traps were baited with peanut butter to attract pill bugs and contained a small amount of sand for the animals to burrow into. All *T. capensis* were counted and released alive.

Table 1: Codes and names of beaches sampled in this study and references to past sampling

Site code[1]	Site name	Status
PB100	Plettenberg Bay, 100 m from the base of Robberg	Sampled only by Wooldridge (1988)
PB400	Plettenberg Bay, 400 m from the base of Robberg	Resampled sites first sampled by Wooldridge (1988)
PB1500	Plettenberg Bay, 1 500 m from the base of Robberg	
PB3000	Plettenberg Bay, 3 000 m from the base of Robberg	
KBE	Keurboomstrand East	
KBW	Keurboomstrand West	Resampled site first sampled by McLachlan *et al.* (1981)
NVW	Nature's Valley West	Sampled for the first time in 2024
NVE	Nature's Valley East	

[1] When differentiating between sampling periods, a suffix of _80 is added to refer to sampling in the 1980s and _24 to refer to sampling in 2024.



Figure 1: The study site's location in the south-east corner of the Western Cape, with eight sampling sites between Plettenberg Bay and Nature's Valley, is depicted in (**a**). As detailed in **Table 1** and depicted in (**b**), the site in yellow was sampled only in the 1980s, sites in blue were previously sampled in the 1980s and resampled in 2024, and sites in green were sampled for the first time in 2024. Sampling followed a triplicate transect design (transects A, B and C) as illustrated by the dotted black lines in (**c**) with ten equidistant stations sampled between the spring high-tide and spring low-tide marks along each transect

Satellite imagery: ESRI ArcGIS **Basemap: DFFE (2022) * Photo courtesy L. Harris*

Data analysis

Beach morphodynamic type was determined by calculating Dean's Parameter (Ω; Wright & Short, 1984), Beach Index (BI; McLachlan & Dorvlo, 2005) and Beach Deposit Index (BDI; Soares, 2003) from the physical variables that were measured according to the following equations:

$$\Omega = \frac{H_b}{W_s \times T_w}$$

$$BI = Log_{10}\left(\frac{M_z \times TR}{S}\right)$$

$$BDI = \left(\frac{1}{S}\right) \times \left(\frac{a}{M_z}\right)$$

Where: H_b = wave height (m); W_s = sediment fall velocity (m.s^{-1}); T_w = wave period (s); M_z = grain size (mm; φ +1 for BI to avoid negative values); TR = tide range (m); S = average intertidal slope; and a = 1.03125 mm and is the median grain size of the sediment classification scheme.

Because the beach widths varied among sites, the count data per species was converted to an abundance of individuals per 1-m strip transect (IST) and the taxonomic groups were aligned between the data sampled in the 1980s and for this study. This step was necessary because several species have been described since the 1980s and the taxonomy of some taxa has changed; thus, the names of the animals needed to be corrected and updated (**Table 2**) so as not to be counted as different

species in the analyses. Species collected in 2024 that are not resident beach fauna were excluded (e.g. planktonic copepods and flying insects that are not known beach specialist species). Species richness and abundance per site were plotted against beach morpho-dynamic type (Dean's parameter) and were compared graphically among sites. A non-metric multidimensional scaling (nMDS) plot and cluster diagram were plotted in R version 4.2.2 (R Core Team, 2022) using the vegan package (Oksanen *et al*., 2022). These analyses were based on a Bray-Curtis dissimilarity matrix that was built after fourth-root transforming the abundance data. An envfit analysis (vegan package; Oksanen *et al*., 2022) identified which environmental variables were significantly correlated with the nMDS biplot, with variables including the vectors: sand grain size (μm), wave height (m), beach width (m), beach slope (1/slope), Dean's parameter (Ω), BI, BDI, year and distance from Robberg (km); and the factors: season, status (rural, urban), protection (MPA, unprotected) and group (Nature's Valley, Keurboomstrand 1980s; Keurboomstrand 2024; Plettenberg Bay 1980s; and Plettenberg Bay 2024). An analysis of similarity (anosim) and similarity percentages (simper) analysis were also performed from the vegan package (Oksanen *et al*., 2022) to test for significant differences among groups and to identify the species contributing most to the dissimilarity among groups (Plettenberg Bay 1980s vs 2024; Keurboomstrand 1980s vs 2024). Finally, the catch per unit effort (CPUE) of *T. capensis* was calculated and compared among sites. No temporal analysis was possible because pitfall trapping for *T. capensis* was not conduced in the area in the 1980s.

Table 2: Taxonomic alignment in the species lists from the 1980s and 2024

Taxon	Alignment
Talorchestia quadrispinosa	This amphipod species, which was revised to *Africorchestia quadrispinosa* (Lowry & Coleman, 2011), is now known to occur only on the southern African west coast with a new species, *Africorchestia meridionalis,* described as occurring along the South African south coast (Lowry & Baldanzi, 2016). Thus, all *T. quadrispinosa* recorded in the 1980s were changed to *A. meridionalis*.
Eurydice longicornis	This isopod species has since been confirmed as occurring subtidally, with two new *Eurydice* species being described for the intertidal (*E. barnardi* on the South African west coast and *E. kensleyi* on the southern African west and south coasts [Bruce & Soares, 1996]) and a further four intertidal species (species A-D) identified for South Africa that are in the process of being described (Hawkins, 2016). Since both *E. kensleyi* and *Eurydice* sp. A occur along the south coast, and both were found in the samples from 2024, all *Eurydice* were analysed at the genus level because it was not possible to split the identifications from the 1980s into the two species.
Sigalion and *Scolelepis*	These polychaetes collected in 2024 could not be confirmed at a species level because of taxonomic uncertainty; thus, both of these taxa were analysed at a genus level. It is assumed that the species

	from these genera that were present in the 1980s are the same species that are present today.
Pontogeloides latipes	The genus *Pontogeloides* was synonymised with *Excirolana* (Bruce, 1986) such that the accepted name is currently *Excirolana latipes*.
Donax sordidus	There was a taxonomic revision in the *Donax* genus (Moncada *et al.*, 2022) such that the accepted name for this species is now *Latona sordida*.

Results and discussion

All beaches surveyed are wave-dominated, intermediate beaches with fine to medium sand (average grain size: 255 µm) and reasonably flat sloped (average 1/slope = 23.7). The wave climate is more sheltered at the sites near Robberg because waves need to refract around the peninsula given the prevailing south-westerly wind and swell direction along the South African south coast. Both species richness and abundance were weakly related to beach morphodynamics (**Figure 2a,b**), noting that Dean's parameter is sensitive to changes in wave height which depends a lot on the conditions sampled on the day. For example, NVE was sampled at the end of a storm surge with unusually larger waves and higher sea levels on the day of sampling, which increased Ω above what it would be under more standard conditions. The trends are also not strong given that a limited range in beach morphodynamic types was sampled (all largely the same beach type). The expected trends of increasing species richness and abundance from reflective, through intermediate to dissipative conditions (i.e. increasing Ω) broadly hold within the relatively narrow range of types that was sampled (**Figure 2a,b**), except that the trend in abundance in 2024 is opposite to what is expected (e.g. McLachlan & Defeo, 2018; McLachlan & Dorvlo, 2005). This is largely driven by the likely artificially high Ω for NVE and particularly high abundances of *E. natalensis* at KBE (n=4215 IST).

Species richness per site across both time periods ranged from seven to 16 taxa and abundance from 448 to 6 270 IST (**Figure 2c-f**). Given that a finer mesh was used to extract the macrofauna in 2024 (1 mm versus 1.5 mm used by Wooldridge (1988) and 4 mm used by McLachlan *et al.*, (1981)), both species richness and abundance were expected to be higher than were recorded previously, but this was not the case (**Figure 2c-f**). Altogether, 18 taxa were collected across the seven sites in 2024 (19 if counting both species of *Eurydice*), primarily amphipods, isopods and molluscs as well as mysid shrimps, insect larvae and one chaetognathan. This is less diverse than the 24 taxa that were collected in the 1980s, despite using a finer mesh sieve in 2024. There are 12 taxa that were collected in both time periods, with most taxa that were missing in 2024 being polychaetes and the taxa collected in 2024 that were not collected previously including isopods (*Niambia*), insect larvae (beetle and fly larvae) and the chaetognathan. Notably, the two sites resampled that are inside the Robberg MPA have declined in both species richness and abundance (**Figure 2c-f**), despite the gear change to a finer mesh for the more recent sampling. In particular, PB400 was the most diverse site sampled in the 1980s (n=16 taxa) and the least diverse site in 2024 (n=7 taxa), with abundance at the site decreasing to <20% over the same time period (2502.9 IST in 1988 and 448 IST in 2024). In contrast, the sites sampled at Keurboomstrand have either remained the same or increased in species richness and increased in abundance

(particularly at KBW), noting that this was the site previously sampled with a 4 mm mesh, which likely would have under-sampled some of the taxa.

In terms of relationships among the communities, the year of sampling (envfit: r^2 = 0.701, p = 0.009), beach width (envfit: r^2 = 0.5825, p = 0.020) and groups (envfit: r^2 = 0.707, p = 0.009) were all correlated with the nMDS surface (**Figure 3a**). Recall, groups are a concatenation of location (i.e. Nature's Valley, Keurboomstrand, Plettenberg Bay) and the time of sampling (i.e. 1980s, 2024). Sites at Plettenberg Bay inside the Robberg MPA from the 1980s are most different from the other sites, followed by most of the other sites sampled in the 1980s plus PB400 sampled in 2024 (**Figure 3b**). Most of the sites at Keurboomstrand and Nature's Valley cluster together, with PB3000 sampled in 2024 splitting off this group with a high dissimilarity (**Figure 3b**). These results highlight the role of location, time and beach morphodynamics (using beach width as the proxy) in structuring macrofaunal communities in the study area. It also illustrates that the beaches are narrower than they were in the 1980s (**Figure 3a**). This may reflect the effects of a rise in sea levels and/or it could be surmised that sampling in the 1980s was performed at a lower spring tide.

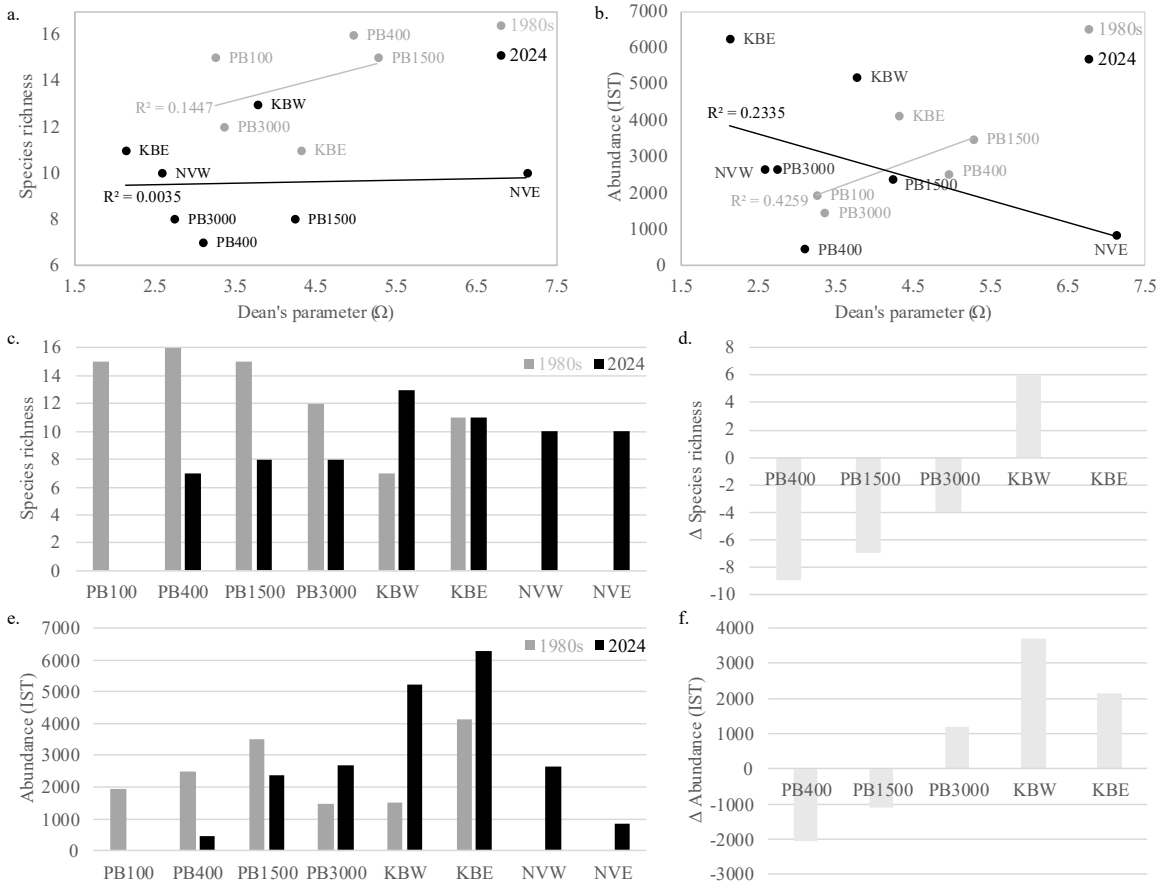


Figure 2: Relationships between (**a**) species richness and (**b**) abundance (individuals per strip transect, IST) with beach morphodynamics (Dean's parameter, Ω), with trends shown for the 1980s (grey) and 2024 (black); (**c**) comparison of species richness recorded at each of the eight sites between the 1908s and 2024, including (**d**) the change (Δ) in the number of taxa recorded, where negative and positive values respectively indicate fewer and more species collected in 2024; (**e**) comparison of total abundance (IST) recorded at each of the eight sites between the 1908s and 2024, including (**f**) the change (Δ) in the number of individuals recorded, where negative and positive values respectively indicate fewer and more individuals collected in 2024

There was a significant difference among the groups (ANOSIM: R = 0.553, p = 0.02). When comparing sites sampled at Plettenberg Bay and Keurboomstrand in the 1980s and in 2024, the species most contributing to the dissimilarity between groups are summarised in **Table 3**. At Plettenberg Bay, all species listed were recorded in the 1980s, but almost all of them were either completely absent or present at much lower abundances in 2024. The only exception was *E. natalensis*, which has increased in abundance (**Figure 4**). At Keurboomstrand, *Niambia* and the Diptera larvae were recorded only in 2024 and the other listed taxa have shown declines in abundance since the 1980s, again with the exception of *E. natalensis* that has increased in abundance (**Table 3, Figure 4**). The declines in abundance over time are evident in almost all of the ten most abundant taxa at each location, with *E. natalensis* being the consistent exception as noted above (**Figure 4**). Interestingly, the same changes in abundance are not evident in the two other Cirolanid isopod taxa, *E. latipes* and *Eurydice* (**Figure 4**).

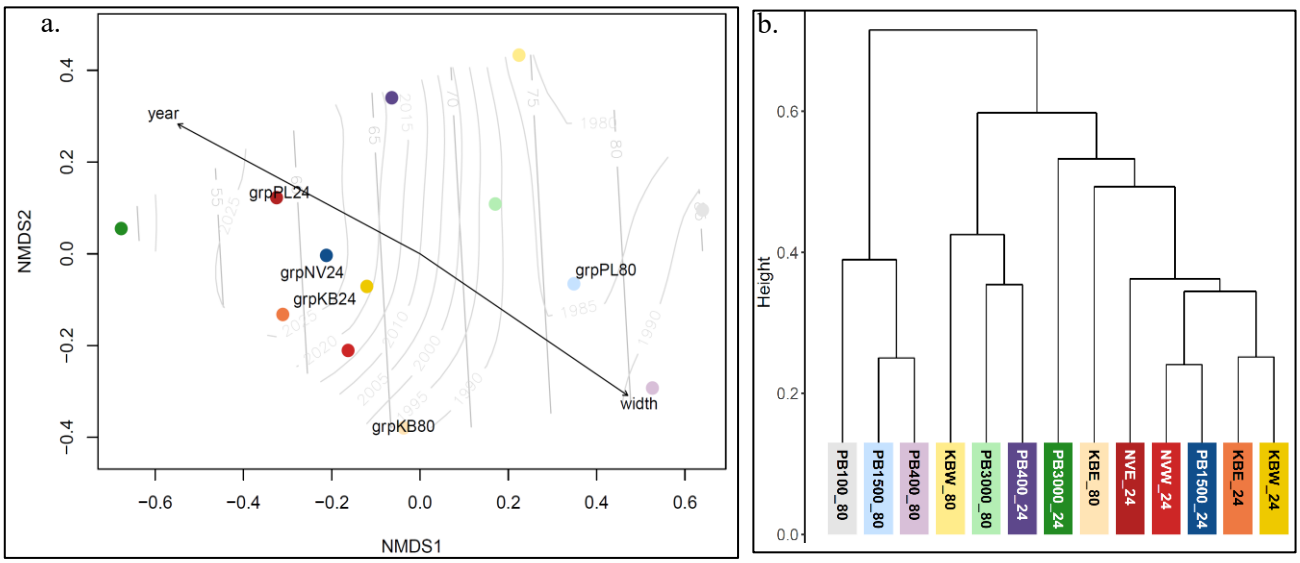


Figure 3: Relationships among macrofaunal communities in each of the 13 sampling events: Data are presented as (**a**) an nMDS biplot (stress = 0.13) and (**b**) a dendrogram from a complete hierarchical cluster analysis, both based on a Bray-Curtis resemblance matrix. In panel a, environmental variables that were significantly correlated with the nMDS surface are plotted in grey as isopleths for the vectors (beach width (m) and year) and as centroids for the factors, being the groups NV24 = Nature's Valley 2024; KB80 = Keurboomstrand 1980s, KB24 = Keurboomstrand 2024; and PL80 = Plettenberg Bay 1980s, PL24 = Plettenberg Bay 2024. Sampling sites are coloured in a rainbow from east (red) to west (purple, grey), with lighter shades representing sampling in the 1980s and darker shades representing sampling in 2024, using the same colour palette in both panels

Table 3: Species with the highest contribution to average between-group dissimilarity in pairwise comparisons of the sampling groups, their ordered cumulative contribution (average contribution divided by the overall average dissimilarity between groups) and significance of the permutation test (significant results at $\alpha \leq 0.05$ are marked in bold)

**Note that the species list was cut when the cumulative contribution was ≥60% (i.e. 0.6), which also included all significant results*

Comparison	Species	Average contribution	Cumulative sum	p-value
PL80 vs. PL24	*Latona sordida*	0.058	0.107	**0.01**
	Excirolana natalensis	0.045	0.191	0.15
	Perioculodes longimanus	0.034	0.253	**0.04**
	Bullia pura	0.033	0.313	**0.01**
	Urothoe coxalis	0.028	0.365	**0.01**
	Tylos capensis	0.028	0.416	0.10
	Gastrosaccus psammodytes	0.027	0.467	0.30
	Dispio magna	0.026	0.515	**0.05**
	Scolelepis	0.026	0.563	**0.02**
	Nephtys capensis	0.026	0.610	**0.01**
KB80 vs. KB24	*Niambia*	0.083	0.191	**0.03**
	Diptera	0.043	0.289	0.11
	Excirolana natalensis	0.034	0.368	0.55
	Eurydice	0.028	0.433	0.37
	Donax serra	0.026	0.493	0.48
	Latona sordida	0.026	0.552	0.81
	Tylos capensis	0.021	0.600	0.39

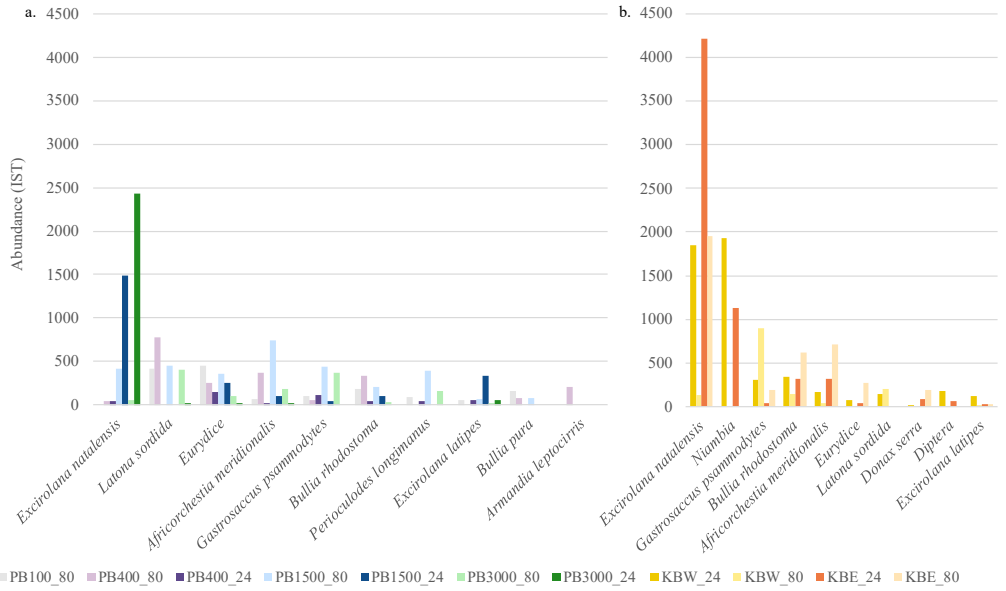


Figure 4: Changes in abundance for the ten most abundant species at (**a**) Plettenberg Bay (cool colours) and (**b**) Keurboomstrand (warm colours)

**Note that the same colour palette as in Figure 3 has been used: Lighter shades represent sites from the 1980s, darker shades sites from 2024*

Tylos capensis was recorded at Nature's Valley for the first time, with an average CPUE of five individuals per trap. *T. capensis* was also captured at Keurboomstrand (KBE: 18.3 CPUE; KBW: 0.6 CPUE) but was not found at any of the three sites at Plettenberg Bay. Because this species was previously recorded as present in the benthic sampling at all sites in Plettenberg Bay except PB3000, it is presumed to have been lost locally given that it was not found in either the pitfall traps or the benthic samples in 2024.

Tylos capensis lives in the supralittoral and comes down to the beach to forage at night and is particularly sensitive to coastal development and night-time lights (Sigqala, 2017). Given the substantial erosion and tramping of the foredune and supralittoral environment, as well as the extent of coastal development in this area, it is suspected that these factors have led to the extirpation of the species.

Conclusion and recommendations

Overall, there has been a decline in beach species richness and abundance in Plettenberg Bay since the 1980s, especially within the Robberg MPA, despite a sampling gear-change that should have favoured the opposite trend and despite large increases in abundance of *E. natalensis*. There are also virtual absences of some species that were previously common (e.g. the clam *Latona sordida*) and suspected extirpation of *T. capensis.* During sampling, many members of the public also commented on their observation of reductions in white mussels, *Donax serra*, that were once very abundant at Plettenberg Bay. In contrast, species richness and abundance at Keurboomstrand have increased or remained the same as in the 1980s. The beach macrofaunal communities at Nature's Valley lie between those at Plettenberg Bay and Keurboomstrand but are more similar to the latter. The sampling in 2024 may have been influenced by the storm surges that passed through the area just before sampling (particularly affecting the NVE site on the day of sampling) and could explain the virtual absence of polychaetes compared with what was sampled previously, potentially as a result of these animals being temporarily washed offshore. However, the broad trends across the region are interpreted as being driven primarily by (1) the level of development and disturbance at each of the beaches and (2) clam wash-outs.

The sites at Plettenberg Bay are far more urbanised than at Keurboomstrand, with much higher numbers of people, dogs and vehicles (e.g. tractors used to remove dead seals) on the beach. Both trampling and beach driving are known to impact beach invertebrates (Schlacher *et al.,* 2016; Schlacher *et al.*, 2008a). Overall disturbance, therefore, is much higher at Plettenberg Bay than at Nature's Valley, where fewer people use the beach, and at Keurboomstrand which is virtually a pristine system with even less human use. In addition, mass mortalities of subtidal clams have been washing out onto the beaches in Plettenberg Bay in thick layers that cover virtually the entire shore, with the shells persisting on the beach for years. It is suspected that these events preclude normal burrowing and emergence activity by many of the beach macrofauna, such that they are excluded from the beach and that only more robust species are able to persist.

It is not clear why the populations of *E. natalensis* have increased so much at both Plettenberg Bay and at Keurboomstrand. Given that the effect is seen at both these sites, it is unlikely to be as a result of local effects (e.g. the clam wash-outs) and seems unlikely to be linked to patchiness given the consistency of the pattern. It is also unlikely to be linked to sampling with a finer mesh, because the same

effect was not recorded in other species and the individuals collected were not juveniles. It is also strange that these increases are not matched in similar isopod species (i.e. *E. latipes* and *Eurydice*) that have similar feeding modes. The trends are also not matched in other high-shore species (e.g. *Africorchestia meridionalis*). Further research would be needed to understand these patterns and confirm if they are an effect of patchiness in the populations or persistent trends and, if the latter, what is driving the increases in this species (and not the others).

An additional concern around declines in abundance of beach macrofauna is that they are prey items for higher vertebrates, such as shorebirds and fish, with potential knock-on effects for these species as well (Schlacher *et al.*, 2016). It is especially unfortunate, therefore, that the declines in macrofaunal diversity and abundance are highest in the Robberg MPA. However, beaches are generally resilient ecosystems and, provided the littoral active zone (dune-beach-surf) remains intact, they are largely able to recover from disturbances such as the clam wash-outs (Harris *et al.*, 2015). Further sampling is recommended to confirm if the temporal trends are persistent and to understand variability in macrofaunal communities in this area.

Further pitfall trapping to search for *Tylos capensis* is also recommended, particularly to confirm whether it has been extirpated at Plettenberg Bay. If this is the case, it highlights the importance of the populations at Keurboomstrand and Nature's Valley. Given the greater beach use at the latter site, it is recommended that higher resolution sampling is conducted at Nature's Valley to determine exactly where *Tylos capensis* is present along the shore and to ensure appropriate supralittoral shore management in those areas to protect the species.

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A source-to-sea informed framework for baseline catchment-level knowledge gathering in understudied systems: Insights from NVT's Sout River project, South Africa

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Abstract

This article presents a catchment-level conservation framework developed by NVT through its "From source-to-sea – nature-based solutions for a river landscape" project in the Sout (Oos) River catchment, located within South Africa's Garden Route Biosphere Reserve. Designed to work within budgetary and data constraints, the framework integrates source-to-sea (S2S) principles with a six-step nature-based solutions (NBS) process to support baseline ecological and social assessments, adaptive planning and long-term monitoring. The project addressed key pressures including invasive alien vegetation, fragmented governance and biodiversity loss through coordinated ecological restoration, stakeholder engagement and knowledge co-production. Outcomes include a replicable, cost-effective model for under-studied catchments, with early indicators of improved ecological resilience, enhanced community participation and strengthened local conservation capacity. By aligning with national water and biodiversity strategies, this baseline framework offers a scalable pathway for integrated catchment management in other ecologically sensitive but understudied systems across South Africa. Recommendations include embedding adaptive governance practices, securing long-term financing and expanding the approach to similar landscapes to advance equitable and sustainable resource management.

Introduction

Rivers and estuaries serve as vital ecological corridors, sustaining biodiversity and delivering critical ecosystem services. As outlined in the Millennium Ecosystem Assessment (MEA, 2005), these include provisioning services (e.g. freshwater and food), regulating services (e.g. climate regulation, flood control and water purification), supporting services (e.g. nutrient cycling and habitat formation) and cultural services (e.g. recreational and spiritual value). These interconnected systems form essential links between terrestrial and marine environments, ensuring ecological integrity, socio-economic well-being and climate resilience (Van Niekerk *et al*., 2022; Van Niekerk & Turpie, 2012).

However, river and estuarine systems are increasingly threatened by a range of anthropogenic pressures, including pollution, unsustainable land-use practices, invasive alien species, habitat

fragmentation and climate-related changes in flow regimes. These impacts disrupt freshwater inflows, reduce ecosystem functionality and intensify vulnerability across the river-to-sea continuum (Rivers *et al.*, 2023; Albert *et al.*, 2021a/b; Grundling *et al.*, 2021). Governance challenges such as fragmented institutional mandates, inadequate enforcement, conflicting land-use priorities and limited technical capacity further hinder effective management (du Plessis, 2024; Granit *et al.*, 2017; Van Koppen & Schreiner, 2014; Meissner *et al.*, 2013). These limitations are particularly evident in implementing integrated catchment and estuarine strategies that require alignment across jurisdictions, disciplines and stakeholder interests.

