Wardanaak Boodjar ‘The Flood’: Connecting the Submerged Landscapes and Subaerial Archaeology of the Swan Coastal Plain

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Abstract

Aboriginal people have occupied southwestern Australia for at least the last 48 ka. Since that time, 2.12 million km^2 of the continental land mass of Australia has been inundated by sea-level rise. Much of this submerged landscape is believed to have been inhabited by people. Where cultural material has survived transgressive events, it has the potential to offer insights into past strategies of occupance and resource usage. However, given the vast scale of inundation, the question remains: how to locate submerged landscape sites on the continental shelf? Recent investigations on Western Australia's northwest shelf have demonstrated that in situ archaeological sites can survive the often-destructive effect of marine inundation, establishing the beginnings of an 'Australian Model' of practice for submerged site detection. This thesis adopts the Australian Model and tests its applicability in a different environmental and cultural region of Australia, specifically, the Rottnest Shelf, being the area of the southwestern continental shelf adjacent to the Swan Coastal Plain. The focus of this study is therefore the development of a method for the identification of areas on the continental shelf adjacent to the Swan Coastal Plain that have high preservation potential for submerged archaeological sites. In the absence of known submerged sites on the southwest shelf, terrestrial analogy is used as the basis for a Geographic Information Systems predictive model for the identification of areas of high preservation potential. This study comprises a critical review of the subaerial archaeological record of the Swan Coastal Plain to establish site-landform associations as the basis for terrestrial analogy. It also includes an identification of the physical processes affecting the topography of the Swan Coastal Plain and Rottnest Shelf to understand their potential impact on submerged site preservation. A Digital Relief Model is created, using topographic data of the Swan Coastal Plain and bathymetric data of the Rottnest Shelf, to locate and map submerged landforms with a high probability of site association. The results illustrate how the modern physical environment and regional archaeological record of the Swan Coastal Plain can help to identify areas of high preservation potential in the search for the submerged cultural heritage of southwestern Australia's first peoples.

Student Declaration

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that, to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where due reference is made in the text.

Marcel Seeman Teschendorff

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1 Introduction

For most of human history, and for a substantial portion of the human occupation of Australia, sea level was markedly lower than it is today. Post-glacial sea-level rise following the peak of the Last Glacial Maximum (**LGM**) c.25–18 ka, when sea levels were -130 m lower than their present position, would have drowned approximately 2.12 million km^2 (Wiseman et al 2021:152). This transgressive event would have greatly impacted Australian Aboriginal people, as Sahul (Australia) lost 23 percent of its mostly habitable landmass. Although the archaeological potential of continental shelves has been long acknowledged (Goggin 1960:351–352; Reid 1913), the study of Australian continental margins is still relatively nascent and a clear overview of the pre-European archaeological record in southwestern Australia is inherently hindered by an incomplete data set.

Aboriginal people have inhabited southwestern Australia for at least 48 ka (Dortch et al. 2019; Turney et al. 2001) and would have occupied the now submerged continental shelf. Submerged landscape investigations are therefore essential to the 'understanding of the first peopling of Australia, the pattern of settlement of the continent, the use of coastal resources and ancient maritime economies, and adaptation to rapid climate change' (Wiseman et al. 2021:152). Seminal work has, and is, being conducted in the Western Australia's northwest, where the first confirmed underwater sites on Australia's continental shelf were recently located (Benjamin et al. 2020). Despite several attempts (Dortch 2002b; Dortch and Dortch 2012; Flemming 1986; Nutley 2014; Nutley et al. 2016), no other Aboriginal sites have been identified in situ on the continental shelf. However, both Nutley (2014) and Dortch (2002b) have highlighted the need to identify and locate the submerged landforms that are associated with human occupation to progress submerged landscape research and site identification.

This study adopts the method of terrestrial analogues (Veth et al. 2019) as a basis for the development of a predictive model for the identification of areas of high preservation potential for submerged landscape sites on the continental shelf adjacent to the Swan Coastal Plain (**SCP**). The terrestrial archaeological record of Aboriginal people who inhabited the SCP is critically analysed to identify patterns of site distribution in relation to landscape features. To identify these landscape features in a submerged context, a Digital Relief Model (**DRM**) is constructed using a combination of topographic and bathymetric data from the study area. This DRM is used in conjunction with the results of a detailed desktop survey of local geomorphology, to better understand the taphonomic processes on the submerged shelf and to outline areas of high preservation potential for submerged landscape sites.

1.1 Research Question, Aims, and Objectives

1.1.1 Research Question

There is now broad acknowledgement that past coastal zones in southwestern Australia were inundated during the Late Pleistocene and Early Holocene. However, important questions remain: where were the human occupation and activity (cultural) sites, now offshore, originally located? Will such inundated cultural sites be preserved underwater, available for archaeological study? To evaluate these questions, we must begin with existing knowledge and a fundamental, underlying question: **How can the terrestrial archaeological record and modern landscape of the SCP inform the search for submerged archaeological sites on the adjacent continental shelf?** The latter forms the basis for this study as the central question and focus of this thesis.

1.1.2 Research Aims

This research aims to contribute to the nascent and emerging discourse of submerged landscape studies in Western Australia. This study also aims to develop a new method for the identification of areas on the continental shelf adjacent to the Swan Coastal Plain that have a high preservation potential for submerged archaeological sites.

1.1.3 Research Objectives

In order to address the research question and aims, the objectives of the study are to:

- Critically review the terrestrial archaeological record of Aboriginal people who inhabited the SCP to identify patterns of site distribution in relation to landscape features;
- Evaluate the topography of the SCP and the adjacent submerged continental shelf, to identify and discuss the physical landscape processes that have affected this topography throughout the last 50 ka;
- Identify areas of high preservation potential for submerged landscape sites on the continental shelf adjacent to the SCP, informed by the results of the desktop survey, landscape modelling, and terrestrial site patterning; and
- Present recommendations for future archaeological investigations on the SCP and adjacent continental shelf.

1.2 Study Area

The proposed study area for this investigation is the SCP and the adjacent submerged continental shelf: the Rottnest Shelf (Figure 1). The Aboriginal people of South Western Australia are the Noongar (also: Nyoongar / Nyungar) people. The SCP sits within Noongar *Boodjar* 'country,' specifically, within Whadjuk *Boodjar*. The extent of the SCP is defined in this study according to the Interim Biogeographic Regionalisation for Australia (**IBRA**) (DAWE 2020). The SCP is intersected at a central point by the Swan River Estuary, which acts as an informal borderline between the Northern SCP and the Southern SCP.

The SCP and the adjacent Rottnest Shelf are proposed as the study area because no archaeological investigations of this nature have occurred in this area thus far; there is a rich terrestrial archaeological record; and the area holds many unique marine environments. Importantly, there is also publicly accessible bathymetric data available for this area that can be used to model the near-shore submerged landscape and allow direct comparison between offshore and onshore contexts.