South Africa's rivers and estuaries span a broad range of ecological zones from near-pristine mountain catchments to densely settled coastal areas making them especially sensitive to upstream-downstream disconnections. As recognised in the National Estuary Biodiversity Plan and the National Water Resource Strategy, integrated management is essential to conserve ecosystem integrity across these gradients (Locke & Winter, 2025; Van Niekerk *et al.*, 2022; Le Maitre *et al.*, 2018). In this context, source-to-sea (S2S) approaches are gaining traction as a holistic framework that explicitly considers the flow and interaction of water, biota, materials and pollutants from catchment to coast. Today, S2S frameworks are increasingly used to guide system-level conservation and restoration efforts globally (Michels-Brito *et al.*, 2023).

This article presents the final S2S baseline framework designed in the course of NVT's "From source to sea – nature-based solutions for a river landscape" pilot project as a practical framework for integrating S2S principles with nature-based solutions (NBS) interventions in a small, under-resourced catchment. Located in the Tsitsikamma region within the Garden Route Biosphere Reserve, the Sout (Oos) River catchment was selected for its ecological significance and vulnerability to anthropogenic pressures (see **Figure 1**). The project applied a structured, budget-conscious framework for generating baseline ecological and social data while fostering community participation and adaptive management.

The Sout River (aka Salt River) flows through the Bitou local municipality and the Garden Route National Park (GRNP), with the lower reaches within the De Vasselot section remaining in good ecological condition (Vlok *et al.*, 2024; SANParks, 2022). In contrast, the upper catchment is increasingly exposed to urban encroachment (e.g. Kurland village, The Crags), agriculture (both livestock and crops), brick-making activities and widespread invasion by alien plant species (Huchzermeyer & Powell, 2024; Bitou Municipality, 2017). These impacts threaten the ecological integrity of the river and its rich biodiversity, including highly sensitive and endemic macroinvertebrate assemblages discovered over a decade ago, some of which include at least 16 undescribed species and three new genera (Bellingan *et al.*, 2022; de Moor & Bellingan, 2011; de Moor *et al.*, 2004; de Moor & Barber-James, 2001).

This article outlines how the S2S-informed framework was used to assess and address these pressures through coordinated monitoring and restoration efforts. The approach was designed to generate actionable knowledge that supports adaptive governance, stakeholder engagement and biodiversity conservation in similar under-studied systems across South Africa.

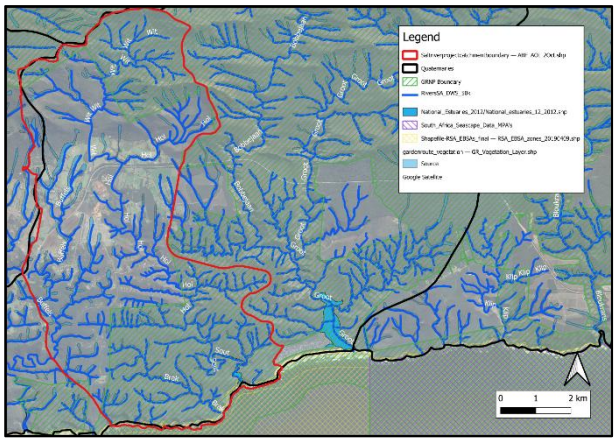


Figure 1: Environmental context of the Sout (Oos) River catchment: The red boundary outlines the Sout River catchment area defined for NVT's "From source to sea – nature-based solutions for a river landscape" pilot project. This map provides the spatial context for implementing the S2S baseline framework and monitoring NBS interventions. The map also shows quaternary boundaries, river networks and protected areas within the Garden Route Biosphere Reserve

Existing literature and derived theoretical framework

Source-to-sea (S2S) concept

Globally, the S2S framework promotes integrated, systems-based management of key flows such as water, sediment, biota and pollutants across entire catchments from upstream freshwater sources through rivers, estuaries and into coastal and marine environments (Michels-Brito *et al.*, 2023; Mathews *et al.*, 2019; Granit *et al.*, 2017). It emphasises the interconnectedness of these systems and acknowledges that changes or disruptions at any point along the continuum can have cascading impacts across the landscape–seascape interface. As such, the S2S approach calls for cross-sectoral collaboration, multi-stakeholder governance and adaptive management practices grounded in a deep understanding of social-ecological interdependencies.

In South Africa, the principles of the S2S approach closely align with long-standing frameworks such as integrated catchment management (ICM), strategic adaptive management (SAM) and social-ecological systems (SES) thinking. These approaches have been particularly influential in managing the complex dynamics of river systems in regions like the Lowveld and the Eastern Cape (Biggs *et al.*, 2011; Pollard & du Toit, 2011; Rogers & Luton, 2011) through initiatives like the Kruger National Park rivers programme and the Tsitsa project which have demonstrated the value of integrated, adaptive and participatory approaches in managing complex river systems (Pollard *et al.*, 2023; Pollard & du Toit, 2011; Roux & Foxcroft, 2011).

Strategic adaptive management (SAM), originally developed for the dynamic ecosystems of the Kruger National Park, provides a structured, learning-oriented process for decision making in uncertain and changing environments (Pollard & du Toit, 2011; Roux & Foxcroft, 2011). More recently, the Tsitsa project has expanded upon this foundation by incorporating SES thinking and adaptive co-governance, particularly within degraded rural catchments. These efforts emphasise iterative learning, inclusive stakeholder engagement and power-sharing, principles that are central to the S2S approach (Pollard *et al.*, 2023; Weaver *et al.*, 2023; Mathews *et al.*, 2019; Blignaut *et al.*, 2014).

At NVT, research efforts draw on the global S2S approach while integrating nature-based solutions (NBS) interventions where appropriate. This integrated approach aligns with an extensive body of literature that emphasises the ecological and social interdependencies within linked freshwater, estuarine and coastal systems. Building on national precedents and locally grounded practice, NVT adapted the S2S approach to guide the Sout River project, tailoring it to the catchment's unique biophysical, social and institutional context. The resulting baseline

framework (see **Figure 2**) outlines the steps undertaken in the catchment-level assessment and illustrates the flow of interventions designed to support long-term conservation, monitoring and collaborative governance outcomes.

Sout River and the S2S-informed framework

Located within the Garden Route Biosphere Reserve, the Sout (Oos) River catchment is increasingly impacted by ecological stressors such as invasive alien plant species, unsustainable water abstraction and habitat fragmentation (Vlok *et al.*, 2024; Baard & Kraaij, 2014; de Moor & Bellingan, 2011). In response, NVT adopted a hybrid approach that integrates the S2S approach with NBS interventions, offering a context-specific and scalable model for identifying and addressing threats along the river continuum. This approach acknowledges the interconnectedness of human and ecological systems and promotes interventions that support both environmental integrity and community well-being (Knight, 2023; Rivers *et al.*, 2023; Mathews *et al.*, 2019; Fabricius & Cundill, 2014).

The resulting framework (**Figure 2**) provides a practical, stepwise guide for conducting small catchment assessments, particularly valuable in data-deficient contexts. It begins with scoping and stakeholder mapping, followed by ecological baselining, a review of existing governance structures and the implementation of locally tailored NBS interventions. Its flexible and cost-effective design makes it suitable for replication in other under-researched catchments within the Garden Route and similar regions.

The S2S approach guided our baseline research and conservation planning for the Sout River project. Each phase (from initial desktop assessments to field-based ecological monitoring, stakeholder engagement and adaptive planning) was informed by this structure. Crucially, the final baseline framework NVT developed is designed to be adaptable and grounded in real-world constraints, thereby supporting long-term conservation goals while fostering socio-ecological resilience through integrated S2S–NBS strategies.

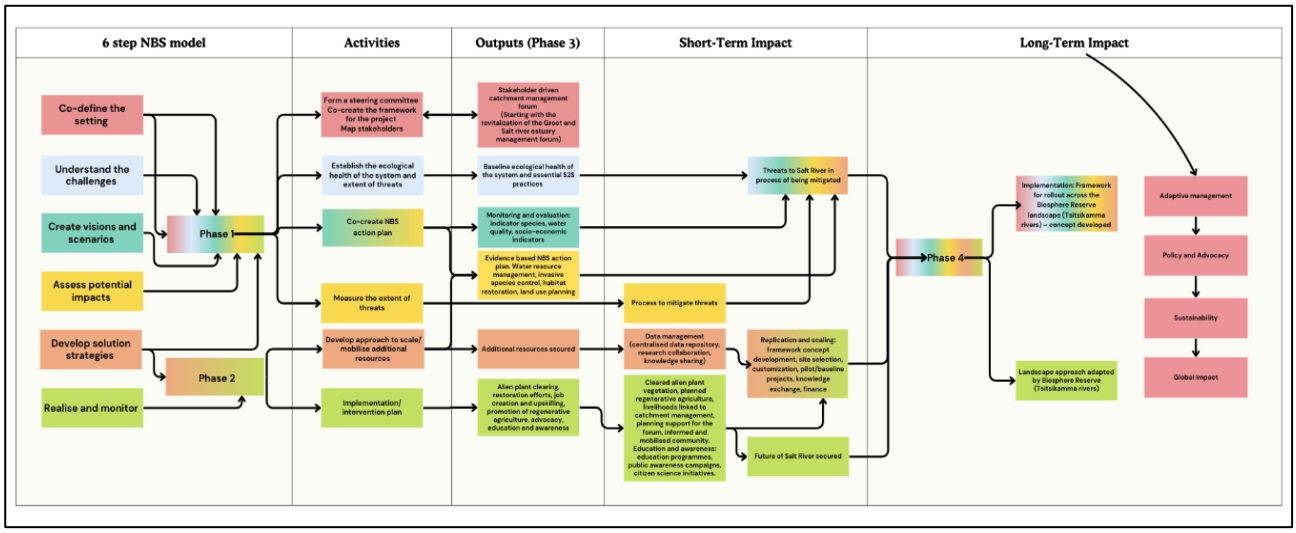


Figure 2: NVT's S2S-informed baseline framework for catchment-level monitoring in the Sout River

Nature-based solutions (NBS)

Nature-based solutions form the core implementation strategy within NVT's catchment-level framework, working in tandem with the broader S2S approach. Rather than acting as a standalone or parallel approach, NBS are embedded within the S2S-informed framework as practical, ecological tools to restore function, enhance resilience and address both environmental and social challenges in an integrated manner. By harnessing natural processes, NBS offer site-specific, cost-effective interventions that align conservation goals with community well-being and long-term sustainability.

In the Sout (Oos) River catchment, NBS interventions included invasive alien plant (IAP) removal, wetland protection, erosion control and community-driven restoration efforts. These actions contribute to the recovery of ecosystem function while simultaneously fostering local stewardship and socio-ecological resilience. Globally, NBS have gained recognition for their potential to generate co-benefits across ecological and socio-economic domains (Knight, 2023; Albert *et al.*, 2021a/b). In a local context, these practices (e.g. the use of riparian buffer zones and rehabilitated wetlands) demonstrate how working with natural systems can enhance biodiversity, improve adaptive capacity and support livelihoods in vulnerable landscapes (Eggermont *et al.*, 2015; Baard & Kraaij, 2014; Chamier *et al.*, 2012).

South Africa's context further underscores the urgency of integrating NBS into catchment management. Recent studies have highlighted the substantial impact of invasive alien plants on national water resources. Le Maitre *et al.* (2019) estimate that IAPs reduce surface-water runoff by approximately 1.44 to 2.44 billion cubic metres annually with the most affected catchments experiencing over five percent loss in mean annual runoff. A report released by CapeNature in 2023 on the state of biodiversity in the Western Cape also warns that IAPs in strategic water-source areas compromise water security by depleting both volume and quality, exacerbated by increased fire risk and IAPs' high-water consumption (CapeNature, 2023).

These findings reinforce the value of NBS as a tool for water security and ecological restoration. By promoting land-use practices that support ecosystem function and climate resilience, NBS can bridge conservation and human development needs. In NVT's Sout River project, we applied NBS interventions to aid restoration of the Sout (Oos) River catchment by engaging local stakeholders in sustainable practices that can be adapted and replicated in neighbouring areas facing similar socio-ecological pressures (du Plessis, 2024; Hoare, 2024; Huchzermeyer & Powell, 2024; Vlok *et al.*, 2024). While NBS are globally relevant, their implementation in South Africa where water scarcity, socio-economic inequality and fragmented governance structures compound environmental vulnerabilities are particularly critical. Community-based, cost-effective approaches like NBS are, therefore, essential for building a more resilient and equitable future (SANParks, 2022).

Long-term monitoring

The S2S-informed framework developed by and adopted throughout the Sout River project is designed to support long-term, catchment-level monitoring by providing a structured, cost-effective approach to tracking ecological change over time. By establishing clear baseline indicators and identifying key environmental pressures, this framework enables repeatable assessments that inform both site-specific conservation actions and broader regional planning efforts.

For instance, changes in riparian vegetation cover can be monitored over time to evaluate the effectiveness of IAP removal interventions. Likewise, community-based water-quality testing, another key component, allows for ongoing monitoring of sedimentation and pollution often linked to upstream agricultural or urban activities. Additionally, macro-invertebrate sampling, previously conducted in the Sout River, served as a robust bioindicator method to detect ecological shifts. This is especially relevant in assessing the impacts of pressures such as water abstraction and alien fish introductions (Orozco-González & Ocasio-Torres, 2023; de Moor *et al.*, 2004; Barber-James, 2000).

Together, these monitoring activities form the basis of an adaptive, participatory monitoring programme that is both grounded in local realities and scalable to neighbouring catchments. By aligning ecological indicators with community engagement and ongoing data collection, the S2S-informed baseline framework supports a responsive management system capable of addressing evolving conservation and sustainability challenges over the long term.

Governance

Effective management of river systems requires more than ecological restoration: It hinges on robust, integrated governance structures that span across sectors and institutional levels. In South Africa, governance challenges in water and environmental management are well-documented, with issues such as institutional fragmentation, overlapping mandates and limited capacity frequently impeding progress (Meissner *et al.*, 2013; Schreiner & Hassan, 2011; Pollard & du Toit, 2008). While local policy frameworks (for example, integrated development plans [Bitou Municipality, 2017] and strategies to counter the impacts of climate change [Eden District Municipality, 2018]) as well as SANParks' 2020 management plan and 2022 assessment reflect growing awareness of sustainability and climate adaptation, implementation is often undermined by weak enforcement and insufficient cross-sector coordination.

In the Sout (Oos) River catchment, these governance limitations manifest as inconsistent monitoring, poor inter-agency collaboration and a disconnect between conservation efforts and land-use planning. The S2S-informed baseline framework developed through NVT's Sout River project addresses these gaps by embedding governance analysis directly into the baseline assessment process. It provides a practical tool for identifying institutional bottlenecks, mapping mandates and fostering alignment with broader national strategies such as SAM and ICM (Rogers & Luton, 2011).

Rather than treating governance as a standalone objective, we recognise it as a cross-cutting factor that fundamentally shapes the success or failure of conservation interventions. By incorporating governance diagnostics into the framework for the Sout River project, we aim to contribute to South Africa's ongoing efforts to strengthen environmental governance through locally informed, evidence-based recommendations (Pollard *et al.*, 2023; Bennett & Satterfield, 2018). In doing so, we hope to support more cohesive, accountable and adaptive decision making at the catchment level.

Despite the growing recognition of the S2S approach and NBS, empirical research on how these approaches are integrated and applied at the catchment level in South Africa (particularly in ecologically rich, yet understudied areas like the Garden Route) remains limited (Guerbois *et al.*, 2019; Mathews *et al.*,

2019; Wilk & Wittgren, 2009; Brownlie *et al.*, 2005; Cowling & Pressey, 2003). The Sout River project contributes to addressing that gap by piloting a replicable, budget-conscious S2S-informed baseline assessment framework within the Sout (Oos) River catchment. The framework is designed to guide baseline knowledge gathering, facilitate stakeholder engagement and support long-term monitoring for conservation and management planning.

Research gap and rationale

Although there is a substantial body of research on riverine and estuarine conservation in South Africa, key knowledge gaps remain in the practical implementation of integrated management approaches at the catchment scale, particularly in smaller, ecologically significant systems such as those found within the Garden Route Biosphere Reserve (Michels-Brito *et al.*, 2023; Roux *et al.*, 2023; Malaza & Mabuda, 2019). While the source-to-sea approach and nature-based solutions have shown success in international contexts, their combined application in South African river systems remains largely untested. Furthermore, the long-term ecological outcomes and governance challenges associated with implementing such approaches in data-poor, multi-use catchments are not yet fully understood (Klaver *et al.*, 2024; Chausson *et al.*, 2020).

The Sout (Oos) River catchment is a relatively small system nestled in the Tsitsikamma landscape, offering a valuable opportunity to explore these dynamics. The catchment faces a range of ecological pressures, including invasive alien vegetation, habitat fragmentation and freshwater species introductions. Notably, recent observations of *Pseudobarbus* sp. (red-finned minnow) and freshwater mullet in a historically fishless system underscore the need for improved biodiversity monitoring and ecological baselining. These species (potentially introduced via inter-basin transfers (IBTs) or passive dispersal by wading birds) may have cascading effects on previously undescribed unique macroinvertebrate communities and overall ecosystem functioning (Vlok *et al.*, 2024; Bellingan *et al.*, 2022; de Moor & Bellingan, 2011; Bok, 2000).

The appearance of *Pseudobarbus* sp. provides a timely case to assess biodiversity responses using the ecological monitoring tools embedded within NVT's S2S-informed framework (Vlok *et al.*, 2024; de Moor *et al.*, 2004; Barber-James, 2000). As such, the Sout River serves as both a local proof-of-concept and a meaningful contribution to broader national efforts to operationalise integrated conservation models through the S2S and NBS lenses.

To contextualise the ecological and spatial features of the catchment, **Figure 3** presents an overview map highlighting key biophysical and management characteristics. These include dominant vegetation types, hydrological networks, protected areas and land-use patterns – all of which shape conservation outcomes. The map also indicates four core ecological monitoring sites, strategically selected to reflect upstream-downstream dynamics, land-use gradients and priority zones for NBS.

By grounding the framework in applied fieldwork, the Sout River project supported the development of community-driven, systems-based conservation models that are replicable across other small river systems in South Africa. The framework's flexibility, affordability and integration of governance and ecological indicators make it well-suited for long-term, adaptive catchment management in similarly constrained landscapes.

This article aims to demonstrate how an integrated baseline catchment-level framework rooted in the S2S and NBS approaches can be applied under realistic budgetary and data limitations to support long-term ecological monitoring and governance evaluation. Specifically, the Sout River project seeks to:

1. Test the practicality and utility of an S2S-informed baseline assessment framework for small, under-studied and under-resourced catchments;
2. Explore such a framework's ability to detect ecological change, inform community engaged NBS restoration and identify governance gaps; and
3. Contribute to the national discourse on implementing scalable, systems-based conservation strategies in South Africa.

By presenting both the process and preliminary outcomes of this pilot project along the Sout (Oos) River catchment, this article contributes to the growing body of work on integrated, adaptive catchment management and offers valuable insights for replication in similar socio-ecological contexts.

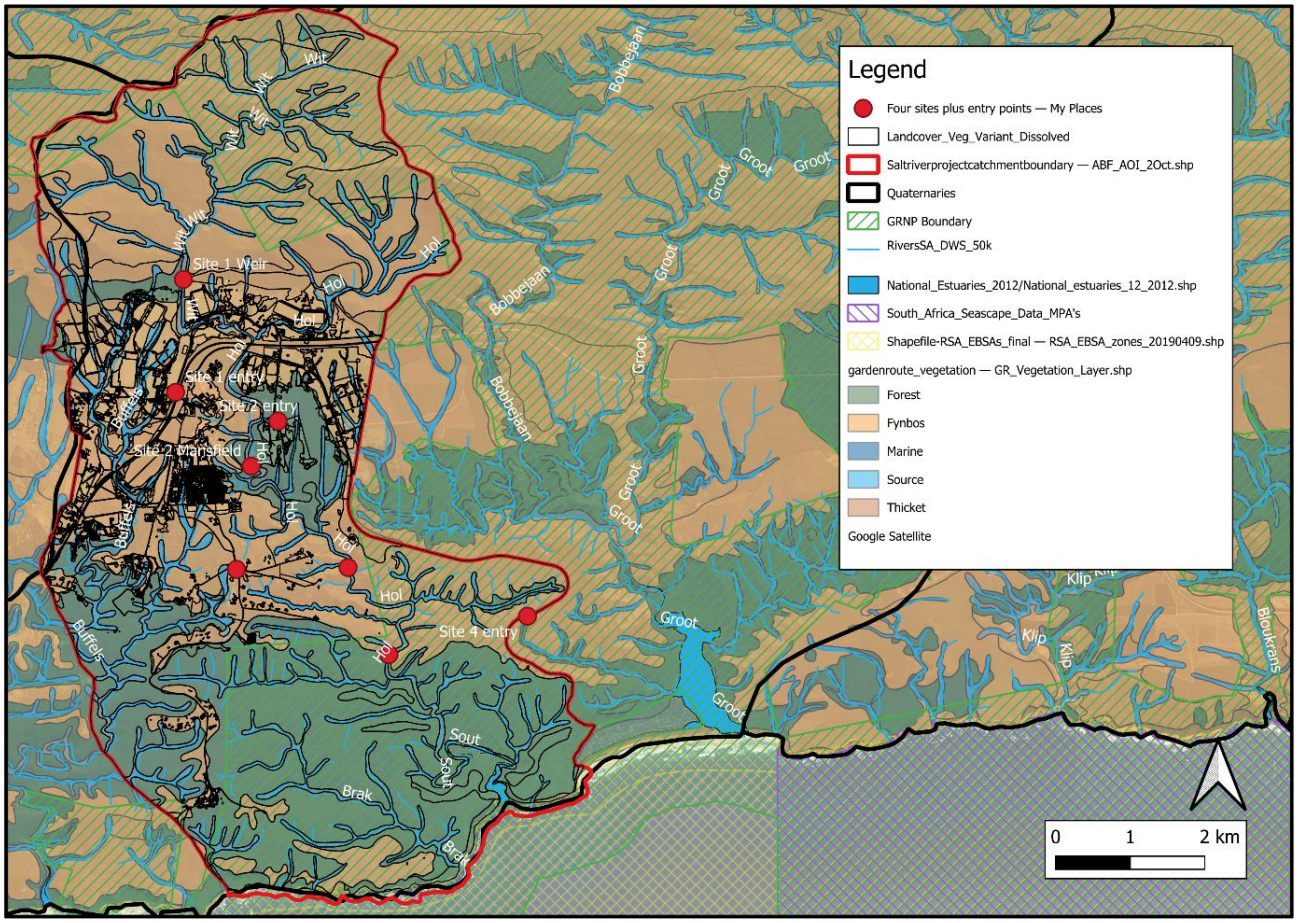


Figure 3: Map of the Sout (Oos) River catchment in the Garden Route Biosphere Reserve, South Africa: The map shows broad land-cover (biomes) types (forest, fynbos, marine and thicket), river networks, quaternary catchments and protected areas. The four monitoring sites and access points are marked in red. The red boundary outlines the Sout (Oos) River catchment area defined for the Sout River project. This map provides the spatial context for implementing the S2S-informed framework and monitoring NBS interventions

Methods

Study area

The Sout (Oos) River catchment is situated in the Garden Route region of South Africa's Western Cape Province, within the K70A quaternary catchment. Covering approx.-imately 3,360 hectares, it lies within the Garden Route Biosphere Reserve and forms part of a strategic water source area (SWSA) due to its contribution to biodiversity and downstream water provision (Locke & Winter, 2025; Le Maitre *et al.*, 2018; Morant & Bickerton, 1983).

The catchment extends from the Tsitsikamma section of the Garden Route National Park to the De Vasselot estuary, a permanently open system with an A-grade ecological health status under the National Estuary Biodiversity Plan (Van Niekerk & Turpie, 2012; SANBI, 2020). The area is ecologically diverse (intersecting fynbos, forest and thicket vegetation types) and includes a mosaic of conservation land, agriculture and peri-urban development. Given that governance transversally resorts under South African National Parks (SANParks), the Breede-Gouritz Catchment Management Agency and the Bitou Municipality, institutional fragmentation and limited integration remain key challenges (Pollard *et al.*, 2023; Schreiner & Hassan, 2011).

The river itself is representative of south-flowing perennial mountain streams of the southern Cape, receiving 700–1,200 mm of rainfall annually (Hoare, 2024; Dallas & Day, 2004). It is characterised by its short, steep course (approximately 15 km), dark tannin-stained waters and oligotrophic, acidic conditions associated with Bokkeveld shale geology and fynbos catchment vegetation (Vlok *et al.*, 2024; Morant & Bickerton, 1983). These features contribute to the river's high conservation value but also render it particularly vulnerable to pressures such as nutrient enrichment, invasive species and flow alteration.

An inter-basin transfer (IBT) diverts water from the Sout to neighbouring rivers. While hydrological impact appears minimal, the IBT may act as a vector for invasive aquatic species such as *Pseudobarbus* sp., now observed in the Sout River system (Vlok *et al.*, 2024; de Moor & Bellingan, 2011). The spread of invasive alien vegetation including *Acacia mearnsii* and *Pinus pinaster* in riparian zones further threatens ecological integrity (Le Maitre *et al.*, 2019; Van Wilgen & Wilson, 2018).

To support the implementation of an S2S-informed approach with NBS inter-ventions for NVT's Sout River project, we delineated a focused catchment area within the broader Sout (Oos) River system for baseline research and ecological monitoring (**Figures 1** and **3**). This delineation captured key tributaries, surrounding landcover types and strategic monitoring sites positioned to represent ecological gradients and varying land-use pressures across the system. Four core ecological monitoring sites were selected based on prior surveys and ecological variation, spanning upstream to downstream zones. These sites enabled testing of the integrated approach across land-use gradients and habitat types (Knight, 2023; Pollard *et al.*, 2023). Details of each ecological monitoring site are summarised in **Table 1**, corresponding with the spatial data in **Figure 3**.

In addition to land-use and governance overlays, the vegetation composition and surrounding river systems (**Figures 4** and **5**) were mapped to inform the spatial context for monitoring, restoration opportunities and biodiversity linkages.