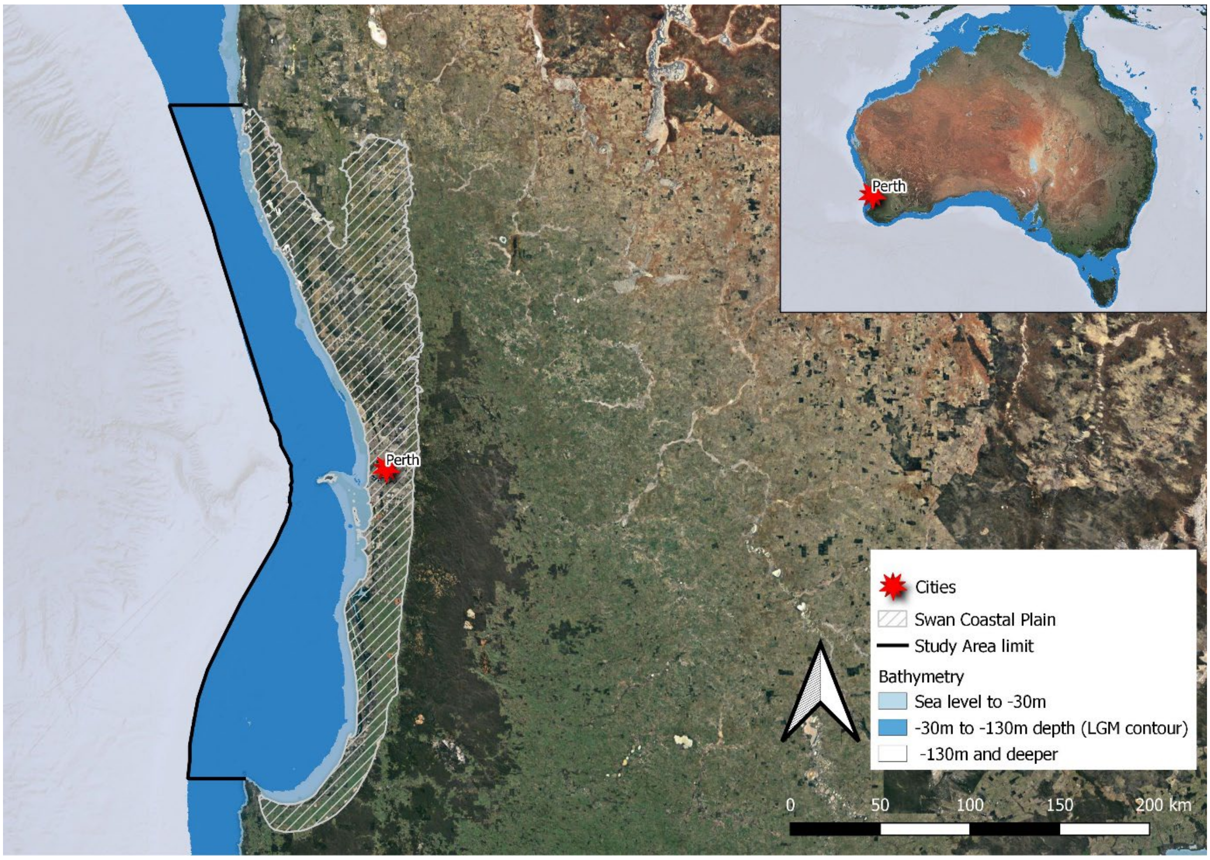

Figure 1: The SCP and adjacent Rottnest Shelf (coloured blue). Satellite imagery: ©2022 Google.

1.2.1 Tectonic Setting

The SCP is situated on a passive continental margin and within the Perth Basin, a vast, diverse sedimentary basin that extends onshore to the Darling Fault and offshore to the Perth Abyssal Plain, encompassing the now-submerged palaeo-coastal plain (Richardson et al. 2005:11; Stagg et al. 1999). The Perth Basin can be separated into four sub-basins (Figure 2). The varying tectonic structures of these sub-basins can influence the formation and spatial distribution of seabed features (Bradshaw et al. 2003). The smallest sub-basin, the Abrolhos Sub-basin, extends 15,200 km^2 and is of the most significance to submerged landscape investigations, ranging 0–300 m of water depth.

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Figure 2: The four sub-basins of the Perth Basin: 1) The Houtman Sub-basin is 52,900 km^2 between depths of 100–3,500 m; 2) the Vlaming Sub-basin is 19,200 km^2 between water depths of 0–3000 m; 3) the Zeewyck Sub-basin is 15,400km^2 between water depths of 1000–5000 m; and 4) the Abrolhos Sub-basin, is 15,200 km^2 between water depths of 0–300 m (Richardson 2005:13).

1.2.2 Geomorphology

The SCP features a succession of north-south trending dune systems (Figure 3). These dunes form a chronological sequence; the coastal Quindalup Dunes being the youngest, followed by the Spearwood Dune system, and the Bassendean Dune system being the oldest (McArthur and Bettenay 1974; Playford et al. 1976:25–29). While it is commonly accepted that these dune systems began as aeolian and marine sand dunes (Mory and Iasky 1995), debate remains ongoing as to their exact relationship (Bastian 2010; Hearty and O’Leary 2008).

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Figure 3: Geomorphic elements of the SCP: Quindalup Dunes (Q), Spearwood Dunes (S), Bassendean Dunes (B), Pinjarra Plain (P), Ridge Hill Shelf (R) (after McArthur and Bettenay 1960:18–19).

The Quindalup Dunes formed directly on the coast as sea levels stabilised and are composed primarily of Holocene white shelly sands that overlie Tamala Limestone (Dortch and Dortch 2019:15; Monks 2018:48). The Spearwood Dunes are characterised by yellow quartzo-calcareous sands and are also underlain by Tamala Limestone, a major lithostratigraphic unit that formed during the mid to Late Pleistocene (Playford et al. 1976). This limestone is typically karstic, containing cave systems, channels, and cliffs resulting from marine erosion. The Bassendean Dunes are characterised by weathered, heavily leached, grey and yellow sand (McPherson and Jones 2005; Mory and Iasky 1995; Playford and Low 1972). Between the Darling Scarp and the Bassendean system lies the alluvial Pinjarra Plain (McArthur et al. 2004). An idealised representation of SCP geomorphology can be seen in Figure 4.

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Figure 4: Idealised representation of the SCP. Note the Tamala limestone underneath the Quindalup and Spearwood dune systems (Semeniuk and Semeniuk 2012:51).