Table 1: Overview of ecological monitoring sites within the Sout (Oos) River catchment

Site	Relative position	Dominant land use	Key features	Monitoring focus
Site 1 – weir	Upper catchment	Conservation / forest reserve	Located near headwaters; within GRNP; relatively undisturbed	Water-quality baseline; reference site for comparative health
Site 2 – Mansfield	Mid-catchment	Agriculture and rural housing	Downstream of mixed-use farmland; moderate alien vegetation	Vegetation cover; invasive species tracking; water sampling
Site 3 – eco-lodge	Lower-mid catchment	Eco-tourism and fynbos habitat	Near ecotourism property; interfaces with tourism, riparian habitat	Riparian habitat quality; stakeholder engagement opportunities
Site 4 – De Vasselot	Estuary-adjacent	Protected (GRNP)	Estuarine interface; inside De Vasselot section of GRNP	Salinity/freshwater dynamics; biodiversity transitions

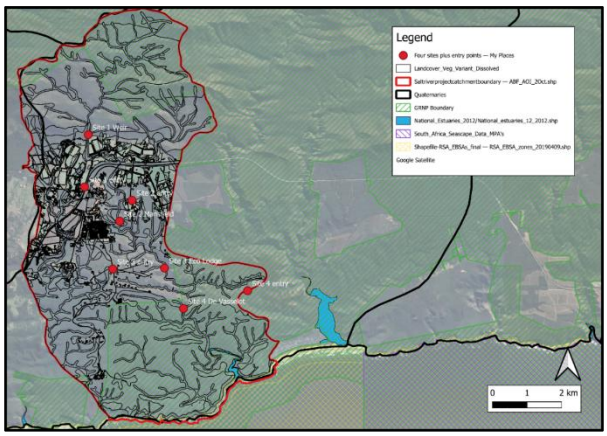


Figure 4: Delineated Sout (Oos) River catchment and ecological monitoring sites: The map displays the project boundary (red line), associated river network, land-use patterns (agriculture, forestry, residential) and the four core ecological monitoring sites (red dots). This spatial framework guided the design of baseline monitoring aligned with the S2S approach and NBS implementation

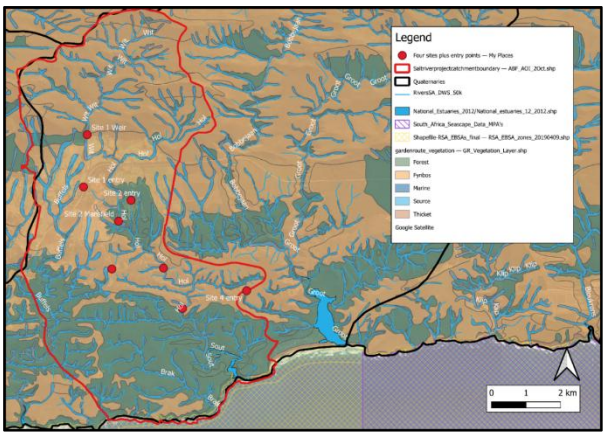


Figure 5: Vegetation biomes and river networks within and surrounding the Sout (Oos) River catchment: Mapped features include forest, fynbos, thicket and marine zones overlaid on the hydrographic system. These biophysical layers informed prioritisation of restoration zones and supported interpretation of biodiversity and hydrological dynamics within the catchment

Approach

The Sout River project employed an integrated approach as discussed above. Grounded in NBS intervention strategies, this NBS framework was adapted from Albert *et al.* (2021a/b) and applied within an S2S conservation context. The framework followed six sequential steps: (1) define challenges, (2) co-design interventions, (3) assess effectiveness, (4) integrate governance, (5) implement adaptively and (6) evaluate outcomes, ensuring that ecological, social and governance elements were considered holistically throughout the project lifecycle.

Unlike traditional social-ecological systems (SES) approaches, which often focus on dynamic system feedback and resilience theory, the final baseline framework (**Figure 2**) is rooted in applied, place-based conservation planning. It is specifically geared toward operationalising ecosystem-based interventions (NBS) within spatially connected systems like catchments and coastal zones, using the S2S logic of flow and connectivity (Michels-Brito *et al.*, 2023; Granit *et al.*, 2017). The integration of the S2S approach allowed us to identify ecological interactions and pressures along the river continuum, while the NBS framework helped structure our intervention design around nature-supported solutions.

To support this, a series of specialist studies (see Acknowledgements) were commissioned to provide focused insights into key baseline ecological, social and governance components of the Sout (Oos) River catchment. These research inputs were designed to align with the six-step NBS framework and the overarching S2S logic, providing the foundational evidence base for adaptive, integrated management planning.

First, stakeholder and governance analyses were conducted to identify the full spectrum of actors involved in the management, use and oversight of the Sout (Oos) River catchment. This included local and provincial authorities, SANParks, private landowners, tourism operators and subsistence users. The analyses mapped institutional responsibilities, existing coordination mechanisms and governance gaps, high-lighting the fragmentation and overlapping mandates that constrain collaborative water and land management in the area.

Second, a social baseline study was undertaken to understand the human dimensions of the catchment. This included household-level surveys, interviews with key informants and community-engagement sessions to explore how people interact with the river system, what ecosystem services they derive from it and how they perceive threats, changes and opportunities related to the system's conservation. Particular attention was paid to vulnerable groups and informal users whose perspectives are often underrepresented in formal planning processes.

Third, a carbon baseline assessment was carried out to quantify the carbon-storage and sequestration potential of the catchment's natural vegetation, particularly forested and thicket areas. This assessment provided spatial estimates of aboveground biomass and identified zones with potential for restoration-linked climate finance through carbon-offset or nature-based funding mechanisms. The results also offer a foundation for tracking carbon gains associated with invasive alien plant removal and ecosystem recovery.

Lastly, an ecological baseline study was conducted to characterise the current ecological state of the Sout River system. This included detailed baseline assessments of vegetation composition, the extent and density of invasive alien plant species, macro-invertebrate community structure, habitat

integrity and general water quality. Sampling was carried out across four representative ecological monitoring sites (see **Table 1** and **Figures 4** and **5**), selected to reflect spatial variation in altitude, land use and connectivity along the river continuum.

Together, these studies contributed to a comprehensive, multi-dimensional baseline understanding of the catchment. Their findings were integrated into a shared spatial and conceptual framework to inform targeted interventions, track change over time and support long-term conservation planning underpinned by both ecological science and local realities. The result is a practical, S2S-informed replicable model for applying the S2S approach and NBS framework in smaller, data-limited river systems in South Africa.

Participants and study integration

The final framework for the Sout River project adopted an S2S-informed, systems-based approach integrating ecological, social and carbon assessments to develop a comprehensive baseline understanding of the Sout (Oos) River catchment's functioning and conservation needs. While framed by S2S and NBS perspectives, this methodology aligns closely with established social-ecological systems (SES) theory which recognises the interdependence of human and ecological subsystems in natural resource management (Pollard *et al.*, 2023; Folke *et al.*, 2016). The research aimed to generate an integrated evidence base for adaptive catchment management, with particular attention to long-term monitoring and locally grounded restoration priorities.

A diverse group of stakeholders participated in the study, including local community members, non-governmental organisations, conservation authorities, municipal officials and academic collaborators. Participants were selected for their knowledge of the Sout (Oos) River catchment, their lived experience or land-use influence within the system and their involvement in governance, research and/or restoration. Community participants, in particular, provided essential insights into historical land-use practices, river-dependent livelihoods and changes in river health – knowledge that shaped the project's contextual understanding and helped to align conservation strategies with local realities.

The research comprised several interlinked components:

- The social assessment included stakeholder mapping, semi-structured interviews and participatory workshops aimed at identifying governance gaps, power dynamics and user relationships with the river.
- The ecological surveys focused on riparian habitat quality, biodiversity patterns and the presence of macroinvertebrate taxa, with 43 taxa identified across the catchment including indicator groups such as Ephemeroptera and Trichoptera. These taxa were used to assess water quality and ecological integrity.
- The carbon study quantified the catchment’s carbon sequestration potential, linking vegetation structure with climate mitigation potential and estimating carbon losses from alien plant invasion and gains from active clearing efforts.

Rather than individual species tagging or tracking, baseline monitoring relied on plot-based surveys and repeated counts to assess patterns in species composition, vegetation cover and aquatic health. Special attention was paid to the impacts of invasive alien

vegetation, particularly *Acacia mearnsii*, *Eucalyptus* spp. and *Pinus* spp. which are the focus of targeted NBS interventions (Hoare, 2024). The removal of these species is anticipated to improve indigenous vegetation recovery, enhance water quality and increase carbon-storage capacity.

The individual outsourced reports generated through this research, including those by du Plessis (2024), Hoare (2024), Huchzermeyer and Powell (2024) and Vlok *et al.* (2024), provide detailed methodologies and findings that underpin the broader integrated analysis presented in this article. Together, these studies offer a robust, multi-dimensional baseline from which future monitoring and restoration efforts can be guided.

By integrating ecological data with social dynamics and carbon-flux information, the Sout River project offers a model for sustainable catchment management that foregrounds both environmental integrity and socio-economic realities. This systems-informed, community-engaged approach establishes a strong foundation for replication in other small catchments across South Africa.

Procedure and data collection

The Sout River project followed a structured, stepwise process aligned with the six-step NBS protocol adapted from Albert *et al.* (2021a/b), as outlined in the *approach* section (see **Table 2**; **Figures 2** and **6**). While this framework is not novel within the South African context where planning logics such as strategic adaptive management (SAM), integrated catchment management (ICM) and national biodiversity strategy and action plans (NBSAPs) have been applied for over two decades (Roux *et al.*, 2023; Pollard & du Toit, 2008; Rogers & Biggs, 1999), their pragmatic use in this project provided a clear structure for sequencing interventions, aligning ecological and social priorities and embedding NBS within a broader S2S approach.

The process began with a co-defining and visioning phase involving participatory workshops where stakeholders identified shared conservation goals, local challenges and priority areas. This collaborative approach fostered ownership and ensured alignment with the socio-economic realities of the catchment.

A comprehensive baseline assessment followed, integrating both ecological and social data. Ecological data were gathered through field surveys at four primary sites, assessing biodiversity (aquatic invertebrates, fish and birds) and riparian vegetation as well as water quality (nutrients, sedimentation and pollutants) (Hoare, 2024; Vlok *et al.*, 2024). Carbon baseline assessments were conducted across the catchment to quantify its climate resilience potential (Huchzermeyer & Powell, 2024).

Social data were collected through stakeholder mapping, structured interviews and participatory workshops, which aided in assessing governance dynamics and local dependencies on river resources (du Plessis, 2024). This engagement revealed the social-ecological relationships shaping conservation in the catchment and informed the design of inclusive, context-sensitive interventions.

Based on these findings, a set of NBS restoration scenarios was co-developed with stakeholders. These focused on invasive alien plant removal, indigenous vegetation recovery and sustainable land-use practices. Priority zones were identified along riparian corridors extending up to 20 metres from the riverbanks to maximise ecological connectivity and recovery. These strategies were consolidated into a formal intervention plan, which was reviewed and endorsed by the project steering

committee comprised of landowners, conservation partners, service providers and local authorities.

Implementation involved hands-on restoration work across the catchment. Local residents from Kurland were trained and employed to clear invasive species such as *Acacia mearnsii*, *Eucalyptus* spp. and *Pinus* spp. Efforts such as these aided in restoring ecological integrity, improving water and carbon cycles and providing socio-economic benefits through employment and skills development. In parallel, coordinated clearing efforts extended into surrounding upland areas in collaboration with private landowners and conservation partners.

The Sout River project has now entered its final phase where the focus is on adaptive management and continuous monitoring. Ecological indicators and community feedback are being used to refine ongoing restoration efforts and guide future decision making. Capacity-building workshops continue to engage stakeholders, covering topics such as environmental monitoring, restoration techniques and regenerative agriculture. Simultaneously, long-term stewardship is promoted through outreach initiatives (e.g. conducting site visits, distributing informational materials and engaging with landowners).

Together, this structured, multi-disciplinary approach has produced a scalable, locally grounded baseline catchment management framework that links ecological restoration with governance improvement and socio-economic upliftment. The integration of qualitative and quantitative data has allowed for a comprehensive understanding of the catchment, thereby supporting adaptive, inclusive and resilient conservation planning.

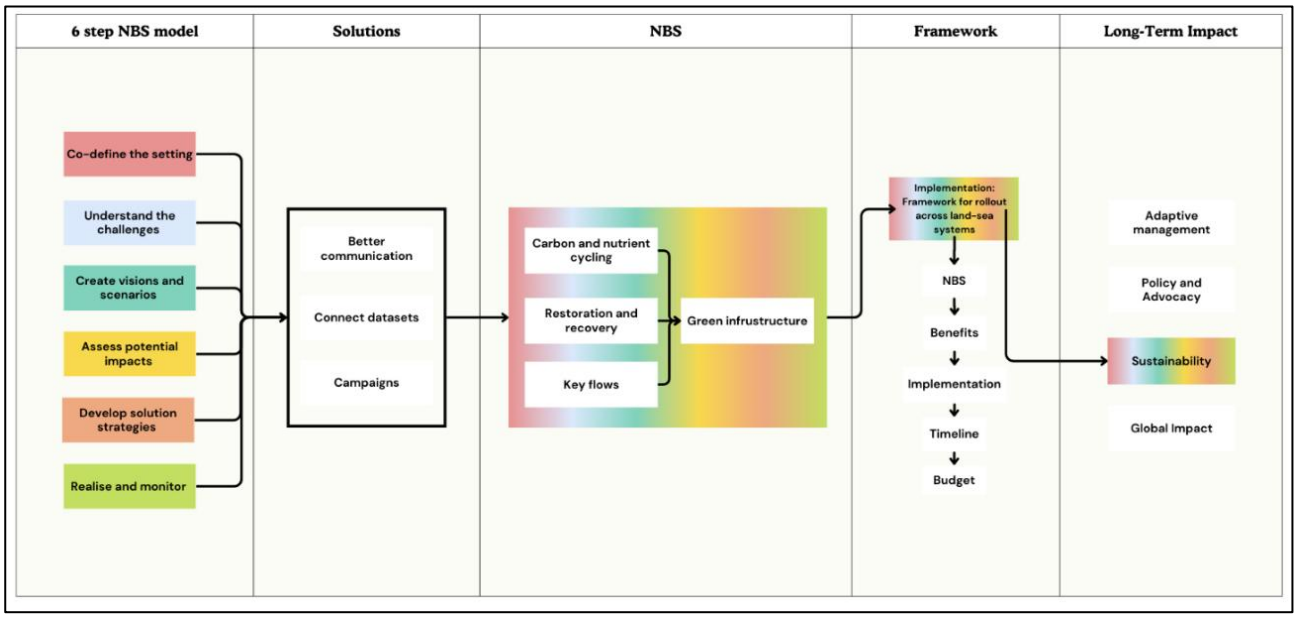


Figure 6: The NBS process followed to arrive at the final S2S-informed baseline framework for the Sout River project: Although visually structured as a logic model, the framework aligns with internationally recognised S2S principles and long-standing South African planning approaches (SAM, ICM). Spatial and stakeholder linkages across the catchment from source to estuary were embedded in each step, ensuring system-wide thinking within a realistic budget. This framework guided project implementation, adaptive management and long-term monitoring design

Table 2: Linking the six-step NBS framework with the Sout River project's activities

Step	NBS framework phase	Application in the Sout River project
1. Define challenges	Co-defining the setting	Stakeholder mapping; formation of a project steering committee; identification of key pressures (e.g. invasive species, habitat loss)
2. Co-design interventions	Visioning and planning	Participatory workshops with stakeholders to co-develop restoration goals and priority areas
3. Conduct baseline assessments	Assessing system conditions	Commissioning/conducting specialist studies (i.e. ecological and social) as well as carbon assessment to establish catchment status
4. Develop scenarios	Developing solution strategies	Identification and mapping of intervention zones; formulation of restoration options; budget planning
5. Implement	Realising solutions	Implementing on-the-ground NBS activities (e.g. removing alien plants, replanting indigenous vegetation, training community members)
6. Adapt management	Monitoring and adapting	Ongoing ecological monitoring; providing stakeholder feedback; conducting workshops; offering outreach initiatives

Data analysis

The data-analysis process integrated the findings (baseline studies) and the outputs (project interventions) with verifiable short-term impacts and the long-term impact of ongoing monitoring with a view to arriving at an S2S-informed baseline framework (**Figure 2**) for the Sout (Oos) River catchment.

The analysis further identified gaps, key threats and underlying drivers influencing the catchment's ecological and social systems. Intervention strategies were evaluated to assess their effectiveness in addressing these challenges, while ongoing monitoring ensured that adaptive management measures were implemented as needed.

The Sout (Oos) River catchment serves as a baseline and pilot study providing guidance for future restoration and management efforts within the system while also serving as a model for other similar data-deficient smaller river systems. The results will go on to inform policy recommendations and conservation strategies to achieve long-term sustainability for the Sout River catchment and, in theory, beyond to neighbouring catchments.

Results

The S2S-informed framework developed for the Sout (Oos) River catchment (**Figure 2**) serves as a locally grounded, yet globally informed framework for integrated catchment management, with **Figure 6** highlighting the role of NBS within the broader implementation strategy. While the framework may resemble a conventional, project-logic model at first glance, its structure and application are explicitly informed by widely adopted S2S principles which focus on the movement and

connectivity of water, sediment, biota and pollutants from upstream source areas to downstream estuarine and marine systems (Michels-Brito *et al*., 2023; Granit *et al.*, 2017). This S2S-informed framework is not a generic template but rather a spatially and socially contextualised approach tailored to the Sout River, an ecologically significant but understudied system.

Unlike broad theoretical models, the framework for the Sout (Oos) River catchment was designed within a fixed and realistic budget, maximising the amount of ecological, hydrological and social knowledge that could be captured during a single baseline assessment phase. It operationalises the S2S approach through spatially differentiated actions across the catchment, thereby linking upstream, midstream and estuarine interventions to their downstream consequences while aligning with the six-step NBS protocol for ecosystem restoration (Albert *et al.*, 2021a/b). NBS interventions were introduced not as theoretical ideals but as practical, budget-conscious strategies during the implementation phase to address localised threats such as invasive alien plant infestation, degraded riparian buffers and erosion.

The framework also incorporates adaptive governance, stakeholder participation and socio-economic co-benefits into the restoration and monitoring framework. It serves both as a replicable framework for use in neighbouring catchments and a tool for continuous learning and feedback within the Sout River system. By embedding global S2S logic within a locally tested, affordable framework, this approach offers a realistic pathway to long-term monitoring and sustainable management in other small, resource-constrained river systems across South Africa.

To follow is a brief overview of what the approaches to develop an S2S-informed framework for the Sout (Oos) River catchment revealed.

Stakeholder and social engagement

Consistent with both S2S and NBS principles, stakeholder engagement formed a core pillar of the Sout River project and the final framework. The incorporation of this essential element in our approach emphasises the importance of local participation, inclusive governance and knowledge co-production as key ingredients for sustainable catchment management (Albert *et al*., 2021a/b; Granit *et al.*, 2017).

Findings from the social baseline assessment (see **Figure 7**) highlighted a range of locally perceived threats and pressures including invasive species, water scarcity, informal land use and institutional disconnects which reinforced the need for participatory governance structures. These findings helped identify opportunities for co-designing solutions and prioritising interventions in ways that reflect lived experience and local values (du Plessis, 2024).

The engagement process drew in a wide range of stakeholders including local residents, landowners, NGOs, conservation practitioners, municipal officials and researchers. Activities encompassed community workshops, interviews, stakeholder mapping exercises and early citizen-science efforts. These engagements not only informed the design of the baseline assessment but also helped establish the foundations for ongoing monitoring, local restoration leadership and knowledge-sharing, all essential components for maintaining long-term system resilience.

Importantly, this inclusive process aligns with existing national frameworks, such as the Bitou Municipality's 2017 integrated development plan, and broader calls for adaptive, cross-sectoral partnerships in water and land governance (Granit *et al.*, 2017; Pollard & du Toit, 2008; Cowling & Pressey, 2003). By embedding community voices from the outset, the Sout River project and the derived framework strengthen both the legitimacy and durability of conservation interventions, thereby ensuring that the catchment's future is shaped not only by ecological priorities but also by social realities and institutional collaboration.

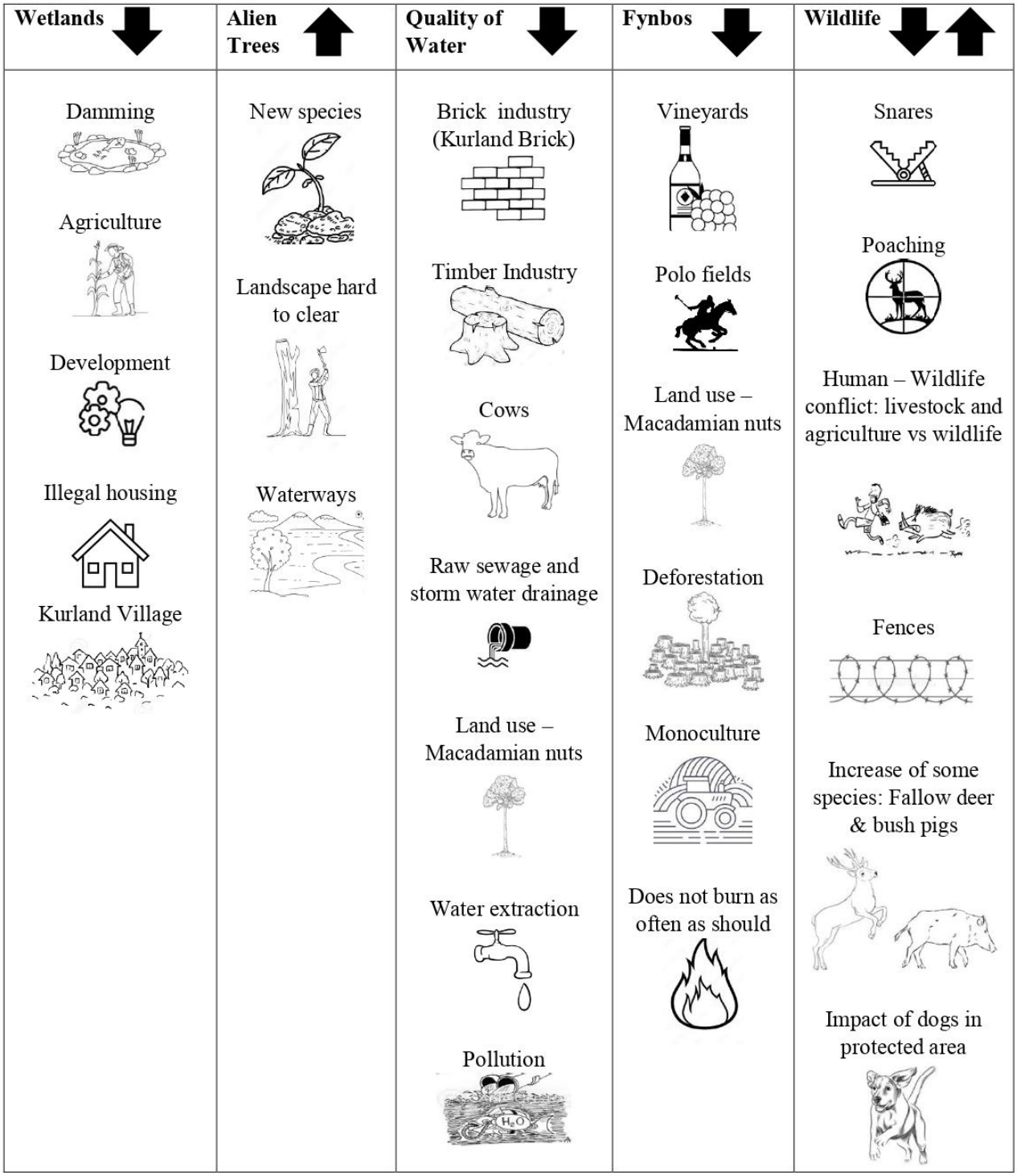


Figure 7: Threats and drivers identified in the social baseline study (du Plessis, 2024)

Ecological restoration and land-cover changes

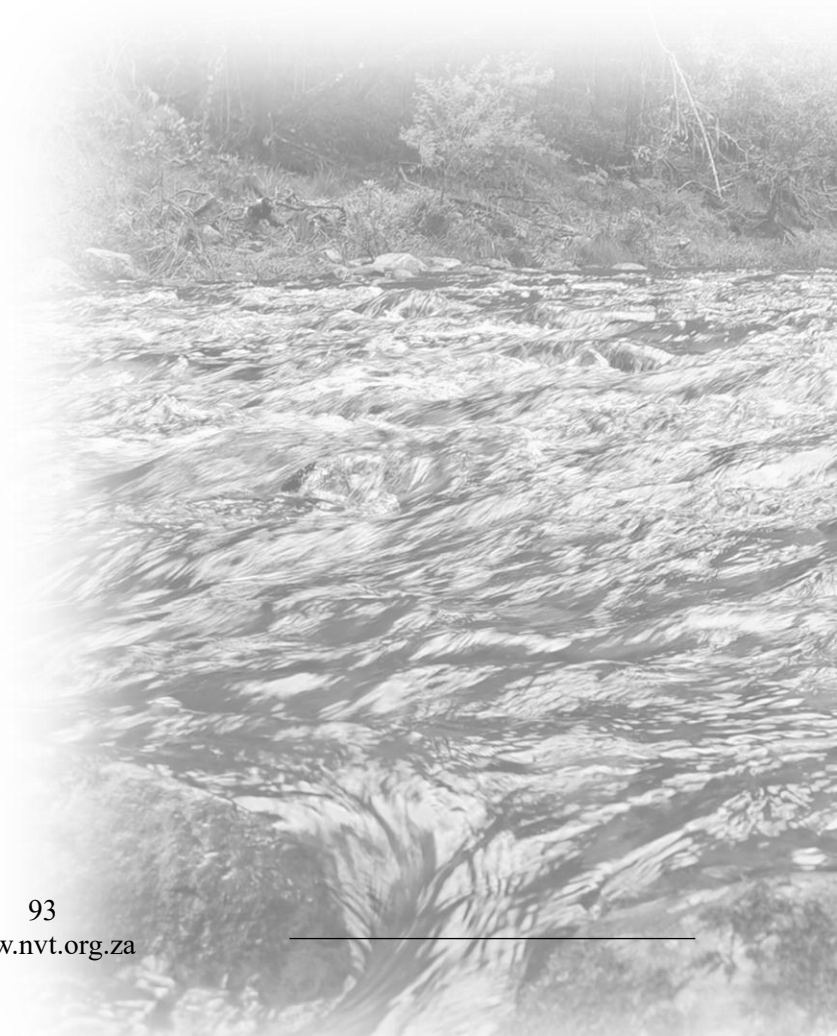
Understanding the extent of ecological degradation and vegetation transformation within the Sout (Oos) River catchment was a key component of the baseline assessment. This information formed the foundation for identifying priority zones for restoration, aligning with both S2S and NBS principles. The land-cover analysis (**Figures 8(a)** and **8(b)**) provides critical spatial insights into long-term land-use shifts and the growing pressure exerted by invasive alien plant species (IAPs), both of which directly affect water quality, habitat connectivity and ecosystem resilience.

In the upper catchment, dominated by the Tsitsikamma perennial-stream ecosystem, approximately 72.6% of vegetation remains natural, while 15.7% is invaded by alien species and 5.5% has been converted to croplands (**Figure 9**). In contrast, the mid-catchment Tsitsikamma plateau proteoid fynbos reflects more intensive transformation: Only 5.3% of natural vegetation remains, with 34.6% invaded and 35.4% converted to crops (**Figure 10**). These patterns illustrate the degree to which biodiversity and ecosystem functioning are being compromised by land-use pressures.

The spatial distribution of invasive alien plants (particularly species such as *Acacia mearnsii*, *Eucalyptus* spp. and *Pinus* spp.) was mapped in detail as part of the ecological baseline (**Figure 11**). This analysis identified approximately 13.72% of the catchment (761 ha) as invaded, though this figure is likely conservative due to the limited detectability of species such as submerged macrophytes, forest invaders and climbers like *Acacia melanoxylon*.

Even though Huchzermeyer and Powell's 2024 mapping of the Sout (Oos) River catchment in support of the Garden Route Initiative marked 1,943 hectares of the vegetation layer as "Degraded" and 34 hectares as "Alien Transformed" (**Figure 12**), further spatial analyses by way of field verifications and expert inputs suggest that much of the degraded land is, in fact, densely dominated by invasive species, even where it has not yet fully transformed to another land-use type. This has significant implications for restoration planning, especially in prioritising zones for alien clearing, indigenous vegetation recovery and riparian buffer rehabilitation.

These landcover insights have been critical in developing a spatially grounded, cost-effective restoration plan as part of the Sout (Oos) River catchment model. Such insights ensure that ecological interventions can be targeted where they will have the greatest cumulative impact upstream and downstream, thereby maximising biodiversity recovery, water retention and climate resilience within a finite project budget.