1.2.2.1 The Rottnest Shelf

The continental shelf adjacent to the SCP is named after Rottnest Island, which it surrounds (Collins 1988; Playford 1997). The Noongar name for Rottnest Island is *Wadjemup*, a name that was recorded by Lyon (1833:64) during the initial years of European colonisation. The Rottnest Shelf ranges from Cape Leeuwin in the south to the Houtman Abrolhos Islands in the north (Carrigy and Fairbridge 1954). It is narrow and incipiently-rimmed, possessing a complex bathymetry with barrier dune systems and remnant palaeoshorelines presenting as shore-parallel ridges and reefs that show traces of subaerial erosion (Richardson et al. 2005:11–37). A variety of geomorphic features exist on the Rottnest Shelf (Table 1). The present-day islands and limestone reefs of the Rottnest Shelf are remains of the coastal dune barrier system, which, during glacial periods formed the seaward edge of an exposed sand plain (Brooke et al. 2010; Playford 1997; Semeniuk 1996).

Table 1: Rottnest Shelf geomorphic features (Richardson 2005 after Harris et al. 2005).

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* *These surface area measurements do not include the area of superimposed features.*

The Rottnest Shelf can be sectioned into three main bathymetric regions: 1) the Inner Shelf up to 100 m depth, where submerged remnant palaeoshorelines developed during periods of subaerial exposure; 2) the Outer Shelf, which extends to 170 m depth and the edge-slope break; and 3) the Upper Continental Slope (Collins 1988). In describing the attributes of the shelf, it is often divided into halves, the intersection occurring at the mouth of the Swan River Estuary and running west to the Perth Canyon (32°S) (Collins 1988; James et al. 1999; Richardson et al. 2005).

Collins (1988) further divided the southern shelf into four sections according to depth: 1) From 0–20 m depth containing nearshore reefs, ridges, topographic highs, and depressions between. The irregular topography and near shore reefs provide shelter from wave energy and results in the development of protected beaches together with cuspate headlands and tombolos (Sanderson et al. 2000). 2) The inner shelf from 20–48 m depth, featuring the Fremantle Blanket sediment unit. 3) From 48–60 m depth, where remnant palaeoshorelines present as shore-parallel ridges that extend across the extent of the shelf (Brooke et al. 2010, 2014, 2017); and 4) the outer shelf, which stretches steeply from 60 m to 200 m, where the shelf-slope break is located. James et al. (1999) described the geomorphology of the northern Rottnest Shelf and found it to be similar to that of the southern shelf.

Holocene sediment bodies on the nearshore shelf are sheet-like and unevenly shaped, ranging from a metre to 40 m thick (Collins 1988; James et al. 1999). Generally, sediment occurs as ‘thin discontinuous sheets’ (Richardson et al. 2005:27); where Pleistocene limestone occurs as a substrate, overlying sediment forms in thin veneers of less than a metre (Richardson et al. 2005:29). The gently sloping, smooth inner shelf plain features the Fremantle Blanket sediment unit, a discontinuous, thick sediment blanket that was deposited at depths of 20–90 m (Collins 1988). The Rottnest Blanket, a thin sediment blanket comprising skeletal grains, was deposited at depths of 90–430 m and overlies the Outer Shelf, extending across the continental slope. Surface sediments are generally composed of carbonate bioclasts; however, terrigenous components can dominate nearshore areas, particularly when adjacent to large river mouths (Collins 1988:29; Richardson 2005:26-27).

During periods of lower sea level, Aboriginal people would have had access to an emergent coastal plain that extended more than twice its current width. Evidence of access to this sandplain is provided by several artefacts found on Rottnest and Garden Islands, including in situ, dated flaked stone artefacts identified in palaeosols on Rottnest Island (Figure 5) (Dortch and Dortch 2019:15). Rottnest’s pre-island locality would have provided a freshwater source (Backhouse 1993), and topographic high point, a few kilometres south of where the ancestral Swan River would have flowed through the exposed coastal plain (Playford 1983:14).

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Figure 5: Block cut from calcrete palaeosol containing an in situ Eocene fossiliferous chert flaked piece (Dortch and Dortch 2019:23).

1.2.3 Regional Setting and Climate

Southwestern Australia and the SCP feature a Mediterranean-type climate. Regional rainfall patterns follow a dry-summer, wet-winter pattern, with precipitation greatest in the far southwest (Figure 6) (Hopper and Gioia 2004). The onshore sand plain surrounding the Swan River Estuary is marked by a network of freshwater lakes and wetlands, which would have provided a rich supply of resources to Aboriginal people inhabiting the region (Hallam 1987). Pollen sequences from the central SCP suggest that melaleuca-fringed wetlands persisted throughout the Late Quaternary, along with banksia, casuarina, and eucalypt woodlands (Backhouse 1993; Newsome and Pickett 1993; Pickett 1997). Environmental records also suggest the Mediterranean climatic conditions that occur in the SCP have been stable for at least the Late Holocene (Bates et al. 2008; Raut et al. 2014; Semeniuk and Semeniuk 2012; Timbal et al. 2006).