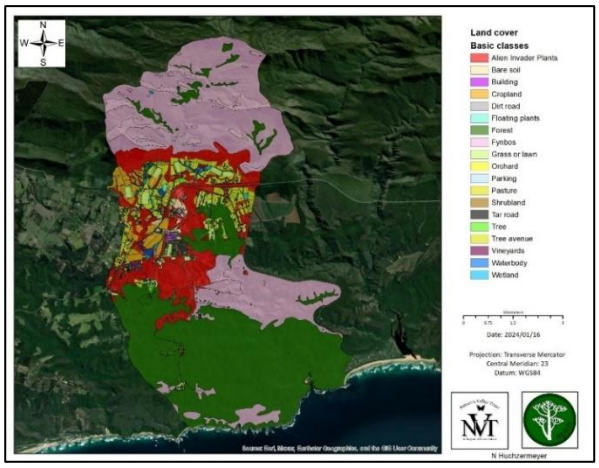


Figure 8(a): Landcover classification of the study area (Huchzermeyer & Powell, 2024)

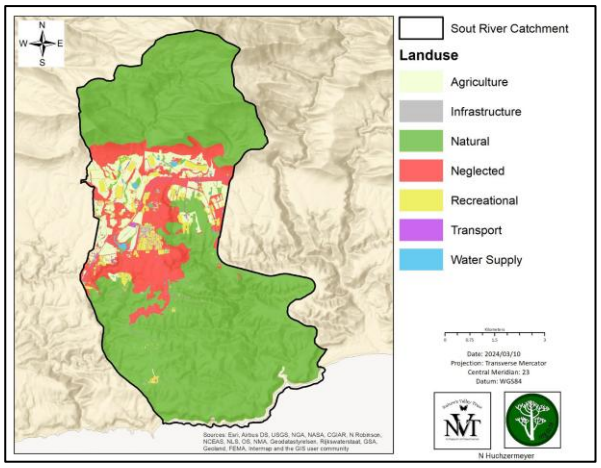


Figure 8(b): Landcover classification of the study area (Huchzermeyer & Powell, 2024)

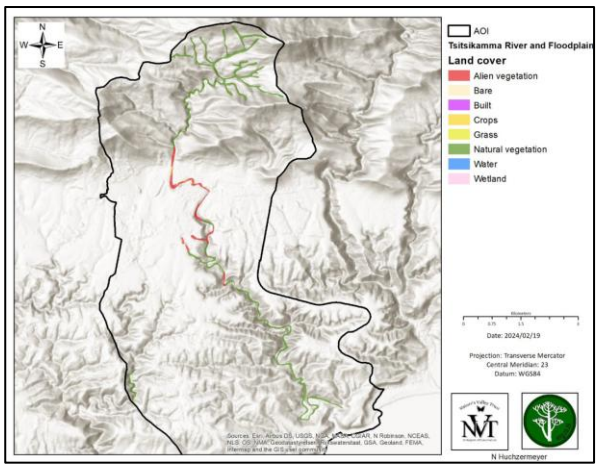


Figure 9: Vegetation status of the Tsitsikamma perennial stream: 72.6% natural, 15.7% alien-invaded and 5.5% converted to crops (Huchzermeyer & Powell, 2024)

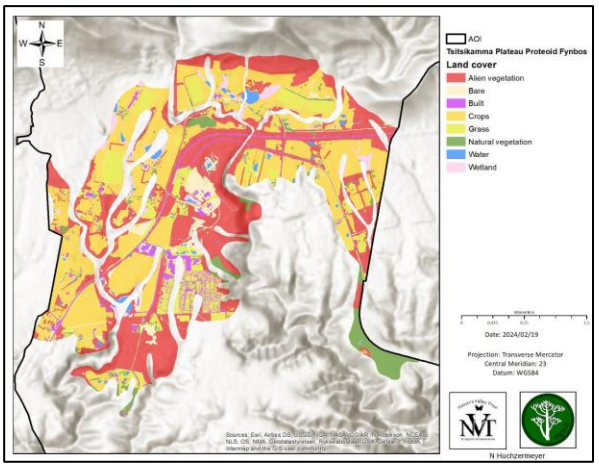


Figure 10: Land-use distribution in the mid-catchment Tsitsikamma plateau proteoid fynbos: 35.4% crops, 34.6% alien-invaded, 12.1% grassland and 5.3% natural vegetation (Huchzermeyer & Powell, 2024)

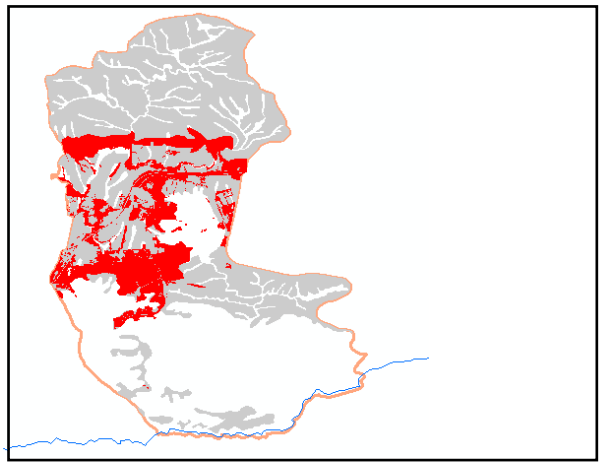


Figure 11: Distribution of invasive alien plants (IAPs) in the study area (Huchzermeyer & Powell, 2024)

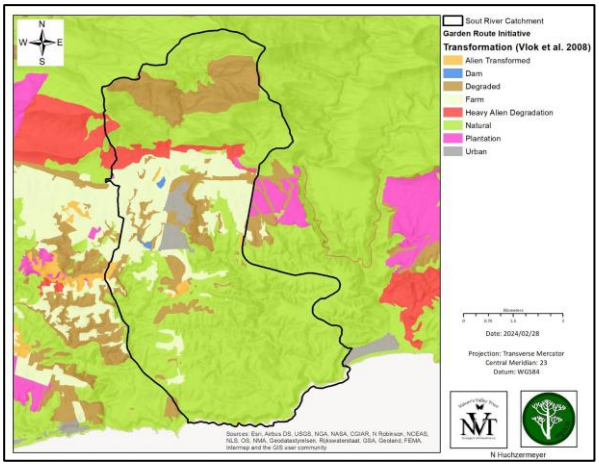


Figure 12: Degradation classification based on spatial data: 1,943 ha "Degraded", including 34 ha "Alien Transformed" (Huchzermeyer & Powell, 2024)

Carbon baseline and land-use impacts

As part of the baseline framework for the Sout (Oos) River catchment, a carbon stock assessment was conducted to understand how land-use practices influence carbon sequestration potential and ecological resilience. This component complements the ecological and social assessments by identifying opportunities for climate mitigation and informing restoration priorities aligned with S2S principles and NBS.

The carbon baseline study, conducted in collaboration with the Rhodes Restoration Group, analysed landcover data from January 2024 (**Figure 8(a)**) to estimate total carbon stocks (TCS) across the catchment. The estimates (corrected for factors such as soil depth, slope and vegetation type) suggest that the catchment currently stores approximately 440 128 tonnes of carbon. These figures provide an important foundation for tracking long-term changes in carbon sequestration resulting from alien clearing, habitat restoration and shifts in land use.

The spatial distribution of carbon stocks is notably uneven, with higher storage potential associated with remnant forest patches and intact fynbos systems. Conversely, degraded areas and zones dominated by woody invasive alien species present both a loss in native biodiversity and a risk of carbon release, particularly through biomass removal or fire. These areas are also often the most vulnerable to erosion and hydrological disturbance, linking carbon loss directly to water quality and flow-regulation challenges downstream.

A separate analysis of landcover change between 1990 and 2020, based on national datasets, reveals that while approximately 50% of the catchment has remained relatively intact (mostly in protected forest areas), the remaining 50% has been significantly altered by land-use change, including agricultural expansion, infrastructure development and widespread alien plant invasion (**Figure 11**). These findings reinforce the urgency of targeted restoration efforts and support the integration of carbon-focused strategies into broader catchment rehabilitation work.

In the context of this project, carbon baseline mapping served a dual purpose: It provided a quantifiable metric for potential climate finance opportunities (e.g. through carbon offset schemes), and it contributed to a more nuanced understanding of land-use trade-offs and restoration benefits. By embedding carbon assessments into a cost-conscious, S2S-informed framework, the project supports not only biodiversity and water system recovery but also long-term climate resilience.

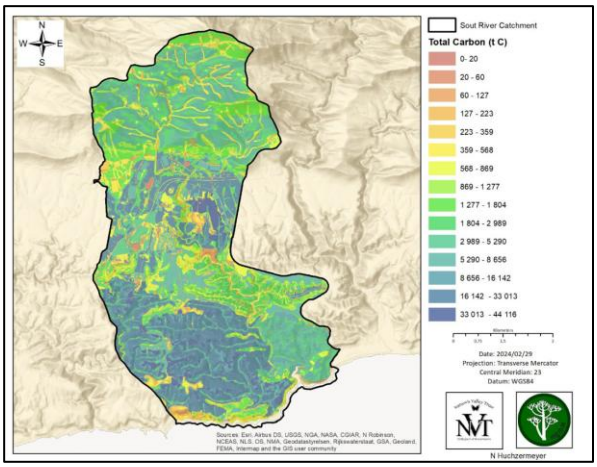


Figure 13: Spatial distribution of carbon stocks and land-use changes in the Sout (Oos) River catchment (1990–2024), (Huchzermeyer & Powell, 2024)

Invasive alien plant removal and habitat restoration

Invasive alien plant (IAP) clearing was a central intervention in the implementation phase of the framework for the Sout River project, aligning with both NBS practices and S2S principles by directly improving ecological function, water security and downstream ecosystem health. The removal of

woody invasive species also supports the baseline framework's long-term objectives of promoting riparian resilience, restoring native biodiversity and increasing carbon sequestration potential.

As of December 2024, field teams have removed approximately 9 771 individual invasive trees and shrubs, including 8 363 black wattles (*Acacia mearnsii*), 477 pines (*Pinus* spp.), 410 blue gums (*Eucalyptus camaldulensis*), 270 bugweed (*Solanum mauritianum*) and 251 Australian blackwood trees (*Acacia melanoxylon*). These figures represent a substantial early achievement in restoring ecosystem processes and reducing biotic pressures on native flora and aquatic systems. The spatial extent of cleared areas, illustrated in **Figure 14**, highlights targeted action zones along key riparian corridors.

In total, an estimated 520 hectares of degraded land have been cleared and are now under active or passive restoration. This effort has improved water flow regulation, stabilised riverbanks and provided space for the recovery of indigenous vegetation communities (i.e. core ecosystem services disrupted by dense IAP stands). The clearing also contributes to water-quality and -quantity improvements downstream, furthering the integrated S2S goal of holistic catchment-to-coast recovery.

To ensure lasting impact, ongoing monitoring and re-clearing are conducted as part of the adaptive management cycle. These efforts are complemented by the operations of NVT's indigenous plant nursery which supplies locally appropriate species for active revegetation and riparian buffer enhancement. Rooted in ecological knowledge and long-term planning, the nursery initiative ensures that restoration is not only reactive but also regenerative.

These integrated restoration actions directly reflect calls by Chamier *et al.* (2012) and Preston *et al.* (2018) for multi-scalar, systems-based approaches to managing invasive species. The Sout River case shows how even within a constrained budget, targeted, data-informed alien clearing can deliver measurable ecological gains and set the stage for sustainable landscape recovery across the broader catchment.

Biodiversity monitoring and species outcomes

Biodiversity monitoring was a key component of the Sout River project baseline assessment, forming part of the project's long-term S2S-informed framework. The goal was not only to document ecological conditions at the start of restoration efforts but also to establish cost-effective indicators for ongoing monitoring of system health across spatial and seasonal gradients.

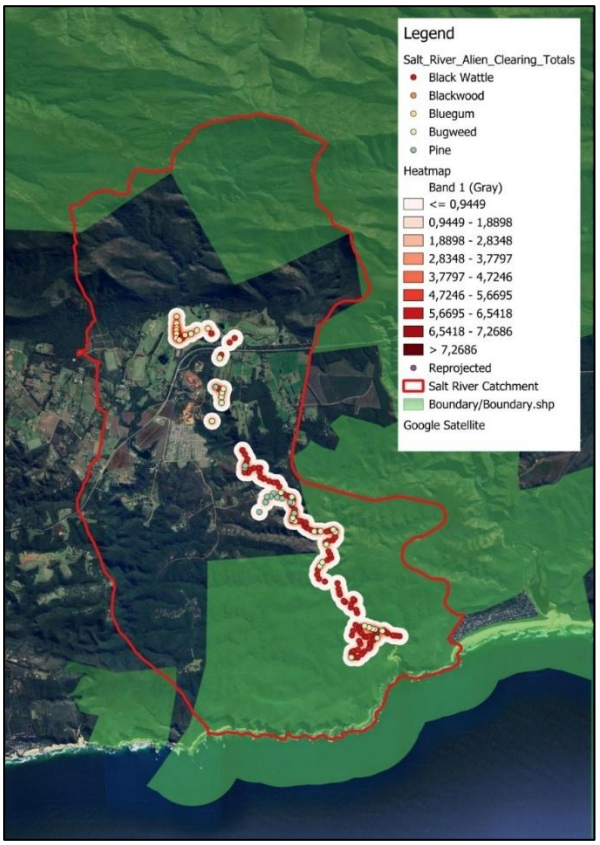


Figure 14: Spatial mapping of cleared invasive alien plants (IAPs) along the Sout (Oos) River catchment

The baseline ecological assessment recorded both biotic and abiotic trends within the catchment. Notably, freshwater fish were observed only at Sites 3 and 4, with approximately 200 individuals believed to be *Pseudobarbus* sp. *nov*. "Forest", a near-endemic species (**Figures 3**, **4**, **5** and **15**). Breeding was observed, and genetic samples were collected to confirm species identity. These observations are significant as the Sout River was historically considered naturally fishless, raising important questions about species-introduction linkages (i.e. inter-basin transfers/passive dispersal by wading birds) as well as the long-term ecological implications of such introductions.



Figure 15: Red-finned minnow (*Pseudobarbus* sp.) recorded in the Sout (Oos) River catchment

Based on survey counts, macroinvertebrate monitoring identified 43 taxa, including sensitive species such as mayflies (Ephemeroptera) and caddisflies (Trichoptera). These organisms serve as well-established bioindicators of water quality, and their presence helped assess river health in relation to land-use and flow variability. Some taxa were classified as "Data Deficient" while others were rated "Stable", reinforcing the need for continued seasonal sampling to track population dynamics and to detect early signs of stress.

Findings from the SASS5 scoring showed variation in site health, with lower scores (C–D) at Site 2 immediately downstream of Kurland village and higher scores (borderline A) at Sites 3 and 4, suggesting clear links between land-use intensity and aquatic ecosystem condition. Seasonal comparison using Sørensen's similarity index and Bray-Curtis ordination revealed high species turnover and spatial shifts from upstream to downstream, which may reflect natural hydrological variation or growing anthropogenic pressure.

Abiotic monitoring further supported these ecological patterns. Eighteen years of flow data suggest a highly event-driven system with decreasing mean annual flow and reduced variability, trends potentially linked to land-cover change and climate dynamics. Water temperatures have increased by 1.39°C over the past two decades, particularly downstream, and conductivity levels indicate a system shifting from oligotrophic toward mesotrophic conditions. These changes point to a river system increasingly sensitive to both seasonal and anthropogenic stressors.

Additional water-quality data, sourced from both Bitou Municipality and NVT field sampling, reveal a general decline in pH, increases in electrical conductivity and rising *Escherichia coli* levels, particularly at Site 4 which acts as a downstream pollutant sink. Chemical analysis showed elevated concentrations of chloride, sulphate, nitrate, ammonium and total phosphorus downstream. While sodium and heavy-metal levels remain within safe limits, the cumulative results highlight growing pressure on the estuarine interface and the urgent need for integrated catchment-wide interventions.

Together, findings with regards to biodiversity and water quality across monitoring sites (summarised in **Table 3** below) offered a comprehensive baseline ecological and chemical snapshot of the Sout River system. More importantly, they provided a set of replicable, budget-conscious indicators for future monitoring across the broader Tsitsikamma catchment network. Within the context of the S2S-informed framework as derived from this study, integrated assessments such as these aid in supporting long-term goals by tracking ecosystem health and evaluating the effectiveness of NBS with a view to informing adaptive management within a scalable S2S-informed framework.

Table 3: Snapshot of biodiversity and water-quality indicators across monitoring sites

Site	Fish presence	Macroinvertebrate health (SASS5)	Water quality	Key observations
Site 1 (upper catchment)	Absent	Moderate (C–D)	Oligotrophic, lower conductivity	Least impacted by downstream pollution, but sensitive to climate-driven flow variability
Site 2 (Kurland village)	Absent	Lowest (C–D)	Declining pH, rising *E. coli*	Poor water quality; clear land-use impacts from adjacent settlement
Site 3 (eco-lodge zone)	*Pseudobarbus* sp. *nov.* observed	High (B–A)	Increasing temperature and nutrients	Possible breeding site; healthy invertebrate diversity
Site 4 (estuary zone)	*Pseudobarbus* sp. *nov.* observed	High (B–A)	Pollutant sink; elevated nutrients, *E. coli*	Downstream accumulation zone; high species richness, vulnerable to cumulative effects

Discussion

The Sout River source-to-sea (S2S) informed framework offers a replicable approach for integrated catchment management that is grounded in ecological restoration, social engagement and nature-based solutions (NBS). While informed by global S2S and NBS literature (Albert et al., 2021a/b; Wilk & Wittgren, 2009), its design is also closely aligned with South Africa's long-standing frameworks in strategic adaptive management (SAM), particularly those developed in the Lowveld and Kruger National Park river systems (McLoughlin *et al.*, 2021; Biggs *et al.*, 2011; Pollard & du Toit, 2008; Cowling & Pressey, 2003; Rogers & Biggs, 1999).

In the context of the Sout River project, the derived framework was tailored to operate within a constrained budget while still supporting long-term monitoring and cross-sectoral collaboration. It mirrors the SAM cycle of setting objectives, monitoring system responses, evaluating outcomes and adapting actions, an approach essential to managing uncertainty in complex social-ecological systems (Roux *et al.*, 2020; Rogers *et al.*, 2013).

Despite its promise, implementation revealed persistent challenges: Fragmented governance structures and data gaps, common in South African catchments (Roux *et al.*, 2023; Pollard & du Toit, 2008), impeded full alignment of conservation objectives across agencies. However, this experience echoes broader findings in adaptive water governance which emphasise the need for learning-oriented systems, stakeholder participation and polycentric governance structures (Pollard *et al.*, 2023; World Bank Group, 2023; SIWI, 2021).

The flexibility and participatory structure of the Sout River project's framework provided an enabling environment for adaptive responses. For example, monitoring data (including SASS5 macroinvertebrate scores and community feedback) have already informed decisions on re-clearing efforts, spatial prioritisation and managing newly-observed freshwater fish populations. This iterative, evidence-based approach is consistent with best practices in SAM applications in the Kruger's river systems (Biggs *et al.*, 2011) and in national water-governance strategies like the National Water Security Framework for South Africa (NPC, 2022).

Socio-economic pressures such as unemployment and informal land use continue to strain catchment health. In response, the framework embedded restoration activities within a livelihoods agenda, offering local employment and training in alien clearing and regenerative land-use practices. These dual-purpose interventions support both ecological and social resilience, reflecting the global shift toward NBS as a mechanism to deliver climate, biodiversity and development co-benefits (World Bank Group, 2023; Seddon *et al.*, 2020).

Importantly, the Sout River project's framework spans global theory and local practice. Although S2S approaches have often been applied at national or transboundary scales, this framework demonstrates their utility in small, data-limited catchments where cumulative upstream-downstream linkages are still critical. The use of spatial mapping, citizen science, carbon and biodiversity metrics ensure that the approach remains scientifically credible while being locally implementable.

Biodiversity outcomes, especially the discovery of *Pseudobarbus* sp. *nov*. in previously fishless sections, highlight both the uniqueness and vulnerability of the system. Monitoring these changes is essential, and should emerging fish populations threaten endemic macroinvertebrates, adaptive

interventions such as species management or removal may be needed, echoing pre-cautionary ecosystem management practices recommended in the SAM literature (McLoughlin *et al.*, 2021; Rogers & Luton, 2011).

Finally, the success of the framework depends on sustained collaboration and policy integration. By embedding the S2S approach into regional and national planning frame-works, such as those promoted through the source-to-sea Framework for Marine Litter Prevention (SIWI, 2021) and the National Water Security Framework for South Africa (NPC, 2022), its impact can be amplified and long-term institutional support ensured.

In addition to biodiversity con-servation, the economic value of river and estuarine systems must be recognised. Coastal and marine biodiversity in South Africa plays a vital role in supporting economic sectors such as fisheries and tourism (Sowman, 2011; Griffiths *et al.*, 2010; de Moor *et al.*, 2004). However, traditional conservation approaches focusing on isolated protected areas have proven insufficient for effectively representing biodiversity (de Vos *et al.*, 2019; Holness & Biggs, 2011; Cowling & Pressey, 2003). A more integrated approach that accounts for ecological connectivity and the socio-economic needs of communities is necessary for sustainable resource management (du Plessis, 2024; Holness & Biggs, 2011).

By aligning adaptive management, biodiversity conservation and community-driven restoration, the Sout River project's S2S-informed framework offers a scalable, budget-conscious model for other similar catchments across South Africa and beyond. Integrating lessons from other South African systems and recent adaptive water-governance research, the framework supports a holistic strategy that combines science, social equity and ecological integrity for resilient river system management.

Conclusion and recommendations

This article introduced a practical, replicable source-to-sea (S2S) informed framework tailored for small, data-limited catchments in South Africa. Informed further by the principles of both strategic adaptive man-agement (SAM) and nature-based solutions (NBS) principles, the Sout River project demonstrates how integrated eco-logical restoration, stakeholder engage-ment and long-term monitoring can be implemented effectively even under budgetary constraints. This work complements national efforts to strengthen river system resilience and aligns with evolving global strategies for sustainable catchment management (World Bank Group, 2023; Biggs *et al.*, 2011; Pollard & du Toit, 2008).

The framework is grounded in a social-ecological systems (SES) perspective that recognises the interplay between environmental health, governance capacity and community livelihoods. Drawing from SAM experiences in the Kruger National Park and Lowveld river systems, the project adopted an adaptive, feedback-driven approach to designing and implementing interventions (McLoughlin *et al.*, 2021; Barendse *et al.*, 2016; Rogers & Biggs, 1999). As is evident from other South African case studies (i.e. the uMngeni catchment [Meissner *et al.*, 2013]), the success of proposed frameworks hinges on inclusive collaboration and locally relevant design.

Key lessons from this initiative include the value of targeted ecological interventions such as invasive alien plant clearing, wetland restoration and indigenous vegetation recovery in reversing land degradation and enhancing

ecosystem services. These findings reinforce broader ecological literature on the role of NBS in supporting water purification, flood regulation and biodiversity conservation (Busayo *et al.*, 2022; Acreman *et al.*, 2021; Seddon *et al.*, 2020). Additionally, consistent with global S2S guidance (SIWI, 2021), the importance of wetlands for natural filtration and habitat connectivity was reaffirmed in this catchment context.

Stakeholder engagement proved vital to the project's outcomes. Through citizen science, workshops and participatory research, the initiative fostered shared ownership and bridged the gap between scientific and traditional ecological knowledge (Rivers *et al.*, 2023; Roux *et al.*, 2020). This collaborative ethos aligns with South Africa's National Water Security Framework (NPC, 2022) and the Western Cape's water resilience strategy (EDP, 2023), both of which advocate for integrated and co-managed water-governance models.

Nevertheless, the Sout River project also faced structural constraints. Fragmented mandates, inconsistent data systems and limited institutional capacity remain common barriers across South Africa's catchments (Pollard *et al.*, 2023). Addressing these challenges will require sustained investment in governance reform, capacity-building and innovative funding models such as conservation finance, green bonds and public-private partnerships (du Plessis, 2024; Pollard *et al.*, 2023; World Bank Group, 2023).

To maximise the broader applicability and long-term impact of the developed framework, several strategic recommendations emerge: First, the framework should be scaled and adapted for replication in other catchments facing similar ecological and socio-economic pressures, ensuring flexibility to accommodate variations in hydrology, governance capacity and community priorities. Second, inclusive stakeholder engagement must be deepened by institutionalising co-governance structures, strengthening local knowledge systems and embedding community participation throughout the planning and monitoring cycle (Meissner *et al.*, 2013). Third, the framework should be embedded into national and regional policy, aligning with instruments such as the National Water Security Framework (NPC, 2022) and integrated catchment management strategies. Fourth, implementing long-term adaptive monitoring systems is essential, with standardised ecological and social indicators supported by feedback loops and scenario planning to inform responsive decision making (Pollard *et al.*, 2023; Rogers & Luton, 2011). Finally, ensuring financial sustainability will require the adoption of innovative funding mechanisms such as conservation finance, ecosystem service payments and cross-sectoral partnerships to support ongoing restoration and capacity-building efforts (World Bank Group, 2023; Wunder, 2007).

By way of conclusion, the Sout River project offered a locally grounded but globally relevant framework for integrating ecological restoration with adaptive management and community co-ownership. By drawing on lessons from strategic adaptive management in the Lowveld, contemporary NBS literature and current South African water-governance strategies, the resultant S2S-informed framework provides a foundation for equitable, climate-resilient conservation.

With proper investment, replication and policy integration, this S2S-informed framework can contribute significantly to South Africa's biodiversity and climate goals, thereby demonstrating that resilient ecosystems and thriving communities are interdependent and achievable through coordinated action.

Acknowledgements

In the course of the Sout River project, a number of specialist studies were outsourced. Deriving the framework proposed in this article would not have been possible had it not been for the invaluable contributions of Micheal Powell and Nicholaus Huchzermeyer who played a crucial role through their carbon baseline study of the catchment. Dr Nick Rivers-Moore and Dr Wynand Vlok (BioAssets) who provided essential insights from their baseline ecological survey of the catchment, and Dr Sandra du Plessis who contributed significantly through her work on the social baseline study.

Thank you for graciously granting permission to include your findings in this article.

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CITIZEN SCIENTIST FORUM

NVT is extremely fortunate that residents and "regulars" take a keen interest in the preservation of the Valley's natural state. All too often, concerns raised by our citizen scientists will alert NVT to the fact that a more thorough investigation may be warranted.

Of equal importance are the "experts" who are willing to share their observations of changes to the Valley's ecological state over many, many years as well as the "historians" who have quite a number of interesting (albeit sometimes gruesome) stories to tell about the life and times of those early explorers who first set foot here.

It took some doing, but we finally got John Blaine (a retired mineral geologist who to this day is still an active member of the Overberg Geoscientists Group) to deliver a talk titled "What's at Blue Rocks?" at one of NVT's on-the-spot gatherings. Needless to say, his recount of the geological history of Nature's Valley had everyone in awe. With John's permission, we adopted his presentation ever so slightly for the purposes of including it in this edition of *Nature's Letters*.

In the second contribution, Des Mahony (NVT's Chair and a keen historian) sheds a little light on how an eagle and a warbler got to be named, as well as how it came about that the first red flag was raised that a large African mammal might be on the brink of extinction. Even though the methods employed to "collect" samples back in the 1850s appear to be rather brutal, it cannot be denied that the early explorers contributed a great deal to the logical ordering of everything that lives on Earth as we know it today.

NVT invites all citizen scientists to share their historical observations/stories and/or concerns about the Valley's ecological state.

Keep in mind that your observations might just alert NVT to an issue that requires closer scrutiny and that recounting what happened way back when has the potential to unlock a treasure trove of data that can inform the studies of environmentalists who endeavour to preserve the Valley in the here and now.

Send your contribution to hendri.coetzee@nvt.org.za

A geological history of Nature's Valley

The extraordinary formation and colouring of the rocky shores and mountains that hug our valley never seize to amaze those who set foot in the village for the first time. Truth be told, even seasoned regulars often wonder how the extraordinary "backdrop" to their favourite spot on Earth came about.

To get to grips with what lies at the heart of the unique geological formations that makes the scenery in and around the valley so unique, one has to go back many, many years.

The geological history of Nature's Valley goes back to the early stages of deposition of rocks of the Cape Supergroup approximately five-hundred million years (~500 Ma) ago and the subsequent building of the Cape Fold Mountains (~280-235 Ma ago). These rocks represent the seafloor of the

now extinct Agulhas Sea. Deposition was in estuaries and a shallow marine environment at or below sea level, and by the end of this active sea, they were buried to at least 4,500 metres below sea level. Mountain building then raised these rocks above sea level to heights equivalent to the Himalayas (> 8,000 m) when the Agulhas Sea was compressed closed and the supercontinent known as Gondwana was being assembled. The breakup of Gondwana lowered sections of the continental margin along the southern and western Cape coastline back below sea level (~135 Ma ago).