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Figure 6: Rainfall regions in southwestern Australia (Monks 2018:44 after Hopper and Gioia 2004:630).

The Early Holocene and Late Pleistocene would have seen fluctuations in climate and current. For example, the Leeuwin Current, which flows southward from the tropics, was weakened during the LGM (Feng et al. 2003; Spooner et al. 2011; Wyrwoll et al. 2009) while the Western Australian current, which flows northward from the Southern Ocean, was likely strengthened (Spooner et al. 2011). These changes would have led to cooler near-shore temperatures in coastal waters and a regional decline in precipitation, affecting resource availability and reliability during these periods.

The dynamic shoreline and changing climate during the Late Pleistocene and Early Holocene would have also seen vegetational transitions as the emergent coastal plain expanded during the LGM. Picket (1997) has determined vegetation change from pollen sequences; while the location and extent of certain vegetation systems across the SCP may have varied throughout the Late Quaternary according to climate fluctuations, exploitable habitats would have persisted and been available to people during periods of shoreline variation (Backhouse 1993; Pickett 1997; Semeniuk and Semeniuk 2012).

1.3 Significance

Submerged landscape investigations along the continental shelf of the SCP have the potential to answer important archaeological questions relating to patterns of occupance and resource use on the SCP (Dortch and Dortch 2019; Hallam 1987; Monks 2021). Answers to these questions can contribute to the development of models of continental colonisation (Bird et al. 2016; Crabtree et al. 2021; O'Connell and Allen 2015) and/or long-distance trade routes (Bird et al. 2021; O'Leary et al. 2017; Ward et al. 2019, 2021). From a methodological perspective, this study can also help to develop a discipline in its neonatal stages in southwestern Australia while providing a platform for the further testing of predictive models as a framework for submerged site detection (Wiseman et al. 2021). The applicability of submerged landscape studies to high energy, open coastline also has international implications (Masters 2010), and the southwestern coastline of Western Australia offers a suitable case study.

An investigation into the submerged landscapes of the SCP also provides benefit to stakeholders involved in proposed Western Australian offshore development, for example, the WA Offshore Windfarm development (Figure 7) (WA Offshore Windfarm 2021). Such an investigation can stimulate further discourse and collaboration with industry, allowing improved sharing of data, and leading to better identification, documentation, management, and regulation outcomes for all stakeholders (Ward et al. 2018).

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Figure 7: The location of the proposed windfarm development on the inner Rottnest Shelf (WA Offshore Windfarm 2021).

1.4 Limitations

The first limitation of this study relates to processing power available for Geographical Information System (**GIS**) based landscape modelling. Available computer hardware limited the resolution output of raster models. As such, the methods outlined are tested as a proof of concept, able to be replicated using the same or additional data inputs. Other limitations of this study relate to accessibility of (environmental and cultural) data, scope, and accuracy.

Regarding accessibility, this study is limited by access to appropriately high-resolution bathymetric data for the Rottnest Shelf. Where this data was not available, detailed analysis was not undertaken. Cultural data used for modelling is limited to publicly available sources (DPLH 2022). As such, the exact location and extent of some included Aboriginal heritage sites is approximate, maintaining their confidentiality. In these instances, a general location has been obtained (DPLH 2022).

Regarding scope, only regional environmental data is utilised for the interpretation of the submerged continental shelf. As such, this study is inherently generalised; understanding that such palaeoenvironmental reconstructions are capable of only broad generalisations about past environments (Kvamme 2006:19).

Regarding accuracy, analysis of data collected from different sources may be affected by inconsistences in collection and documentation (Jones and Gabe 2015). Data management software was utilised (Chapter 3) to limit these potential inconsistencies. It is also acknowledged that the use of terrestrial analogues has its limitations (Grøn 2018), particularly when applied to deep water contexts (Ford and Halligan 2010:278), as subaerial sites may now be located in a different context than during the period of habitation. Further, sea-level variation led to massive landscape and habitat change, potentially affecting resource availability and different patterns of settlement. Accordingly, the use of terrestrial analogues to guide underwater research is adopted based on previous submerged landscape investigations (Benjamin et al. 2020; Braje et al. 2019; Duggins 2012; McCarthy et al. 2021; Veth et al. 2019; Wiseman et al. 2021) and the current knowledge of the SCP archaeological record. Lastly, the high sedimentation rates in localised areas of the Rottnest Shelf and the generally high-energy marine dynamics within the study are acknowledged as a major limitation regarding submerged site preservation and the certainty of the hydrological modelling results. The results of hydrological modelling and subsequent areas of high preservation potential are therefore presented as a starting point based on available methods and current knowledge.

2 Literature Review

This chapter contains an examination of the theories that guide investigations of the relationship between humans and the environment. The use of terrestrial analogues as a predictive tool for the identification of submerged landscape sites on the Rottnest Shelf is also acknowledged. This chapter critically reviews the archaeological context of the SCP, focusing on identified subsistence and occupation patterns and discusses ethnohistorical records relating to sea-level rise.

2.1 Environmental Archaeology and the Archaeology of Land Use

Environmental archaeology focuses on understanding the relationship between humans and the environment (Reitz and Shackley 2012:469–473). Many aspects of environmental archaeology overlap with the study of and search for submerged landscapes, for example, taphonomic processes, geophysics, geomorphology, sedimentology and palaeoethnobotany (Cook Hale et al. 2021; Flemming et al. 2017:3; Reitz and Shackley 2012:19; Wiseman et al. 2021). Key to environmental archaeology is the reconstruction of past environments, (Dincauze 2000:20; Renfrew and Bahn 2016:223) as it is also for submerged landscape studies (Flemming et al. 2017). Indeed, Flemming et al. (2017:3) suggest that answers to the 'search for anthropogenic signals from the periods of glacial-maximum low sea levels… are not themselves directly archaeological in nature, but rather palaeoenvironmental.'

The dominant theoretical frameworks in environmental archaeology are mainly 'classified as environmental determinism, environmental possibilism, cultural ecology, human ecology, and historical ecology' (Reitz and Shackley 2012:6). Key differences between these theoretical philosophies are how important 'the internal dynamics of cultures, historical trajectories, and non-cultural biotic and abiotic factors [are considered to be] as facilitative or causal stimuli for cultural change' (Reitz and Shackley 2012:7). Environmental determinists contend that culture is a passive force; the environment determines human behaviours and cultural trends can be attributed to the characteristics of that environment (Semple 1911), whereas environmental possibilists argue that cultures are broadly the result of histories; the environment acts as a constraint on cultural and behavioural variations (Reitz and Shackley 2012:7). Both environmental determinism and possibilism are grounded in the assumption that the physical landscape is stable throughout history (Arnold 1996:4; Semple 1911:2).

The growth of processual archaeology saw the development of ecological theories that provide an alternate view on the human/environment relationship: cultural ecology, human ecology, and historical ecology (Reitz and Shackley 2012:7). Cultural ecology seeks to describe the origin of certain cultural phenomena and patterns which characterise different, specific areas (Steward 1955:36). Within the paradigm of cultural ecology, environments are believed to play an active, reciprocal role in human matters but are not deterministic (Ellen 1982:52–65, Reitz and Shackley 2012:7).

Human ecology and historical ecology expand upon the framework of cultural ecology. Human ecology employs systemic models and ecological ideas to understand and predict human/environment interactions (Ellen 1982:66, 73–79). Ecological principles, including 'populations, communities, niches, evolutionary ecology, and systems theory are important in human ecology' (Reitz and Shackley 2012:7). Systems theory proposed that humans and environments are interrelating systems, where the environment and culture are studied as an integrated whole (Ellen 1982:50: Reitz and Shackley 2012:8). Systems theory has also been argued to be ahistorical, excluding the element of human agency and choice from the landscape (Biersaack 1999; Dove 2001; Wolf 1999). Historical ecology seeks to overcome this by providing the temporal perspective of dynamic landscapes (Balée 2006; Winterhalder 1994).

Historical ecology asserts that landscapes have history; that humans are historical agents of transformation in the landscape (Balée 2006). Historical ecology questioned the idea of 'pristine primitives' (Wolf 1982) and untouched wilderness (Denevan 1992), in doing so, differentiating itself from cultural ecology. Historical ecology allows for 'landscapes [to] have history, and that natural things in given environments are historiographic indices of those environments' (Balée 2006:77). This theoretical position aligns with Hallam's (1977) 'topographic archaeology', which proposed an extension of the concept of artefact to encompass 'not only assemblages of stone tools and debris but the areas from which they come… not only fish weirs but fords, wells, and the tracks between them'. Hallam (1977:175) rejected that landscapes are static, instead, proposing a dynamic relationship between humans and environments; recognising 'the linkage of landed groups and peopled landscape.'