Continental uplift over approximately the next 60 Ma led to erosion of the land and the incision of at least two major still stands of sea level between five and 24 Ma ago, visible as terraces on the modern landscape. Further uplift exposed the Tsitsikamma Platform and led to the down-cutting of the Grootrivier (aka Groot River), Bloukrans River and others as the sea level dropped even further to 130 metres below the current sea level at the outer edge of the Agulhas Bank and some 70 kilometres offshore of Nature's Valley (~20,000 years ago).

A subsequent rise in the sea level to at least eight metres above the current sea level led to the erosion of identifiable wave-cut notches at The Point and on Blue Rocks. The Holocene Highstand of the sea level approximately four to five thousand years ago eroded the area now known as Nature's Valley and provided space for deposition of sand dunes leading to the present distribution of cliffs, sand dunes and river terraces in the Grootrivier valley.

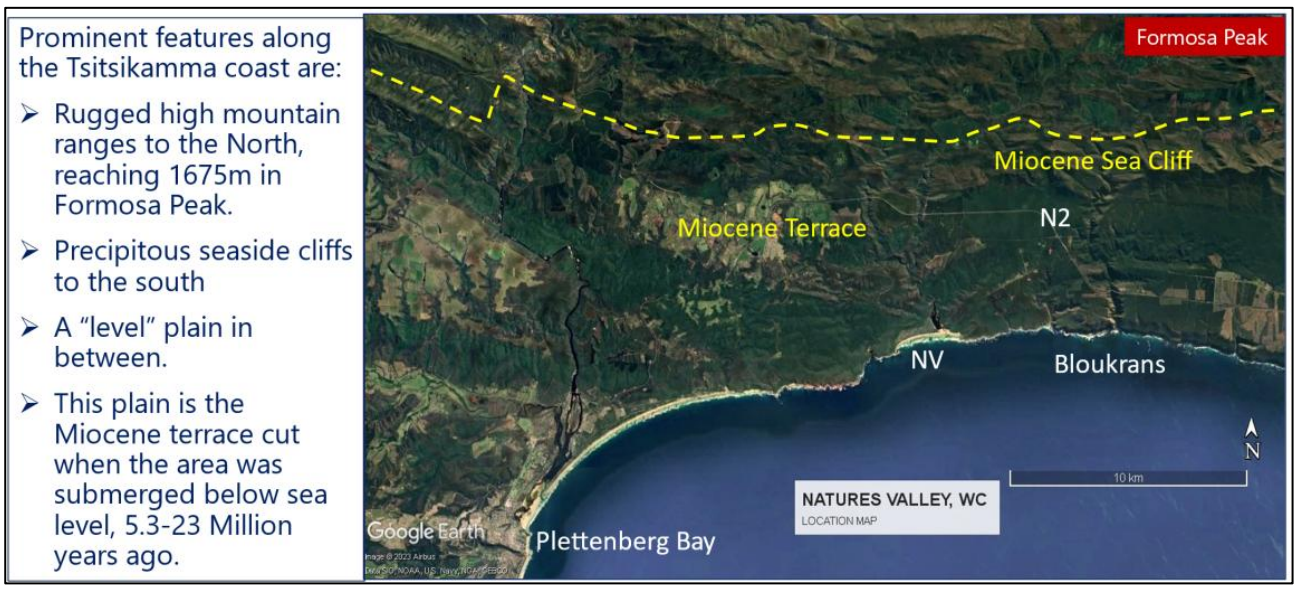


Figure 1: Location of Nature's Valley in one of the few rare sandy patches between the Tsitsikamma (Miocene) Terrace and the sea

Having broadly sketched the scenario, to follow is a brief overview of the sequential formation of the "major players" (i.e. groups) that contributed to creating the scenery in and around Nature's Valley as we know it today.

CAPE SUPERGROUP

The Cape Supergroup was deposited in a broad, slowly subsiding trough across the southern edge of the Gondwana Supercontinent (commencing approximately 500 million years ago) as the first stage in the repeating cycle of plate tectonics (**Figures 2-5**, adapted from *Cape Fold Belt*, https://en.wikipedia.org/wiki/Cape_Fold_Belt).

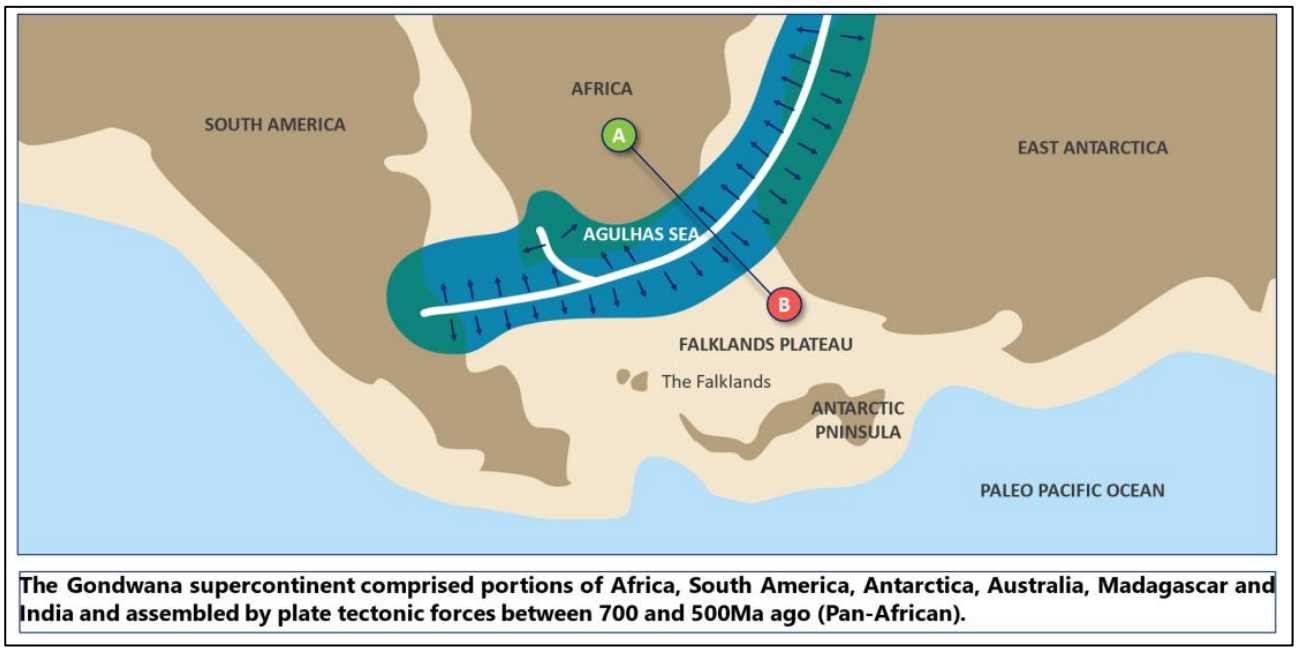


Figure 2: Deposition of the Cape Supergroup in an extensional/subsiding trough: Plate tectonics - Stage 1

Note that due to the eruption of basalt, subsidence and extension did not reach the stage of a fully-developed ocean basin, viz. the Atlantic Ocean (**Figure 3**).

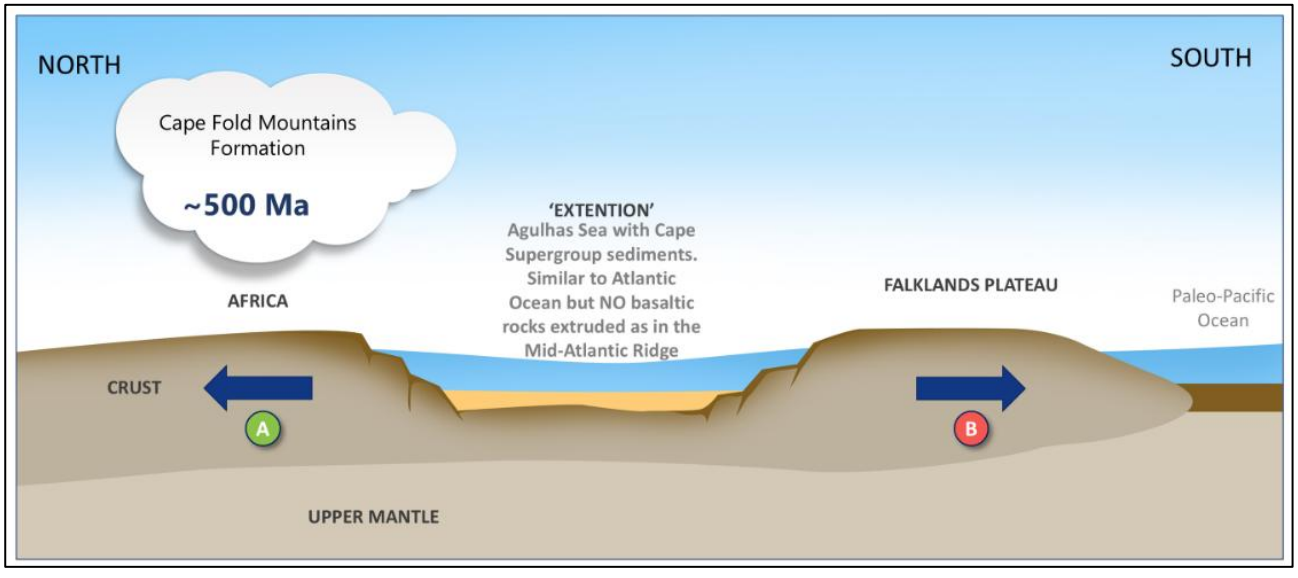


Figure 3: Deposition of the Cape Supergroup: Plate tectonics – Stage 2

This was followed by compression as the plate tectonic cycle continued with the Paleo-Pacific Ocean moving in from the "south" (**Figure 4**).

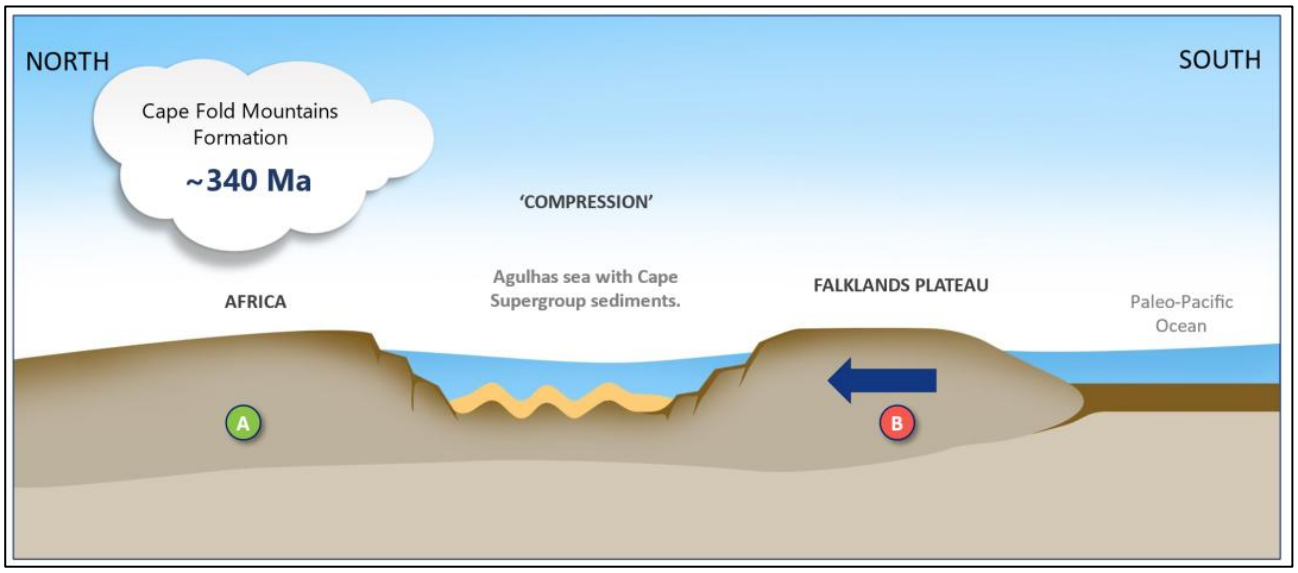


Figure 4: Deformation/folding of the Cape Supergroup: Plate tectonics – Stage 3

Continuing compression from the Paleo-Pacific plate caused deformation, i.e. the folding and uplift of the Cape Fold Belt to elevations likely similar to the present-day Alps and Himalayas (**Figure 5**).

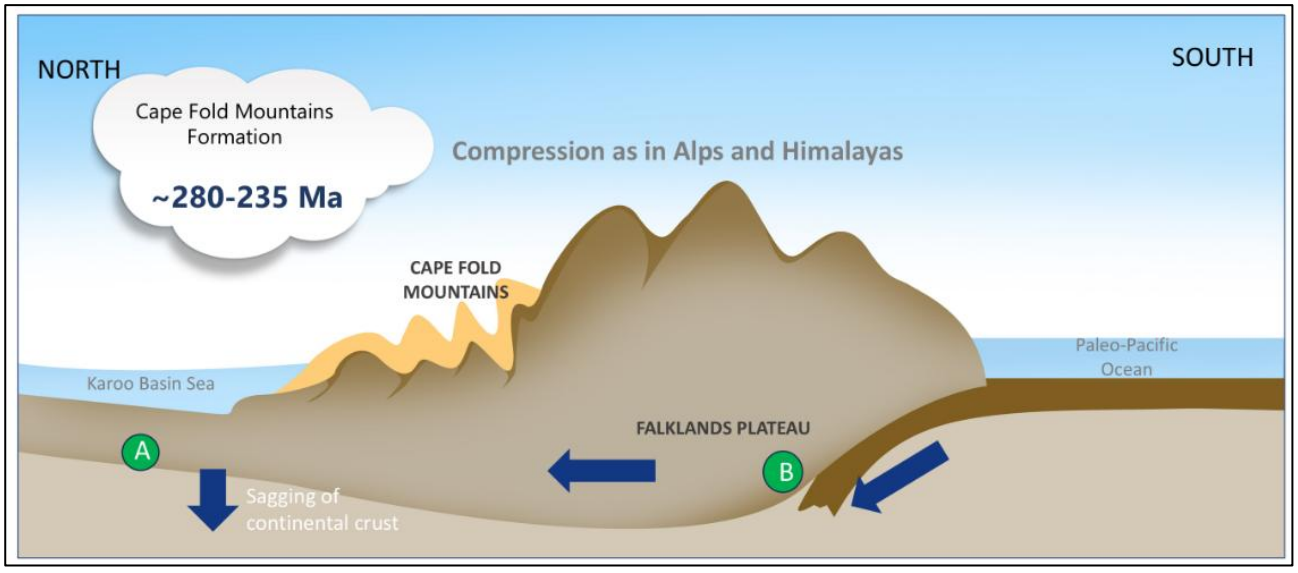


Figure 5: Deformation/folding of the Cape Supergroup: Plate tectonics - Stage 4

A cross section through the Cape Fold Belt from George to Prince Albert illustrates the complexity of the deformation as it is presented today. It also shows the location of the edge of the continent after the breakup of Gondwana (**Figure 6**).

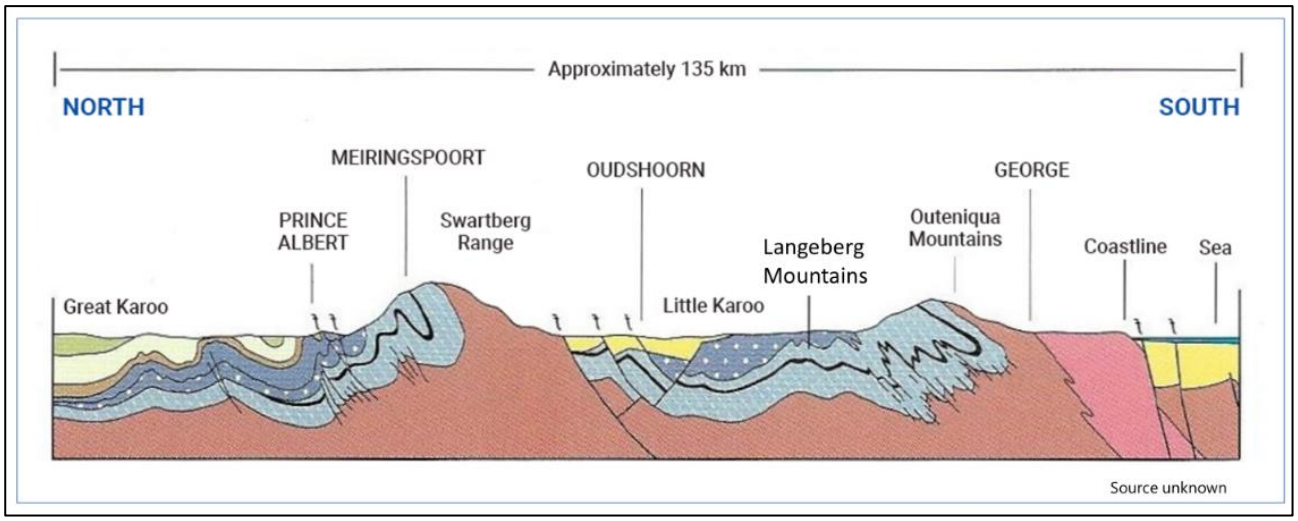


Figure 6: The southern Cape Fold Belt: Present time north-south geological cross section from Prince Albert (Great Karoo) to George (coastline)

The remaining extent of the Cape Supergroup in South Africa stretches along a 1,200-kilometre coastline from the west (Vanrhynsdorp) to south of Durban and extends approximately four hundred kilometres inland where boreholes drilled north of Beaufort-West revealed the presence of the Cape Supergroup beneath the Karoo rocks. The origin of the sediments that were deposited were derived from the weathering of ancient mountains in the hinterland to the north and northwest (**Figure 7**).

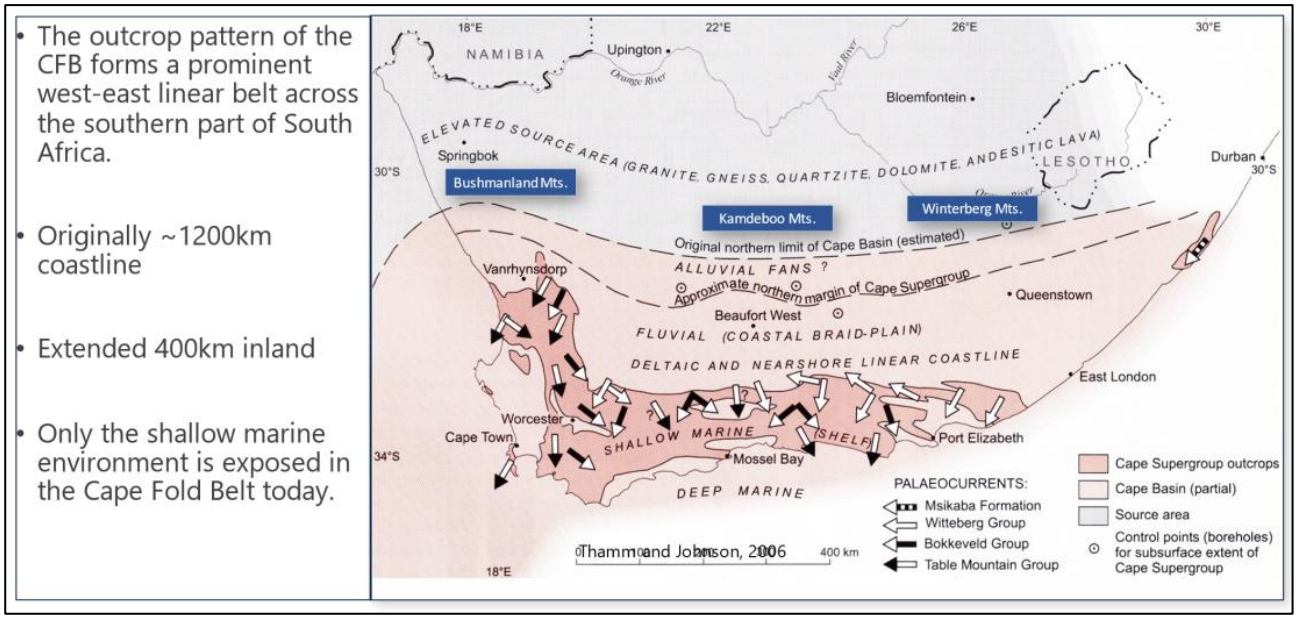


Figure 7: Deposition of sediments weathered from the hinterland into the Cape Supergroup Basin (Agulhas Sea)

TABLE MOUNTAIN GROUP

Originally sandstones and lesser mudstones, the composition of the Table Mountain Group rocks is predominantly quartz-rich. Quartz, made up of silicon and oxygen (SiO_2), is a very stable and hard-wearing mineral measuring eight on the Mohs Hardness Scale. Back then, the interior of Gondwana was made up of granitic rocks (containing 20-60% quartz) and older sandstones and quartzites (metamorphosed sandstones). In his book titled *The rocks and mountains of Cape Town,* Compton (2004) describes the Cape Supergroup as "an enormous pile of sand" deposited between 510 and 340 million years ago that is over 7,000 metres thick and includes intervals of mudstone (**Figure 8**).

This predominantly sandstone sequence is known as the Table Mountain Group, as well represented in the front north face of Table Mountain.

AGE	STRATIGRAPHIC UNIT			COMPOSITION
	Bokkeveld Group			Predominantly fine-grained sandstone and mudstone
<416 Ma	Baviaanskloof Formation (<200 m)	Represented around Natures Valley	TABLE MOUNTAIN GROUP	Light coloured, feldspathic, quartzitic sandstone
	Rouga Formation (200 – 400 m)			Thick bedded, profuselycrossbedded white weathering quartzitic sandstone and minor conglomerate
<444 Ma	TchandoFormation (200 -300 m)			Brown weathering quartzitic sandstone, thin shale and siltstone
	Cedarberg Formation (50 – 120 m)			Dark shale and siltstone
	Pakhuis Formation (~40 m)			Diamictite, pebbly sandstone, varved mudstone with dropstones (Glacial)
	Peninsula Formation (~2700 m)			Quartz arenite, minor shale and conglomerate
<510 Ma	Graafwater Formation (<430m)	Not represented		Reddish shale, siltstone, quartzose sandstone
>500 Ma	Kaaimans Group (Metamorphic) (480– 550 Ma) and George Granite (Intrusive) (510-555 Ma)			

Figure 8: Table Mountain Group: East of 21° East – ages and rock composition descriptions

At the time of the formation of the Table Mountain Group, the southern part of the Gondwana continent was situated in sub-polar latitudes during a time when no or very few land plants existed yet. As depicted in **Figure 9**, the climatic environment is envisaged to be similar to modern-day Alaska or Iceland.



Figure 9: Table Mountain Group's depositional environment: Fluvial braid plain, grading distally to a low-energy, shallow marine with evidence of invertebrates and trace fossils indicative of the early Ordovician period (~480 Ma ago)

During the Ordovician period, the icy, windswept plains were depositing the load of rivers in a large, braided river system on the shoreline of a shallow sea (Visser, 1974). The relative rise in sea level or subsidence of the sea floor allowed multiple stacked beach deposits to build up, the cross-bedded sequences of which are very common and serve as an indication of the direction of flow or deposition (**Figure 10**).

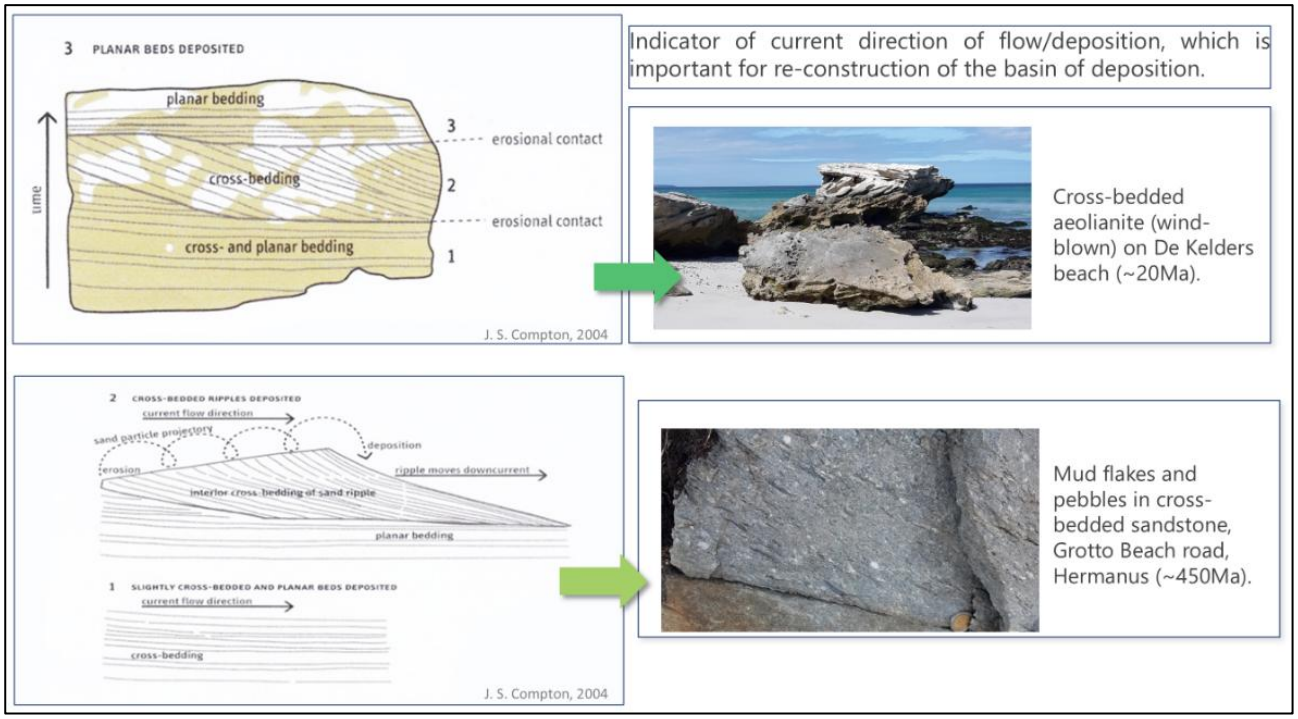


Figure 10: Depositional environment: Cross-bedding in sandstone by wind and water

Evidence of the ensuing sub-glacial environment (dating back to approximately 440 Ma ago) can be found in the deposits of glacial outwash-sands, -gravel and -muds in the Pakhuis and overlying Cederberg Formation (**Figure 11**). In these rocks, some of the earliest evidence of invertebrate creatures (e.g. brachiopods and trilobites) as well as various trace fossils can be found near Ceres.

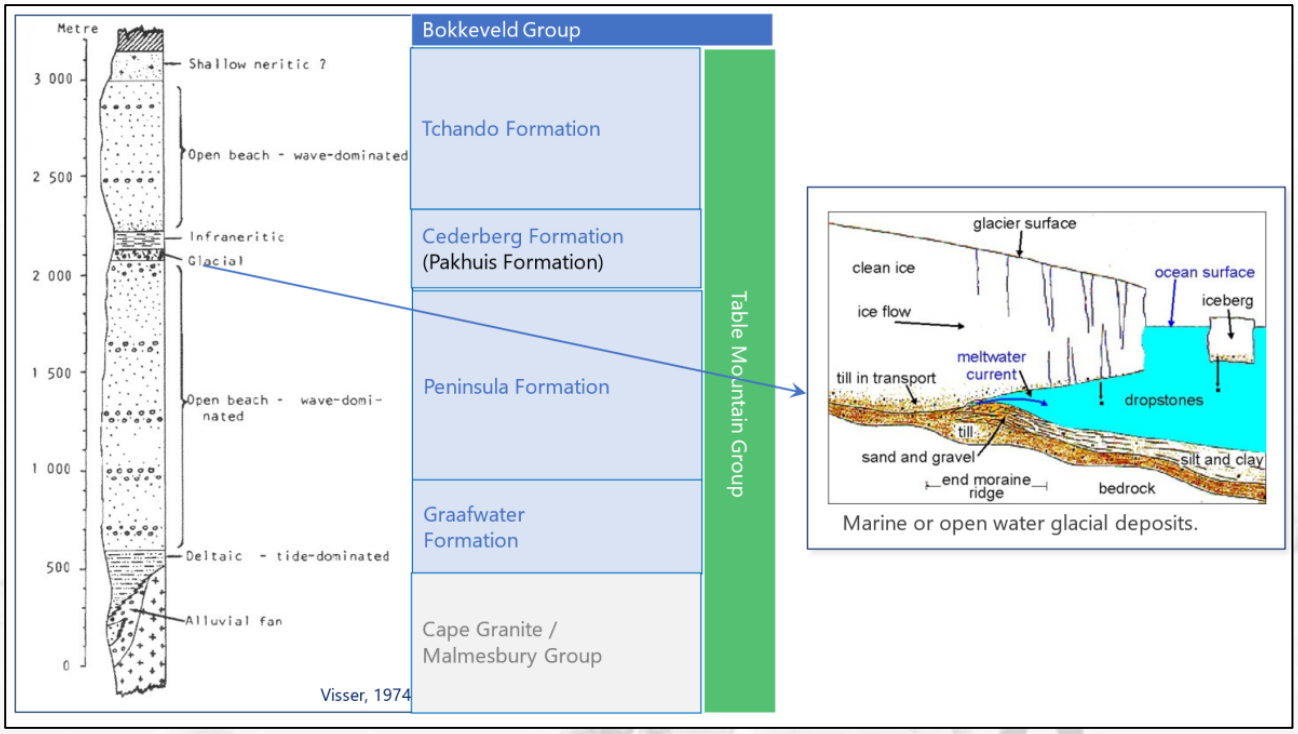


Figure 11: Pakhuis and Cederberg Formation depositional environment: Glaciogenic rocks (diamictites)

BOKKEVELD GROUP

The Bokkeveld Group follows conformably on the Table Mountain Group and, by comparison, is dominated by mudstone with lesser sandstone in a repeating sequence with a thickness of approximately 1,300 metres in the west and up to 3,300 metres in the east, indicating wider spread deepening of the shallow Agulhas Sea (**Figure 12**). The Bokkeveld sequence is widely recognised for providing the first records of fossil fish in a storm-and-wave dominated paleoenvironment at high sub-polar latitudes. The age range for these rocks is approximately 400 to 380 Ma.

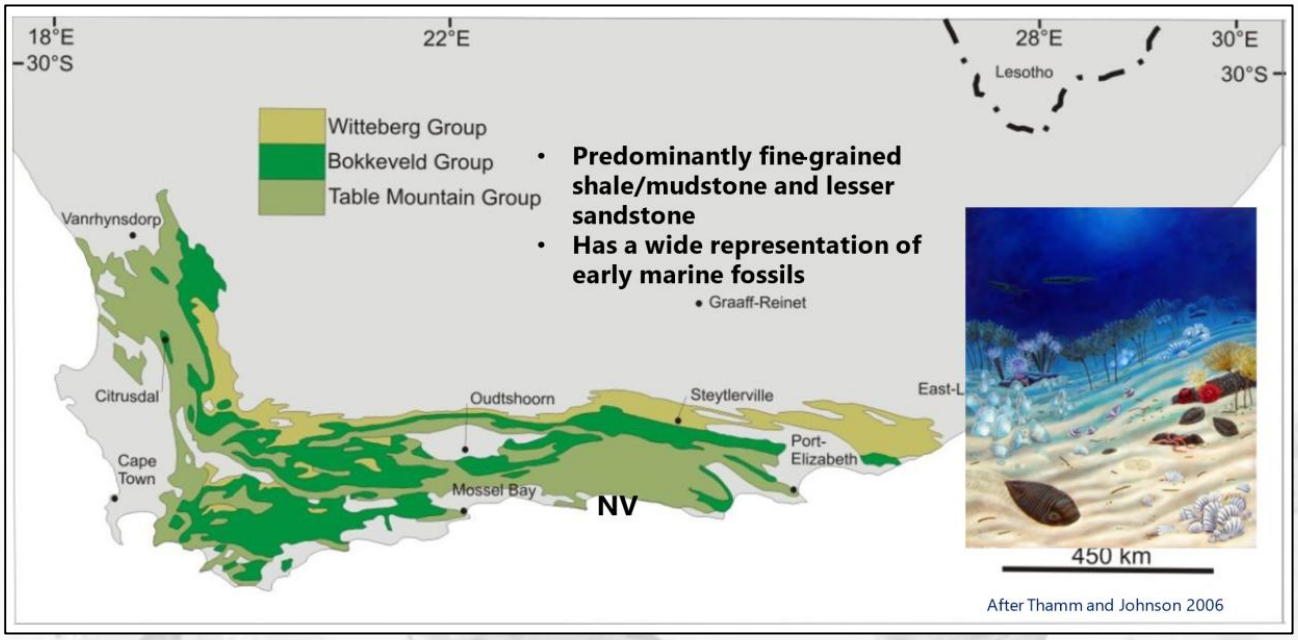


Figure 12: Distribution of the Bokkeveld Group

Most of the Bokkeveld stratigraphy (**Figure 13**) is not represented around Nature's Valley, with only the lowermost Gydo Formation present. A characteristic of this unit is the presence of iron sulphides (usually as pyrite in black mudstone) that is indicative of a highly reduced environment (e.g. stagnant, muddy ponds). This characteristic is well displayed in the rusty layers at Blue Rocks (**Figure 13**).

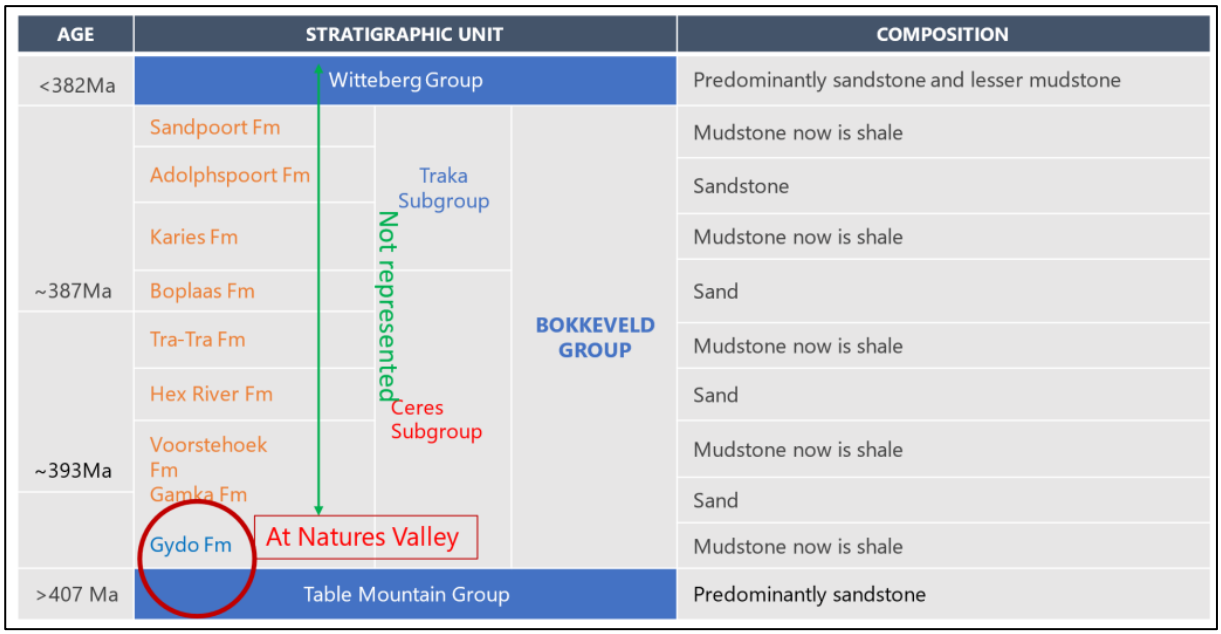


Figure 13: Bokkeveld Group: Ages and rock lithology compositions

The schematic section in **Figure 14** depicts the position of the rocks around Nature's Valley in the context of the wider stratigraphy of South Africa.

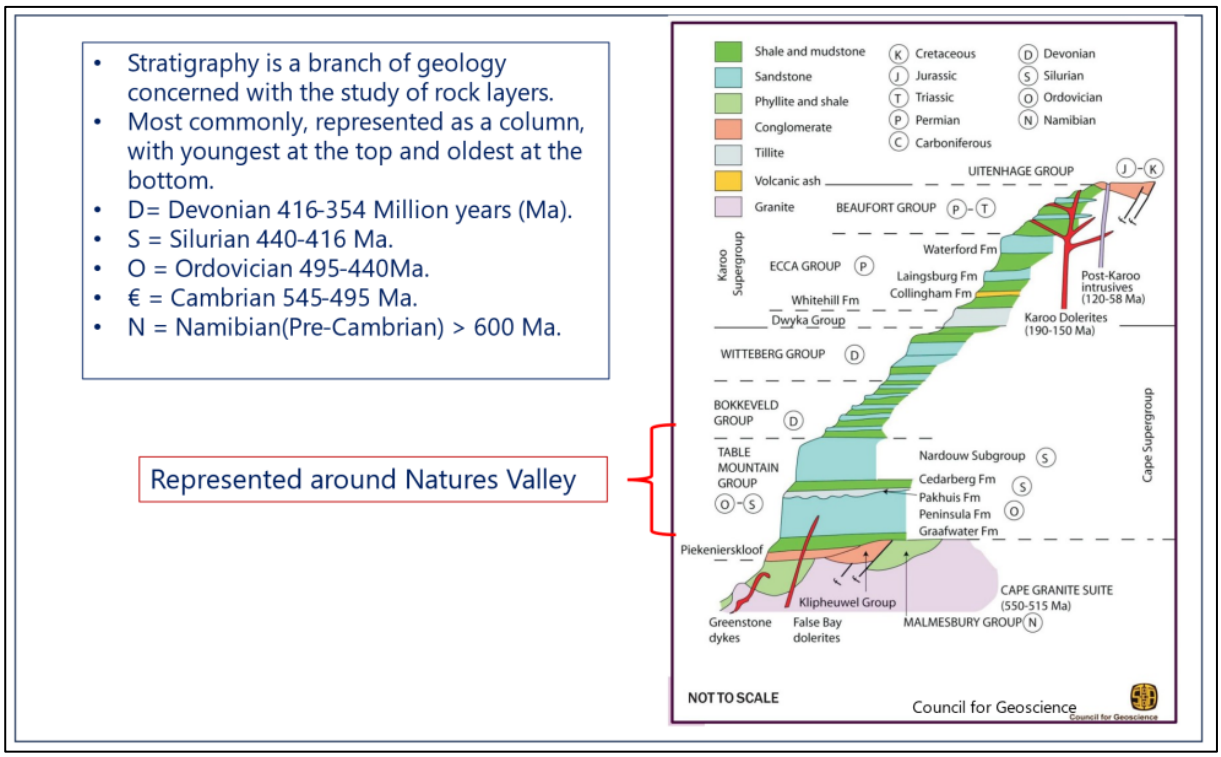


Figure 14: Nature's Valley in the context of the wider stratigraphy of South Africa

Having briefly sketched the timeline and the contributions of the "major players", let's take a closer look at how they impacted the valley's rock formations.

Conspicuous rock formations in and around Nature's Valley

The sketch dated 1792 in **Figure 15** depicts an early representation of the area around Nature's Valley, the most conspicuous features being the Tsitsikamma Terrace (Miocene Platform) (Van Zyl, 1997). When travelling west from Gqeberha (aka Port Elizabeth), the N2 highway is built along this relatively level plain, particularly around Van Stadens Pass and from Humansdorp westwards towards the Keurbooms River, with the Tsitsikamma mountain range to the north and the ocean below a sudden cliff edge to the south.

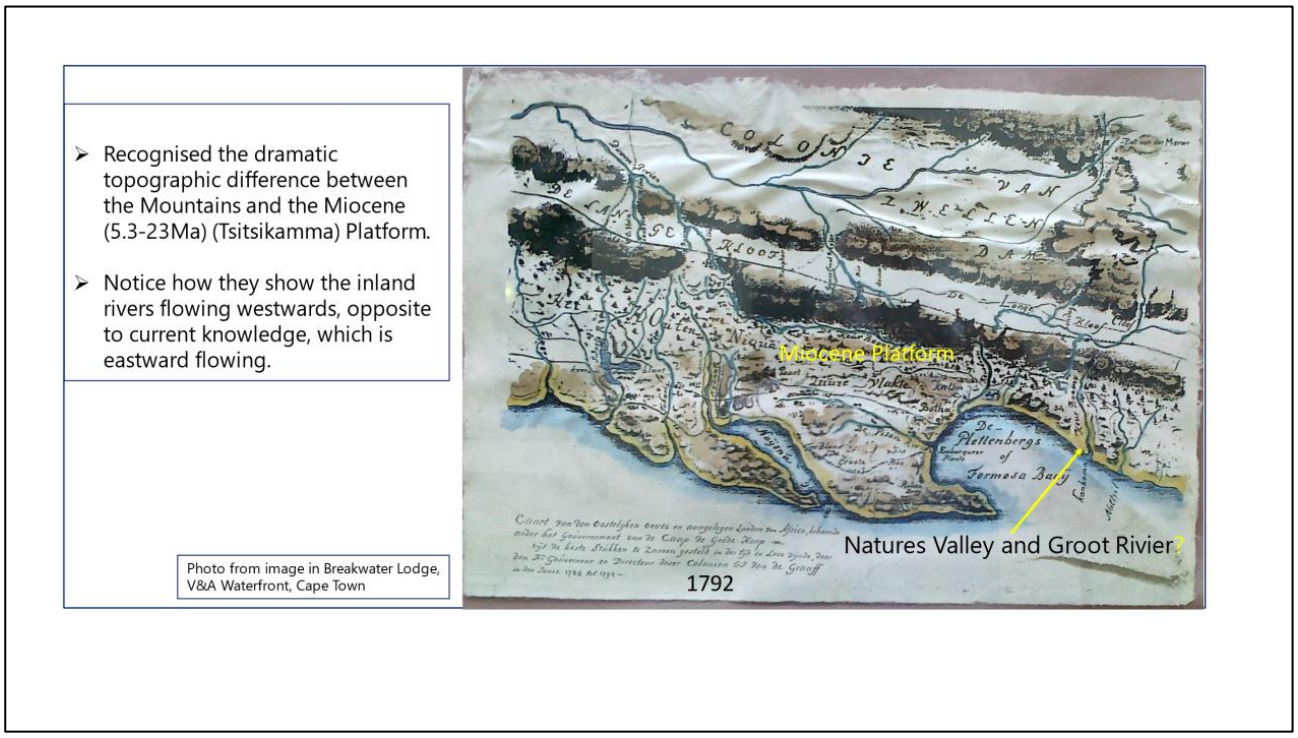


Figure 15: Early representation of the area around Nature's Valley (1792)

The Tsitsikamma Platform (Terrace) is the remnant of the seashore in Miocene times (~5.3-24 Ma ago). This area was below sea level as a result of the separation of Gondwana. From 135 Ma ago, it was slowly rising in response to isostatic[1] forces acting on the southern African hinterland.

Aided by modern technology, more recent representations of the same area show the Miocene sea cliff at the base of the Tsitsikamma Mountains (**Figure 16**). The inset photograph in this figure shows a waterfall at this sea cliff that can be seen along a section of the Tsitsikamma hiking trail between Nature's Valley and the Blaauwkrantz hut.

[1] **Isostacy**, derived from the Greek words *isos* ('equal') and *stásis* ('standstill'), describes the state of equilibrium that exists between parts of the earth's crust, which behaves as if continental blocks (less dense) float on the underlying (more dense) mantle. That is why mountain ranges do not sink below sea level and why the crust rebounds after major deglaciation.

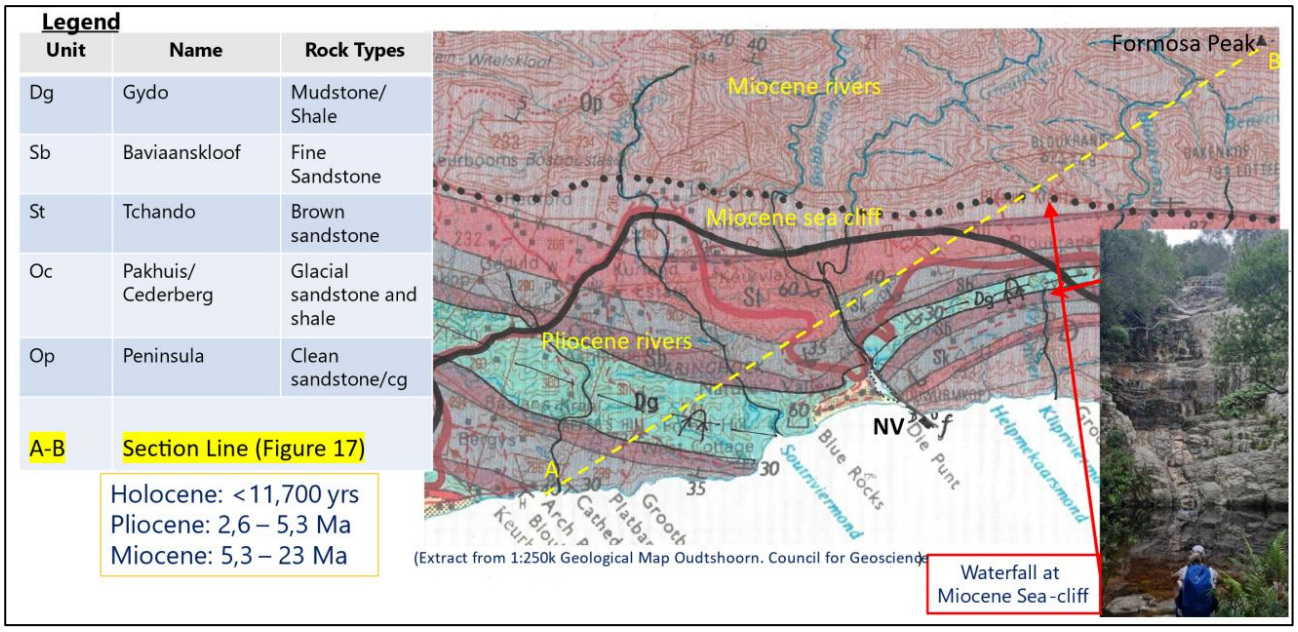


Figure 16: A geological map of the Tsitsikamma coastline today

Rivers extended across the Tsitsikamma Platform as the sea receded due to further isostatic uplift began to cut down into this platform with a pause in the Pliocene between 2.6 and 5.5 Ma ago before dropping further to the present sea level. Rivers that do not cut back into the Tsitsikamma Mountains, such as Matjiesrivier that rises near The Crags, likely only developed in the Miocene/Pliocene period and only cut through the Miocene and Pliocene terraces.

A detailed investigation of river/stream patterns on the Miocene Platform shows a preference for erosion in more easily-eroded rock units such at the Gydo Formation (Dg), extending west from Blue Rocks towards the N2 west of The Crags. The winding section of the N2 between The Crags and the bend at Fairview House to the west runs along the water divide between Matjiesrivier and Whiskey Creek, both of which join the Keurbooms River.

The section line A-B in **Figure 16** from Keurboomstrand to Formosa Peak shows the well-developed Miocene and lesser Pliocene Terraces with the incised Sout- (aka Salt) and Grootrivier valleys eroded down in post-Pliocene times **(Figure 17)**.

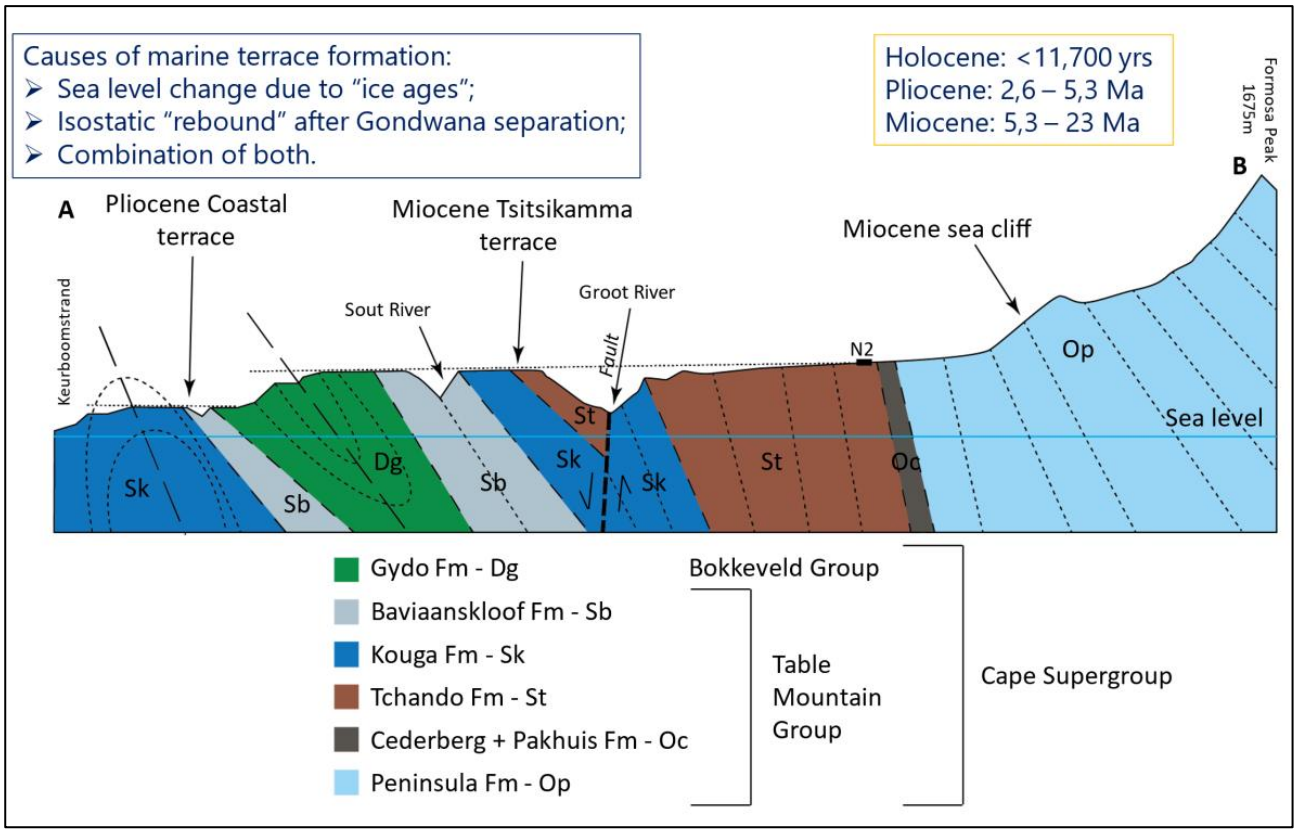


Figure 17: Tsitsikamma coastline today (refer section line A-B in Figure 16)

Undeniably, throughout the millennia, the rise and drop in sea levels as a result of climate change had a major impact on shaping the landscape. To understand this phenomenon, one must get to grips with what is referred to as a "eustatic[2] climatic change" in sea level. Keep in mind that when ice forms, water is extracted from the sea. Consequently, the sea level will be lowered all over the world.

Isostatic rebound and the resultant effect of eustacy on sea levels

Before the breakup of Gondwana approximately 135 million years ago, sea levels were largely driven by tectonic forces. Isostatic rebound occurred in response to the Gondwana separation and erosion during the "African Cycle" from 65 to 15 Ma ago (**Figure 18**). The latter part of this period was starting to show the effects of sea-level change due to climatic conditions and the rhythmic effect of "colder" and "warmer" periods and the attendant cycles of "glaciation" and "melting". This phenomenon is referred to as the eustatic effect.

[2] **Eustacy** denotes or relates to worldwide changes in sea level as contrasted with local diastrophic uplift or subsidence of the land (i.e. tectonic movement) that are particularly due to the occurrence of major glacial periods.

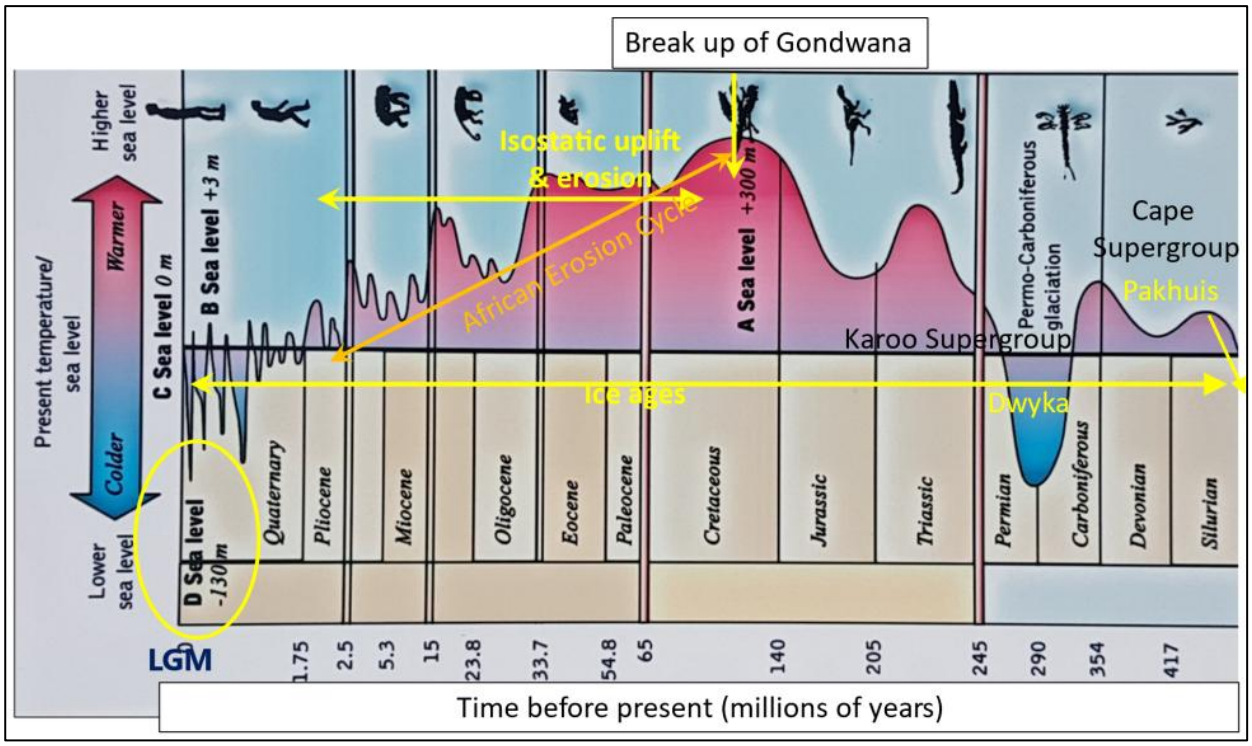


Figure 18: Sea-level change as represented relative to current sea level, geological ages, ice ages and the development of living creatures adapted from a poster developed by the Department of Forestry, Fisheries and the Environment for Overstrand Municipality

**LGM: Last Glacial Maximum*

Apart from the composition and the long history of the rocks around Nature's Valley, three main periods of sea-level change and planation undoubtedly had a huge hand in creating the marine terraces that are clearly evident from just about anywhere in the valley (**Figure 19)**.