Hallam (1977) argued for a dynamic model of population-pattering that drew from the British tradition of landscape archaeology and geography (e.g., Fowler 1972, Cunliffe 1973). Hallam aimed to replace static models of continent-wide patterning that relied on the determinist hypothesis that tribal areas (Tindale 1940) and population density (Birdsell 1953, Stanner

1965) were directly proportional to rainfall. While acknowledging that this was true at a general level, Hallam (1977) identified that it ‘is in detail wrong.’ It was not precipitation but rather, specific resources, which supported the highest populations (Hallam 1977). Further, Hallam argued that in those areas of high population density, Aboriginal land use created a landscape that was more habitable. Consequently, high populations, and the resources that enabled them, resulted from human/environment interactions over time. As Hallam (2014:xi) put it, ‘the land the English settled was not as God made it. It was as the Aborigines [sic] made it.’ Toward understanding relationships, or patterns, between Aboriginal populations and their terrain, it is not sufficient to take the environment as static throughout time (Hallam 1977:173–175).

Hallam’s (1977) topographic archaeology and her interest in surface artefacts at a regional scale (Hallam 1972) preceded Binford’s (1982) influential ‘archaeology of place’. Binford (1982:6) was also ‘concerned with site patterning’ and suggested that in order ‘to understand the past we must understand places.’ Understanding a landscape’s past places allows a greater level of accuracy when attempting to comprehend the past processes that resulted in archaeological sites (Binford 1980, 1982). How an archaeological site is defined is not only a result of past activities but also dependent on a variety of factors such as taphonomy, visibility, legal requirements, and research design (Bird and Rhoads 2020:94). Notwithstanding the ambiguities of defining a site, all archaeological sites are to some degree ‘the fixed places in topography where man [sic] may periodically pause and carry out actions’ (Binford 1982:6). Binford (1980, 1982) believed that by understanding the distribution of past environmental variables it is possible to anticipate site-patterning in the archaeological record. The correctness with which one can give meaning to these contemporary patterns, both within- and between-place contexts, is contingent upon an understanding of the processes that bring into existence the observed patterning. With past landscapes a focus of this study, a historical ecological position such as Binford’s (1980, 1982) or Hallam’s (1977), that recognises fluid landscape change resulting from human/environment exchanges over time, is adopted here as a theoretical framework for the exploration of site patterning in the SCP relative to exploitable habitats and their associated landform features.

Binford’s (1978, 1980, 1982) exploration of hunter-gatherer land use and site formation strongly influenced Veth’s (1989, 1993) conceptual model, ‘Islands in the Interior’, which emphasised the importance of permanent water sources in assemblage composition and regional site patterning. Veth’s model provided a platform for additional predictive statements of land use and site formation in the Pilbara's Dampier Archipelago (McDonald 2015; Vinnicombe 2002). Cumulatively, these predictive statements (McDonald 2015; Veth 1993; Vinnicombe 2002) have allowed the identification of terrestrial landform features in the archipelago that are associated with the highest site densities (Veth et al. 2019:487). The use of these site-landform associations or 'terrestrial analogues' (Veth et al. 2019:484), when combined with new high-resolution technologies that allow substantially improved mapping of the seafloor, allows for the speculative extrapolation of a culture history of an area, with its attendant settlement patterns, onto an offshore setting (Benjamin et al. 2020; Braje et al. 2019; Duggins 2012; Veth et al. 2019; Wiseman et al. 2021). The use of terrestrial analogues as a predictive framework for the identification of areas of high preservation potential in an offshore environment is applied in this study as the basis for the investigation of the offshore component of the SCP.

2.2 Terrestrial Analogues: Predictive Modelling for Submerged Landscape Sites

The nineteenth century saw the onset of the first submerged landscape investigations; in the 1850s Ferdinand Keller identified a series of wooden pile dwellings in Lake Zurich, Switzerland (Müller-Beck 1961), while in 1884 divers of the Austro-Hungarian Navy assisted with the archaeological survey of the Ljubljanica River in Slovenia (Gaspari 2003). While fishing trawlers have been scraping up chance artefactual finds as far back as 1931 in the English Channel and North Sea (Spinney 2008:151), it was not until the 1950s that the systematic search for submerged landscapes became established when, in the United States, a series of studies in California and Florida 'successfully linked paleo-hydrology, relative sea levels, and changing human use of the landscape' (Garrison and Cook Hale 2021:29–30). The 1970s saw the establishment of systematic submerged landscape investigations around the world, notably in Denmark, Bulgaria, and Israel (Bailey et al. 2020), however, despite this, Flemming (2020:16) has highlighted that 'the overwhelming number of prehistoric sites reported globally have been found by chance.' Further, Bailey and Flemming (2008:2159) have noted that 'the probability of finding prehistoric materials and terrestrial environmental indicators in situ by targeted survey is inevitably low.' The use of predictive models in an offshore context aims to increase the probability of successfully identifying areas that contain submerged landscapes and associated cultural material. Benjamin (2010a:266) has suggested that with the implementation of predictive modelling in the search for submerged landscapes 'archaeologists will hopefully begin to find substantially more needles in a somewhat less-daunting haystack.'