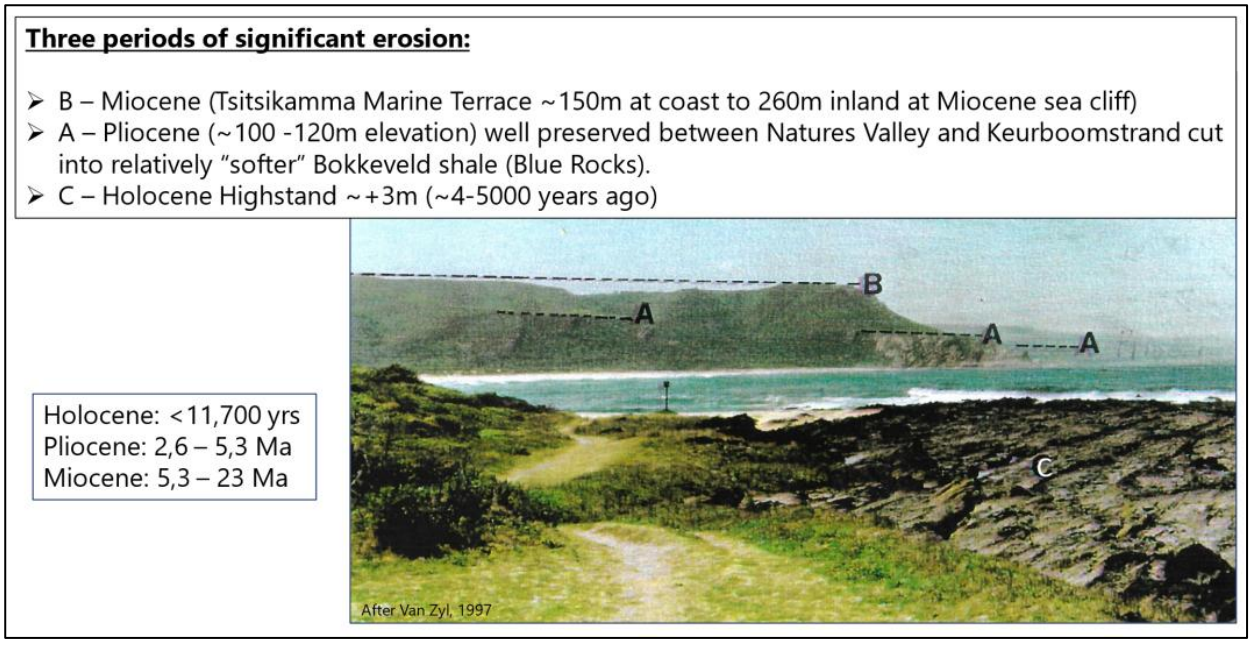


Figure 19: Sea-level change as represented in the scenery around Nature's Valley

Standing on Blue Rocks, looking east, the headland of The Point clearly exhibits the upper Miocene and lower Pliocene Marine Terraces (Platforms), while the surface on which you are standing is the most recent Holocene (Highstand) Marine Terrace.

Climb up to Pig's Head, and you are standing on the seaward edge of the Pliocene Terrace with well-preserved, rounded quartzitic pebbles cemented into the top (**Figure 20**). Well-rounded quartzitic pebbles, cobbles and boulders are a characteristic feature of the Tsitsikamma Terrace. When driving along the N2 from Gqeberha, this feature is clearly evident in the cuttings approaching Van Stadens Bridge, capping the quartzite bedrock below.

As one drives up the east side of the Grootrivier Pass, at the Lookout, the Miocene Marine Terrace is clearly visible to the west (**Figure 20**), with the incised Grootrivier valley below. The white, weathered sandy rocks in the cutting at this point are further evidence of the Miocene Marine Terrace's long period of erosion.

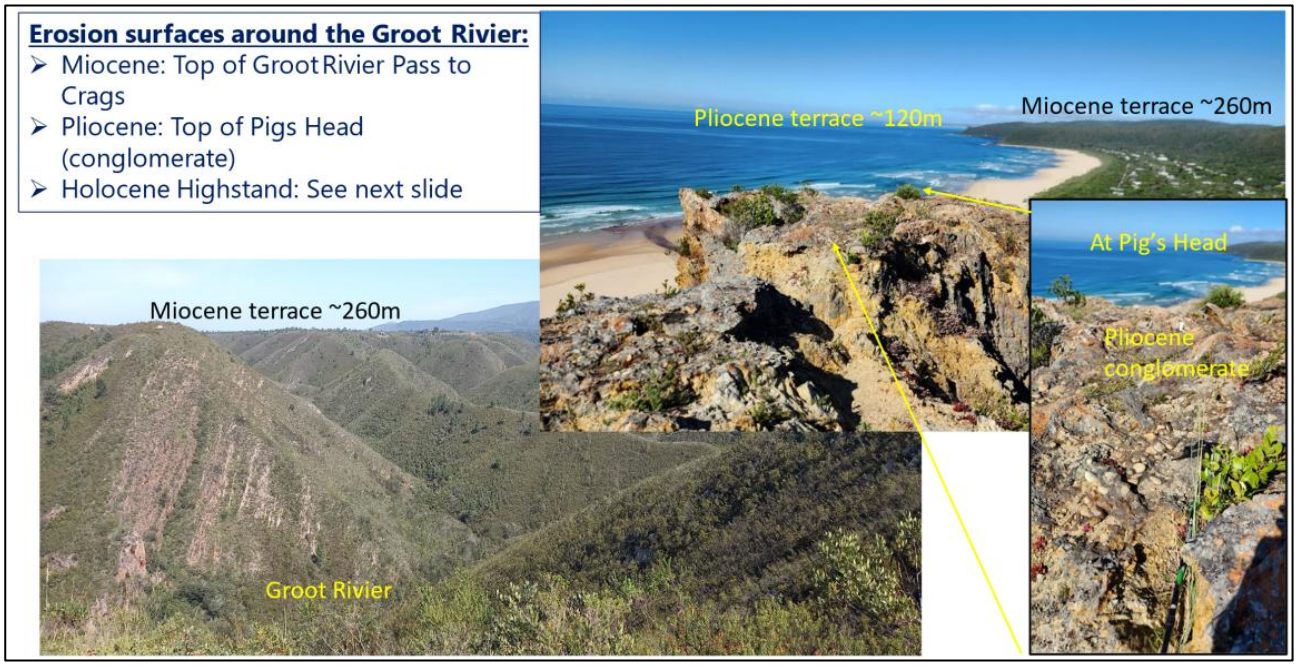


Figure 20: Sea-level change: Evidence of planation

As the sea level rises then recedes over millions of years, the "buzz-saw effect" breaks up the outcropping rocks due to the hydraulic action of the breaking waves and rolls them around, just as you see on "Pebble Beach" around the corner from Blue Rocks and all the way to the mouth of the Sout River. Most of these are probably pebbles and cobbles that have fallen from the Miocene and Pliocene Terraces above. They were then reworked during the Holocene Highstand and are once again being reworked at the present time.

Around the Grootrivier estuary (lagoon), there is further evidence of the Holocene Highstand, as shown by conglomerate beds in the lower part of the western Grootrivier Pass just before the turn-off to Nature's Valley. Along the road to the Grootrivier rest camp, there are deposits of conglomerate and beach sand on the upper side of the road approximately five metres above the present river level (**Figure 21** and **30**). Looking south towards The Point, one can clearly see the level of the Pliocene

Terrace as well as the "notch" at the base of The Point that extends into the lagoon mouth, where rugged outcrops of brecciated quartzite are planed off approximately one to two metres above the river level (the Holocene Highstand).

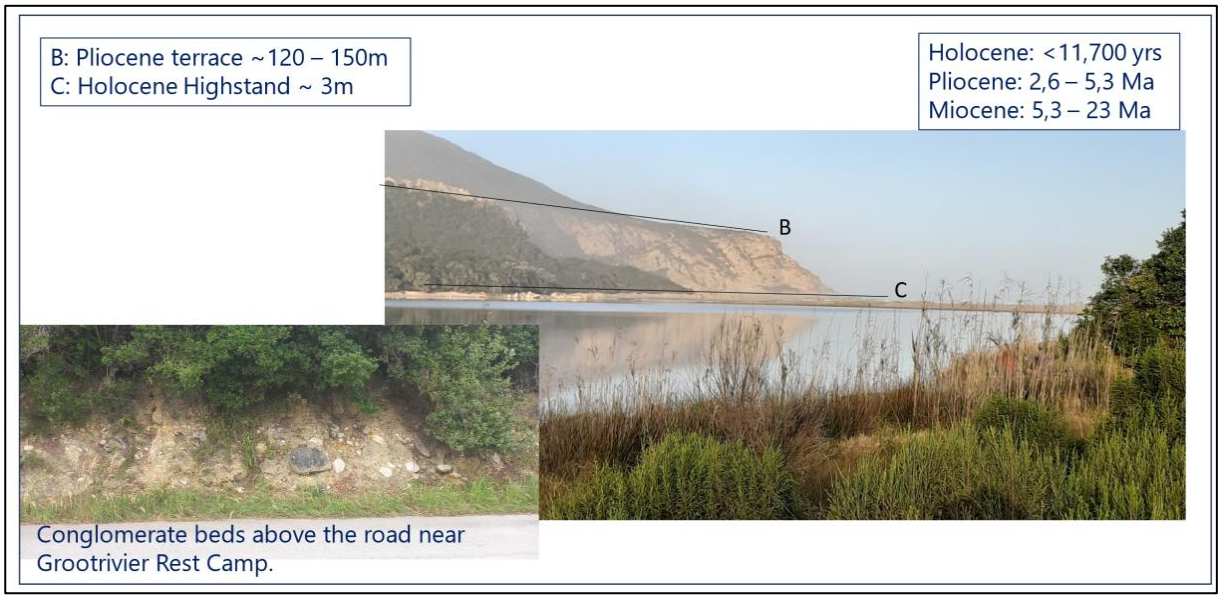


Figure 21: Sea-level change: Evidence in the estuary of the Grootrivier

In fact, the effect of sea-level changes is evident all along the southern Cape coast. For example, extensive work has been undertaken in recent years by the Council for Geoscience to map the topography and geology of the Agulhas Bank that extends in a triangular wedge from east of St. Francis Bay to a point some 130 km south of the Breede River, then back towards Cape Agulhas and False Bay (**Figure 22**).

This work maps the extent of the Pleistocene (<1 million years) shoreline across the Palaeo-Agulhas Plain that was exposed during two major ice ages that, each time, dropped the sea level to approximately 130 metres below the present sea level (Cawthra *et al.*, 2019).

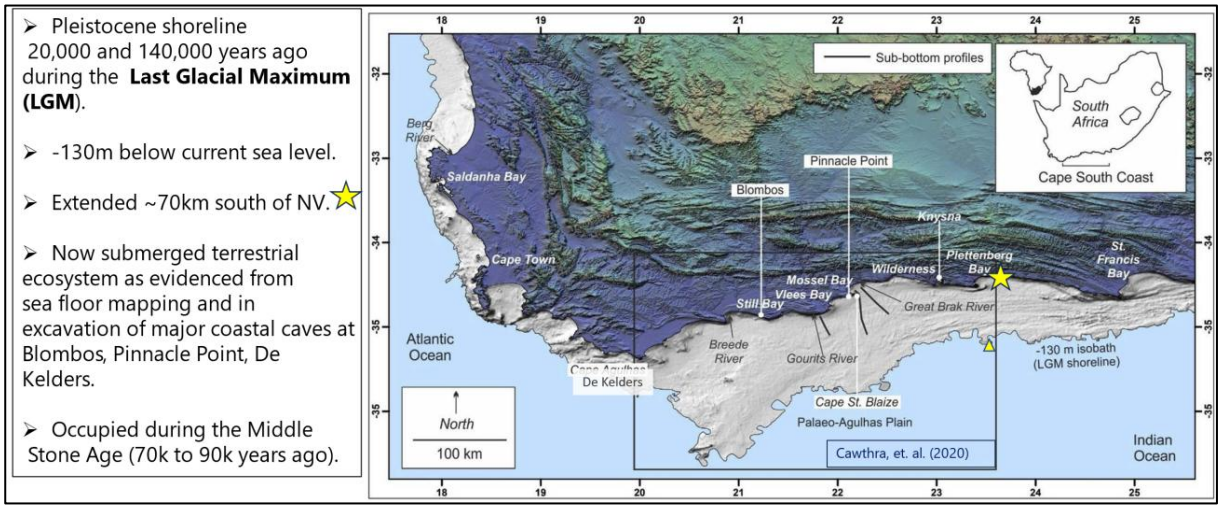


Figure 22: Sea-level change: Evidence from recent research work on the Aghulas Bank

The first of these two glacial maxima was approximately 140,000 years ago, and the last drop in sea level to the edge of the Palaeo-Agulhas Plain occurred approximately 20,000 years ago as the Last Glacial Maximum (LGM) (**Figure 23**). Note that the phases of cooling are punctuated by times of warming (interglacial periods).

In sum, eustatic changes are a feature of the last 900,000 years, with warming periods raising the sea level up to 11 metres above the present level. The stages (shown as 2, 3, 4, 5, 6 and 7 in **Figure 23**) represent markers of oxygen isotope anomalies representing glacial periods (even numbers) and interglacial periods (odd numbers). In South Africa, we experienced a "Holocene Highstand" where the rising sea level reached the present level approximately seven thousand years ago, then overshot by approximately three to five metres about four thousand years ago, fell back to zero metres, and is now back on the rise.

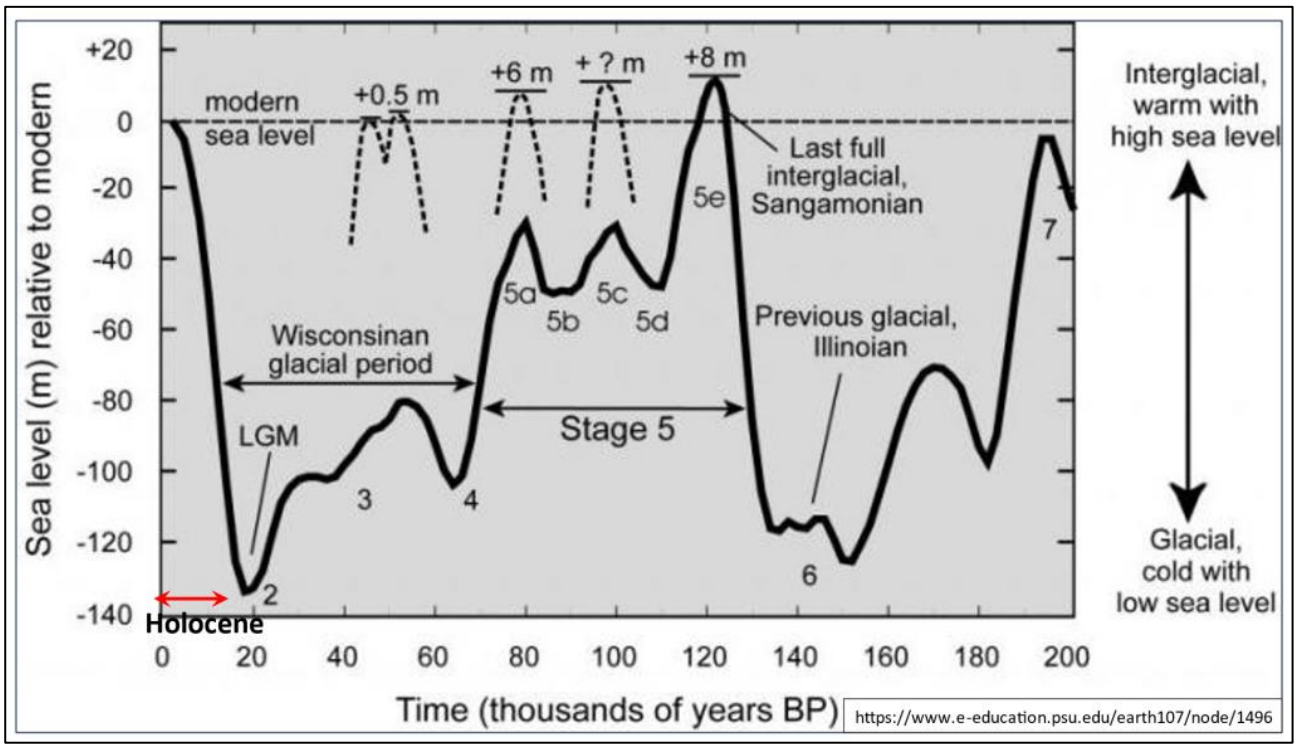


Figure 23: Sea-level changes over the last 200,000 years: Eustacy due to ice ages

In an attempt to arrive at an answer as to whether changes in sea level can solely be ascribed to global warming or whether other factors might also be at play, Hayley Cawthra (a senior scientist in the Geophysics and Remote Sensing Unit of the Council for Geoscience and a research associate at the Nelson Mandela University) responded by sketching the paradigm outlined in **Figure 24**.



Figure 24: Sea-level change: A paradigm

Clearly, only time will tell what the future holds but, for now, let's focus on a couple of niggling questions we might just have found the answers to.

Why rocks are sharp, rough … and blue.

Apart from the natural beauty of Blue Rocks, perhaps the most interesting aspect is the sharp and jagged outcrops that make up this end of the Nature's Valley beach. The sharp edges of these rocks are as result of the folding and up-turning of layered beds of the Gydo Formation mudstone now metamorphosed to shale by the pressure of deep burial in the Palaeo-Agulhas Sea and later by the compression that resulted in the formation of the Cape Fold Belt.

A characteristic of this compression and deformation is the transposition of compositional bedding to become a cleavage (a tendency of a rock to break in a particular way because of its structure). This cleavage (a sharp division or split) is approximately parallel to the axes of folds in the rock caused by the compression (**Figure 25**). For the most part, at Blue Rocks, the compositional bedding has been transposed to be parallel to cleavage. However, there is a good example of the relationship between bedding and cleavage along the path to the Sout River where there is a high angle between cleavage and the compositional bedding. This is usually apparent near the axis of a fold as depicted in **Figure 25**.

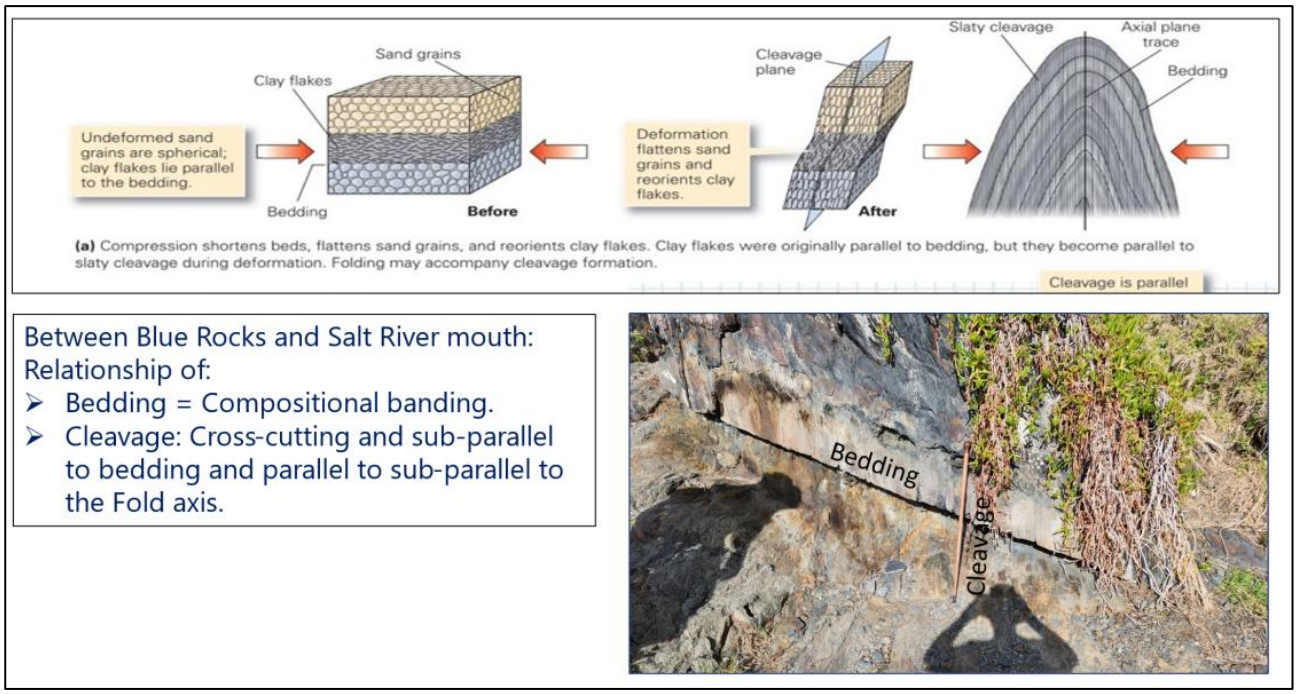


Figure 25: Rock structures (cleavage) and bedding at Blue Rocks

On a broader scale, at Blue Rocks (**Figure 26**), there is clear evidence of the effect of wave action causing the erosion of the marine terraces. The Holocene Highstand is clearly the upper level of the eroded surface. In the distance and above Blue Rocks are the Pliocene and Miocene Terraces.

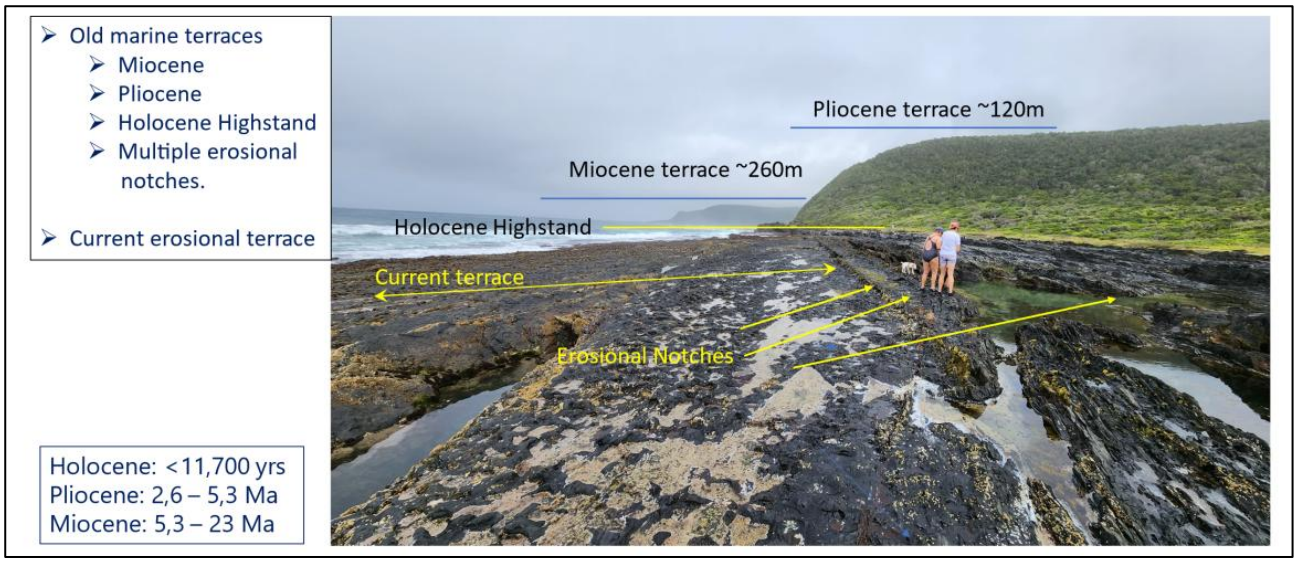


Figure 26: Rock structures (cleavage), bedding and erosion surfaces (marine terraces) at Blue Rocks

Interestingly as well, in the position of the people on the rocks, there is evidence of wave-cut erosion forming a new marine terrace as a result of the aggressive wave action on these brittle and relatively soft rocks to form an erosional “notch”.

When viewed from above at the Nature's Valley lookout en-route to the Sout River, the presence of faults are interpreted to bound the sides of "Sinker Bay" itself and the extent of the Blue Rocks outcrops towards the beach on the east (**Figure 27**). These fold cleavages cause the linear pattern of the rock outcrops with faults bounding the edges of the outcrop areas. Faults are quite often evidenced by narrow quartz veins, mostly sub-parallel to cleavage. The age of this southeast trending faulting may relate to the breakup of Gondwana similar to those bounding the major gas- and oil-bearing sedimentary basins between Cape Agulhas in the west and Cape Recife in the east.

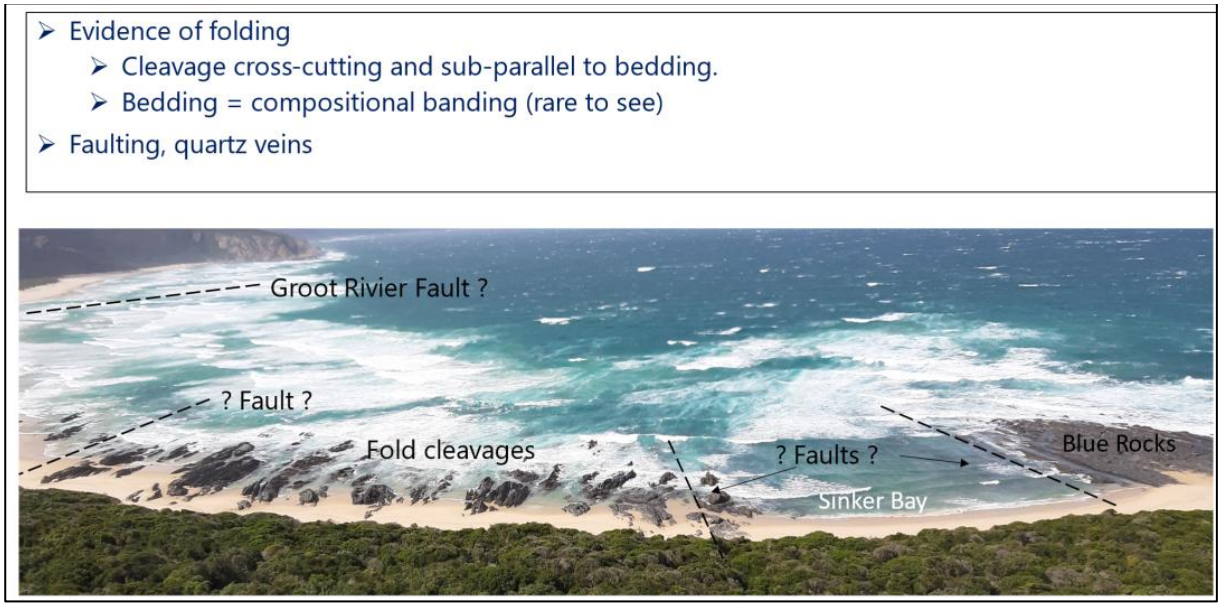


Figure 27: Rock structures (cleavage) and faulting at Blue Rocks

The mouth of the Sout River, just west of Blue Rocks, is an idyllic and isolated embayment. When next bathing in this tranquil environment, take a moment to note one of its characteristic geological features: The narrow cleft leading out to the open sea (**Figure 28**).

It is interpreted that a fault, similar to those forming the edges of Sinker Bay, forms the seaward edge of the embayment. In fact, a fault breccia can be seen in the cliff face where the shoreline path from Blue Rocks descends to the Sout River bay.

The Sout River is a Miocene-age river system that rises in the Tsitsikamma mountains and cuts down through the Miocene and Pliocene Terraces. Insufficient sub-sea data is available to show this, but when the sea level was 130 metres lower in the Pleistocene, it is likely that the Groot and Sout Rivers as well as the Bloukrans River to the east all extended out onto the Palaeo-Agulhas Plain.

The edge of the Palaeo-Agulhas Plain in this area (reached when the sea level falls by 130 metres in times of glacial cooling) is positioned approximately 80 kilometres out to sea relative to the present shoreline. This means that a significant landscape opens up when the sea level drops.

Having attempted to provide a synoptic explanation as to why people find the landscape in and around Nature's Valley so intriguing, perhaps it would be prudent to take a closer look at what the valley likely looked like at the time of the Holocene Highstand and what else has been "uncovered" in more recent times.

The valley then and now

The first unique characteristic one can't help but notice about Nature's Valley is that it is an isolated sandy bay along a largely rocky coastline extending 110 kilometres from just west of Oyster Bay to Keurboomstrand just west of the village itself.

It seems to be one of a few places where easily-eroded Bokkeveld rocks (in this case Gydo Formation shale) outcrop on the coastline – a feature it happens to have in common with Keurboomstrand. Given the Grootrivier fault to the east bounding hard quartzite outcrops, the Holocene Highstand enabled the sea to invade the Palaeo-Grootrivier valley and to cut back to the "underlying" hard sandstone of the Table Mountain Group behind the village. This, coupled with the effects of the Agulhas Current that formed "half-heart" bays along this coastline, caused sandy beach deposits to be trapped in this eroded embayment (**Figure 29**).

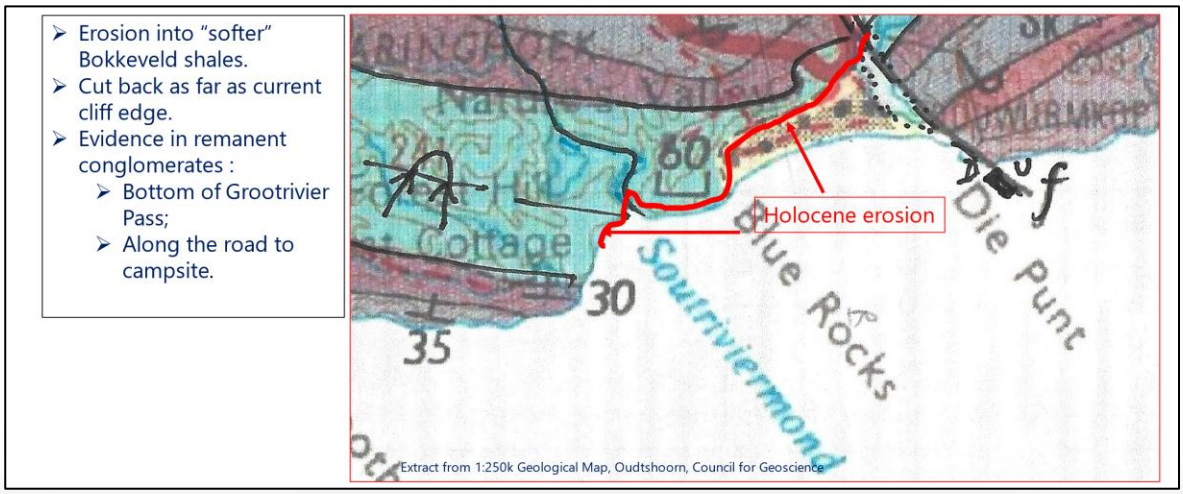


Figure 29: Nature's Valley during the Holocene Highstand approximately four to five thousand years a

The elevated deposits of conglomerates and old beach/river sand bars along the R102 near the Grootrivier campsite are evidence of the higher sea level at that time (**Figure 30**).

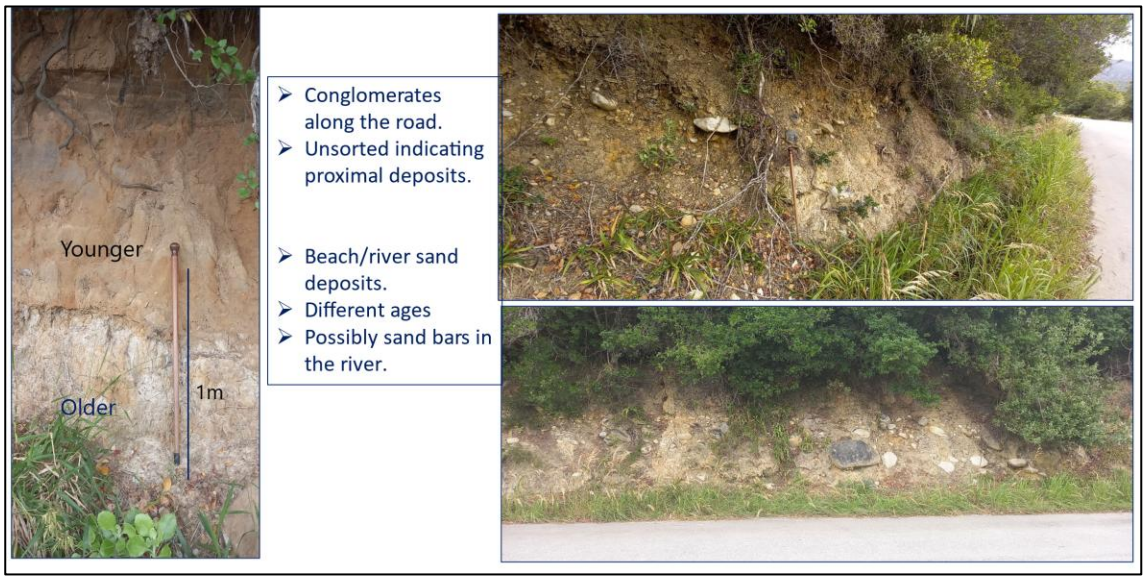


Figure 30: Holocene Highstand: Conglomerate/old beach levels in the Grootrivier valley

An interpreted geological map of Nature's Valley during the Holocene Highstand would likely have looked as depicted in **Figure 31**: The sea embayment would have pushed up the Grootrivier valley probably at least as far as the confluence of the Groot- and Bobbejaanrivier, depositing conglomerates and forming beaches and sand bars along its length. Streams flowing eastwards from the heights behind the village were probably in existence bounded by ridges of more resistant rocks and flowing into the Grootrivier valley near the present-day syndicate. These streams still flow today during periods of high rainfall but have been canalised between Forest Drive and St. George's Avenue to flow out at the lagoon-end of St. Andrews Avenue.



Figure 31: Interpreted geological map of Nature's Valley during the Holocene Highstand approximately four to five thousand years ago

One of the big challenges of an ***isolated*** but growing population in Nature's Valley, apart from the provision of potable water, is the disposal of sewerage.

In 2008, Ninham Shand Consulting Engineers undertook a study on behalf of the Bitou Municipality in an attempt to find a sustainable solution to sewerage disposal in Nature's Valley in combination with the septic tanks which continue to serve most of the properties. This work involved the drilling of several boreholes that were logged (recorded) by Frans Wagener (a former Anglo-American geologist who resides in the valley). As a "bonus", this drilling work revealed additional information that aided in enhancing the geological story of Nature's Valley (see **Figures 32** and **33**, courtesy Ninham Shand).

Evidently, a clearly identified "clay area" lies at the north side of the village against the mountainside. Between the "clay area" and the sea, there is a "shale ridge"[3] and "fossil" sand dune that runs along the middle of the village (**Figure 32**).

Although the boreholes were not very deep, they did provide a reasonable understanding of the sub-surface rock and sediments. A cross section through the geological plan (**Figure 33**) derived from this drilling exercise shows the "clay layer" to be confined to the north side of the "fossil" dune and at a level currently five metres above the present sea level[4]. Hence, the clay layer (weathered shale) developed in the paleo-streambed behind the fossil dune running east through the village.

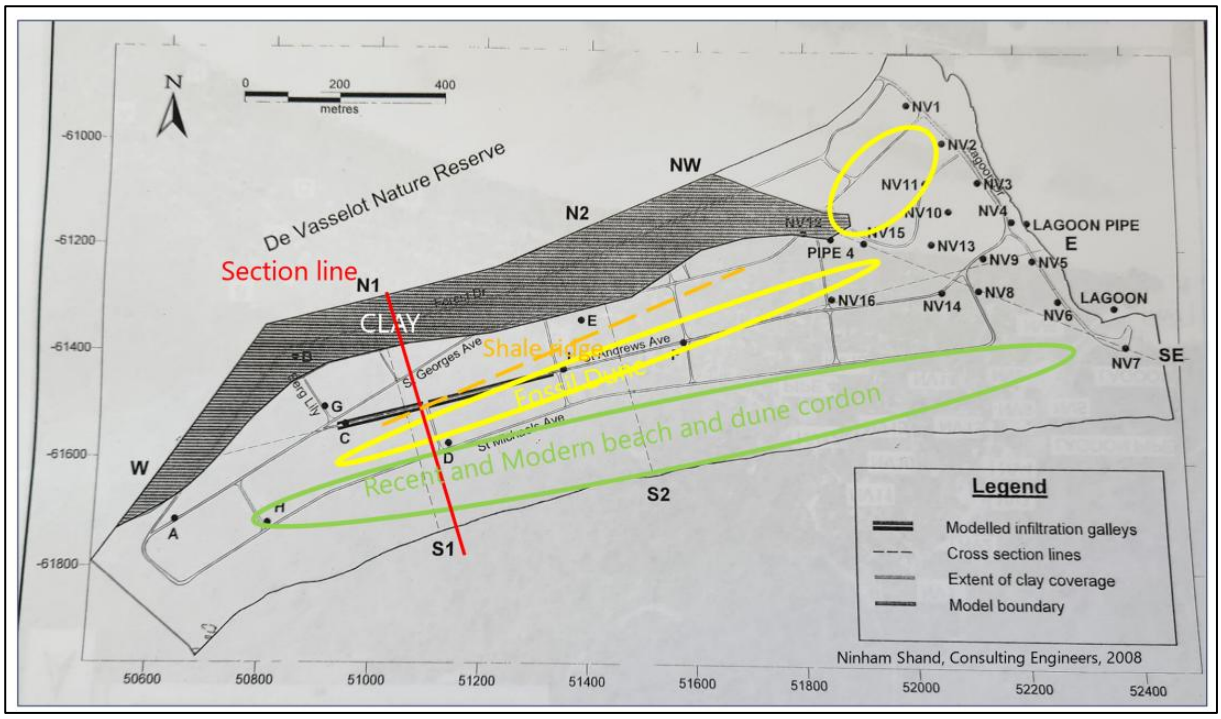


Figure 32: Cross section through the geological plan derived from drilling conducted by Ninham Shand in 2008

[3] The shale ridge is evident in-house foundations on at least two sites (239, 240) along St. George's Avenue.
[4] Clay forms an impervious layer, inhibiting the percolation of outfall from septic tanks and soak-aways in certain areas in Nature's Valley, hence the municipality's insistence on the installation of conservancy tanks in affected areas.

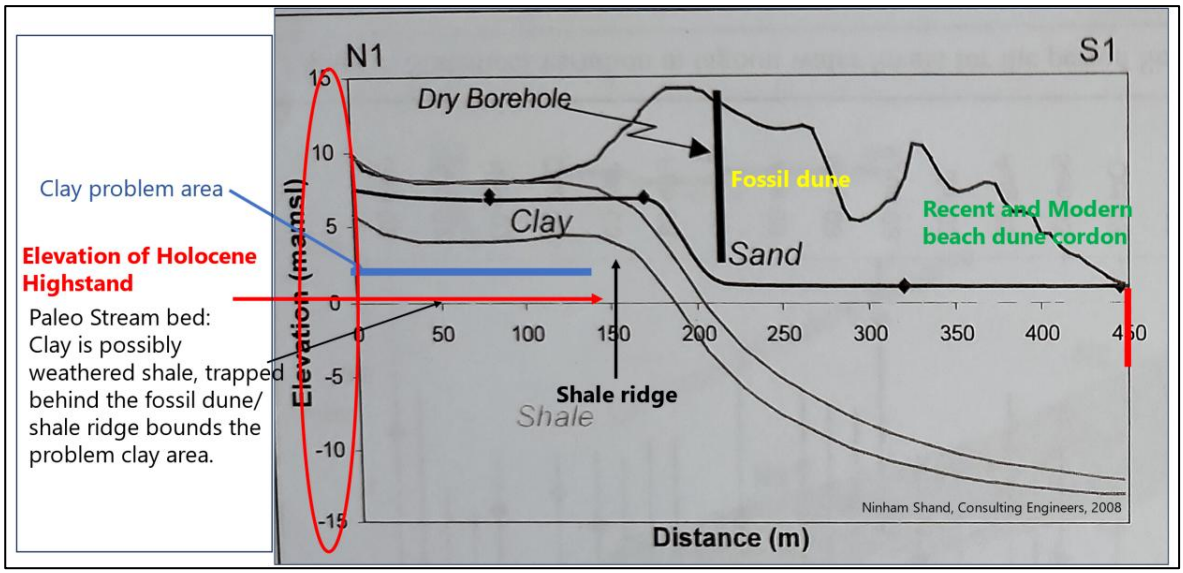


Figure 33: Confines of the clay layer as determined by Ninham Shand in 2008

Also noteworthy is that "modern" and "recent" dune cordons have developed between the current beach and the "fossil" dune as is evident from the current geological map of Nature's Valley (**Figure 34**).

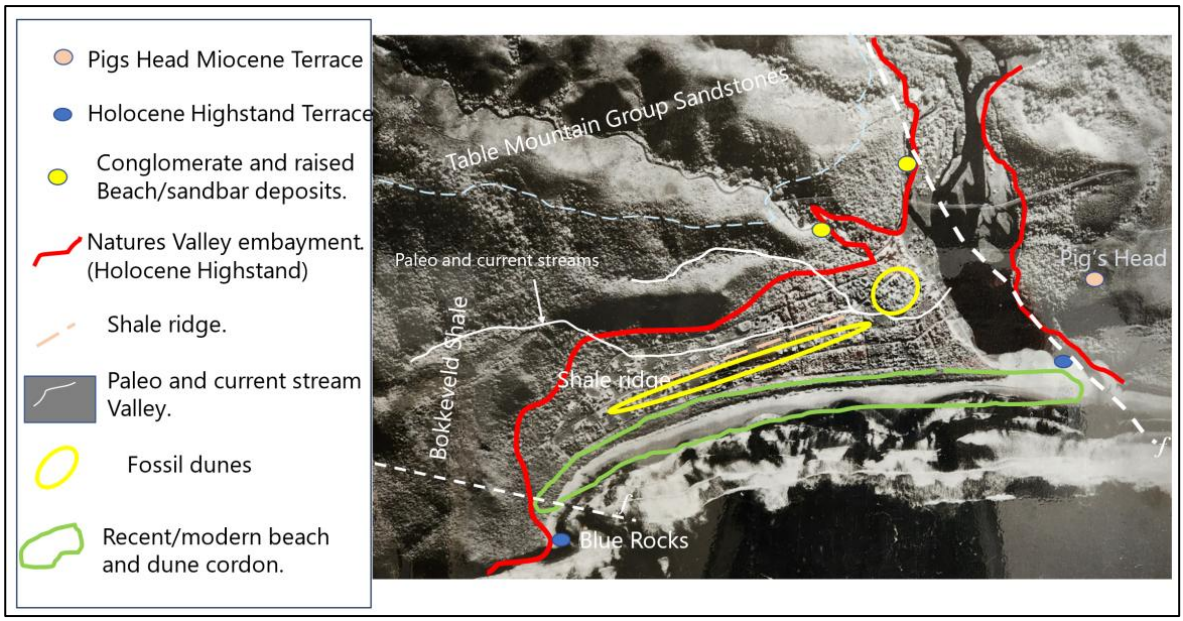


Figure 34: Nature's Valley: Current geological map

By way of conclusion

Many of the features that serve as a record of the long history of the "rocks" around Nature's Valley are evident today. To really get to grips with the valley's astounding geographical history, it might be advisable to also take a look at the video recording of this presentation available at https://youtu.be/YWB6kE5-oHI as well as a presentation on the same subject delivered to the Overberg Geoscientists Group available at www.youtube.com/watch?v=O32eWDVm0fU&t=206s.

Also, apart from the sources cited in this contribution, consider paying a visit to geologylearn.blogspot.com to learn more about folds and foliations as well as https://www.e-education.psu.edu/earth107/node/1496 to get to grips with the impact sea levels had over the past 200,000 years.

As far as extra reading is concerned, the book titled *The story of earth and life: A southern African perspective on a 4,6 billion year journey* by Terence McCarthy and Bruce Rubidge is a must-have for anyone with a keen interest in earth science.

Acknowledgments

It took me a mere 40 years to get round to presenting my liberal interpretation of the area's geology based on several observations in and around Nature's Valley.

Thank you to all contributors (named or not) who had a hand in the content of this story and to those (both professional and lay-persons) who did their utmost to help polish the final presentation.

I apologise for any unintentional distortion of the material contributed, be it visual or otherwise.

I must also thank Prof Hendri Coetzee who gave the final "push" by inviting me to talk about the geology around Nature's Valley.

Forty years on, now through the eyes of a retired mineral exploration geologist that has time on his hands, I think I might just have succeeded in "connecting the dots".

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The remarkable legacy of a young Swedish explorer: Johan Fredrik Victorin

Although Johan Fredrik Victorin was only 24 when he died in 1855[1], his name lives on in and around Nature's Valley. He spent 16 months of his short life in the southern Cape[2] and some of this time around Nature's Valley, more specifically in the Sout River area.

Victorin was a student of natural history at Linnaeus' Uppsala University in Sweden and returned from the Cape with a collection of 83 mammals (30 species), 517 birds (153 species)[3] and 20 amphibians (14 species). Victorin prepared and preserved his own specimens. He also collected 31 bird eggs (11 species), some two-thousand insects, several shells and other invertebrates as well as plants, seeds, bulbs and lichens[4]. Twenty-four species from his collection were new to science, including one that was named in his honour: *Pentatoma victorini,* a forest shield bug found in the Tsitsikamma. Generally, his specimens were well prepared and his descriptions meticulous. He stuffed around six birds a day. Most of his collection is housed in the Royal Swedish Academy of Sciences which became the Swedish Museum of Natural History.

On arrival in the Cape, Victorin was hosted by the Swedish Consul Jacob Lettersetdt at his estate Mariadal[5]. Lettersetdt introduced Victorin to another Swedish botanist Johan August Wahlberg[6] who convinced Victorin to go up to "Neysna" (i.e. Knysna), "*a splendid region, rich in birds and animals of many varied species*".

On Wahlberg's recommendation, Victorin sailed via Mossel Bay to the Garden Route and did his first hunt nearby on 11 March 1854, which he referred to as his "*first one in Africa, because the Cape is not Africa*".

[1] Victorin was born on 24 February 1831 in Kristberg, Sweden and died there on 3 November 1855.

[2] Victorin docked in Cape Town on 11 November 1853 and left South Africa on 18 March 1855, about ten months prior to his death.

[3] Victorin's collection included about one in five species of birds found in the Western Cape.

[4] His collection of lichen was not surprising as Victorin was the grandson of JP Westring (1753-1833), early lichen expert and author of *Svenska Lafavrnes Farghistoria* ("The colourful history of Swedish lichens"), an early textbook on them. Specimens of ten species collected by Victorin remain in the Swedish Museum of Natural History, including *Chrysanthemoides monilifera* or Bitou bush, commonly found near Nature's Valley and now largely considered an invasive species in Australia.

[5] Jacob Letterstedt (1796-1862) arrived in Cape Town to work as a gardener for the Newlands widow, Maria Dreyer. They ended up marrying and around the time of Victorin's arrival in the Cape, Jacob built the Mariendahl Brewery in Newlands, naming it after his wife. Their daughter, Lydia, and her husband leased and later sold the brewery to Anders Ohlsson. South African Breweries (SAB) purchased Ohlsson's Cape Breweries in 1956. The original Mariendahl Brewery and original cellars are now a well-preserved heritage building and serve as the "heart" of the operation and home to the craft brewery, Newlands Spring. Lettersetdt lives on through the Letterstedt Association (which still promotes Nordic cooperation and to which he donated most of his fortune) as well as through Jacob's Pale Ale (made by what is now known as Newlands Brewery).

[6] Johan August Wahlberg (1810-1856), who explored much of present-day Namibia and Botswana, was honoured by having four bird species (including *Aquilia wahlbergi* or the Wahlberg's eagle), a frog, a tree and four lizard species named after him. Sadly, he was elected to the Royal Swedish Academy of Sciences in October 1856 before news of his death had reached Sweden: An elephant killed Wahlberg in the Okavango in March 1856. Wahlberg is the only person to be honoured in this way posthumously.

The first bird he recorded seeing is the Knysna turaco[7], but he considered the secretary bird[8] finer and both the "golden cuckoo"[9] and the "black sugarbird"[10] being the most beautiful. The first animal he mentioned was a bluebuck[11], which he shot on 7 April 1854.

On 11 June 1854, Victorin proclaimed: "*Now I have seen a real African forest*." And it is no surprise that the yellowwood is the first tree he refers to, but this turned out to be the Breede River yellowwood[12] rather than the real yellowwood[13] or the Outeniqua yellowwood[14].

Victorin suffered (and eventually died) from tuberculosis and came to the area for health reasons. Remarkably, his health problems seemed to have 'dissipated' during his visit to the area: "*I feel as well as possible, and like it here better than possible, if there is such an expression…*" On many an occasion, he also commented on the clear air, the beautiful landscape and the awe-inspiring, rose-coloured sunsets: "*… the clear air of the South, fresh and just warm enough and an extremely beautiful landscape. The evenings are especially pleasant.*"

He was also most pleased with the fact that "*there are no more dangerous things here than in Sweden. There are no lions ... nor any hyenas. Just the occasional leopard called 'Tiger' occurs, some few jackals and a small kind of wolf*[15]*. The only beasts of prey that occur here are small, that the two species of 'Mousehounds'*[16] *and 'Bush cats'*[17]*. Elephant and buffalo occur not so seldom ... further inland, in the impenetrable forests; but the road there is so difficult that they are not hunted as the cost of bringing them out would exceed the value of the whole animal*[18]*."*

Victorin compared his trip to that of Wahlberg's (especially to the big-five territory around Lake N'Gami [Botswana]) and wrote: "*Such adventures could not happen to me. I do not know of any dangers except being bitten by a poisonous snake, which is a rare occurrence*."

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[7] *Corythaix albocristatus*

[8] *Gypogernus serpentarius*

[9] *Chrysococcy cupreus* (African emerald cuckoo)

[10] *Chalcomitra amethustina* (Amethyst sunbird)

[11] Blue antelope (*Hippotragus leucophaeus*) are extinct but lived in South Africa until the 1800s. It was smaller than the other two species in its genus *Hippotragus* (roan and sable). Hunted by Europeans, the bluebuck became extinct around 1800. As early as 1774, the Swedish explorer Carl Peter Thunberg (1743-1828) noted that bluebuck were rare. The German biologist Hinrich Lichtenstein (1780-1857) claimed that the last bluebuck had been shot either in 1799 or 1800. Given the timeline, it is possible that Victorin might or might not have been one of the last hunters of bluebuck. Irrespective, the bluebuck was the first recorded species of large African mammals to face extinction. Only four mounted skins remain in museums in Leiden, Stockholm, Vienna and Paris, along with horns and possible bones in various museums.

[12] *Podocarpus elongatus*

[13] *P. latifolius*

[14] Afrocarpus *falcatus*

[15] It is not certain which animals were being referred to as wolves do not occur in the region. It might have been the African wild dog (*Canis pictus*).

[16] *Herpestes paludinosus* (Marsh mongoose) and *H. pulverulentus* (Cape gray mongoose)

[17] *Viverrra genetta* (Common genet)

[18] Thomas Baines (1830-1893) opened the "impenetrable forests" with the completion of the Prince Alfred, Grootrivier and Blaaukrantz passes in 1867, 1880 and 1880 respectively. The lions and buffalo have disappeared.

Despite the lack of 'threats', Victorin called the fire that occurred around the Sout River on 16 July 1854 "*one of the most ghastly sights*" he had ever seen "*These fires,"* he wrote, "*are started to burn small thickets of heath, Proteaceae and such things, together with old grass and at the same time to fertilize the ground. (The forests do not suffer from the fire, as they are green and juicy.)*"

As good-natured as he might seem, Victorin's writings do include some rather gruesome details as to how he spent his time in the Cape: "*… on 7-8 May I shot my first nightjars*[19]*...on 10th I shot a particularly fine kind of falcon*[20]*... on 11 May I killed the first owl*[21] *worth stuffing*". Luckily, this 'killing spree' seemed to have dissipated by the time he reached the area around Nature's Valley. Possibly this was because, as he put it, "*the birds at Plettenberg Bay are almost the same as in the neighborhood of Knysna; but the wealth of species does not appear to be so great. The same Kingfishers are there. On the other hand, sea birds are rare, with the exception of Larus fuscus*[22]."

On 13 July 1854, he recorded his first clear reference to the Nature's Valley area: "*On the 5th of this month, in the afternoon, I took my gun and went out for a while, and although it was late and windy and rainy, I still had the pleasure of shooting a bushbuck. I tied its legs together and hung it over the gun on my shoulder – to look as a hunter should – and walked homewards. Now it was raining, so I found it necessary to wind paper around the gunlocks. Just when I was about to cross the Salt River – a stream at which Erik Sutherland's Place is situated – I saw something swimming in it. I immediately bent down and hardly had time to relieve my gun of its burden and to remove the paper before a wild duck*[23] *came within range. I shot, and was not surprised when I did not hear the bird fly away. It was dead*."

His collection continued to grow with the addition of bats[24] and "Haddidow"[25] from the area and specifically mentioned: "*On the 9th* [August 1854] *when I was out with the gun in the afternoon and came to the Salt River, I saw something big moving on the hill on the other side, but what it was I could not see before I got there and climbed the hill. All at once I had a secretary bird in sight and within good range. It stood with its head towards me and appeared quite out of its mind. I shot, the bird flapped its wings and then fell backwards. In its crop I found a couple of musky smelling shrews*[26]*, quite unharmed, and some lizards and snakes.*

"As I continued walking, I heard the well-known call of some monkeys (Cercopithecus)[27]*, and got so close that the poor beggars had no time to climb down from the yellow-wood tree, according to their habit, and to hide in some bushes or elsewhere. After much wasting of time and three shots, I at last killed one, but to get it down turned out to be impossible*.

[19] *Caprimmulgus atrovarius* (Fiery-necked nightjar)
[20] This turned out to be a black-winged kite (*Elanus melanopterus)*
[21] Confirmed to be an African wood owl (*Strix woodfordii*)

[22] Ironically, *Larus fuscus* is the lesser black gull that does not occur in southern Africa, let alone South Africa. It does, however, share a lot of similarities with the kelp gull [*Larus dominicanus*].

[23] *Anas sparsa* (African black duck)

[24] *Pteropus hottentottus* as per Grill's translation (1968)

[25] *Bostrychia hagedash* (Hadada ibis)

[26] *Sorex cafer* as per Grills' translation (1968)

[27] *Chlorocebus pygerythrus* (Vervet monkey)

"*On 24 August I was out with the gun as happens almost every day, except Sundays. I happened to get away far from home and did not return until was getting dark. As it was high water and spring tide, I had to make a detour across the Salt River, which lead me through a lot of mud holes. Muddy to above the knees, I had at least reached the other side, when I heard a splashing down the river. As I suspected that it might be an otter, and I knew that the side where I was flat and without any bushes, I could not approach on that side, but had to wade through the river and mud again, where the water reached halfway up my legs. At last, after much trouble, I reached the place and saw to chagrin that it was too dark, not only to shoot, but also to be able to see anything at all. However, I found just a few cows or oxen walking in the water, instead of an otter. Vexed, I had again to wade through all the mud and walk across the 200-300 feet high hills, as the water was so high and I could not walk along the beach. I came home at 8pm, quite exhausted*.

"*On 1 September, a very cold and frosty morning, I came upon an eagle's nest. As I had earlier been crawling after one of the sea eagles*[28] *which had been sitting in a dead tree, the gun was loaded with the right charge, because these birds are specially hard to kill. At the same moment as I saw the nest, I also saw one of its occupants standing in it, so I raised my gun and shot. Two of the beasts flew out and a loud splashing told me that I had not missed. When I came there I found my lord eagle sitting on a dead tree stump, which was quite close to the bank. As the bottom was muddy and swampy and an eagle is not to be trifled with, I sent it some small shot out of my second barrel, which did not harm it at all, but only made it flap its wings and come ashore, where I went for it, hit it to the ground with my fist and with the other hand I grabbed its neck. With my one knee on its back I could hardly hold it until it suffocated*."

From his writings, it is clear that Victorin collected/killed at least a bluebuck (perhaps the last?), a secretary bird, a hadada ibis, a vervet monkey and a fish eagle in the area around Nature's Valley. However, his last kill in the area is the one that lives on:

"*On the 8th of this month* [i.e. September 1854] *I went out early in the morning and shot many smaller birds, among them is a new species to me*."

That species turned out to be the Victorin's warbler (*Cryptillas victorinii)*.

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[28] *Icthyophaga vocifer* (African fish eagle)



Photo courtesy Sky Beveridge



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