The American continental shelf has provided several examples of submerged landscape investigations resulting in the successful identification of sites (Dixon and Monteleone 2014; Faught 2004; Fedje and Josenhans 2000; Pearson et al. 2014), that built on earlier submerged landscape investigations in North America (Dunbar et al. 1992; Gagliano 1982; Hudson 1979, Masters 1983, Murphy 1990; Josenhans et al. 1997; Ruppe 1988). In Denmark, Fischer's (1995) 'fishing site location model' has also been successful, with a purported eighty percent effective find rate. In his revaluation of the fishing site location model, Benjamin (2010a) also incorporated Ruppe's (1988:57) 'three major factors to be considered in a study of inundated terrestrial sites: sea-level change, coastal geomorphology, and coastal settlement patterns'. Benjamin (2010a:266) argued that by expanding upon the fishing site location model and adapting it for regional use 'prehistorians can improve the prospects of site discovery and investigation'.

Benjamin's (2010a) revised Danish model reignited global discourse relating to the systematic search for submerged sites (Benjamin 2010b; Faught 2010; Flemming 2010; Ford and Halligan 2010; Hale 2010; Masters 2010) and reinforced the need for archaeologists searching for submerged landscape sites to familiarise themselves with regional settlement patterns as well as local geological, geomorphological, oceanographic, and hydrological information. Specifically, Benjamin (2010a:259) highlighted the need to acquire information relating to Holocene sedimentation and coastal erosion in order to understand their potential impact on submerged site preservation. The revised Danish model provided a framework for predictive modelling reliant on terrestrial analogues in an Australian context, in particular, Western Australia's Dampier Archipelago (Benjamin et al. 2020; McDonald 2015; Veth et al. 2019; Ward et al. 2013, 2014, 2015; Wiseman et al. 2021). The resultant 'Australian Model of practice for submerged site detection' led to the first identification of in situ artefacts on Western Australia's continental shelf (Wiseman et al. 2021:168).

The success of the model in the Dampier archipelago was dependent on the analysis of a sufficient number of analogous terrestrial sites. Veth (2019:486), for example, identified 2,534 sites that have been mapped in the Dampier Archipelago. Predictive modelling in other locations that relies on terrestrial analogues will require a similarly substantial archaeological record. The terrestrial archaeological record of the SCP offers a suitable location, with 1,653 Aboriginal sites reported to the Registrar of Aboriginal sites under the *Aboriginal Heritage Act 1972* (WA). However, as Benjamin and UIm (2021) highlight, the size of the Australian continent and its varying environmental conditions mean that models should be developed at the regional or local scale to be most effective. The methods that have been successfully implemented in the Dampier Archipelago (Benjamin et al. 2020; Veth et al. 2019; Wiseman et al. 2021) are therefore recognised here as a useful starting point that can be adapted for the archaeological and environmental context of the SCP.

2.3 Archaeological Context of the Swan Coastal Plain

Southwestern Australia has been inhabited for at least 48 ka (Turney et al. 2001). Artefact horizons buried in sand dunes and river terraces on the mainland, and dated isolated artefacts on Rottnest, Garden and Carnac Island indicate that the SCP has been inhabited for at least 40 ka (Pearce and Barbetti 1981; Dortch 1991; Dortch and Dortch 2019; Dortch and Morse 1984; Schwede 1990; Ward 2016). Poor organic preservation in the SCP, however, means that there is relatively limited archaeological evidence relating to occupance and resource usage, compared to the more southerly regions that contains numerous stratified cave deposits (Balme 2014; Monks 2021; Schwede 2011; Turney et al. 2001). Datable, sub-surface assemblages do exist, notably in the Northern section of the SCP, within cave deposits (Archer 1974; Dortch 2004; Hallam 1974; Monks 2018; Monks et al. 2016) and shell middens (Dortch et al. 1984; Monks et al. 2015; Morse 1982). Some of these stratified sites, such as Walyunga, demonstrate repeated habitation within areas of the SCP throughout the Holocene (Pearce 1978). Other sites date to the Pleistocene, including a select number of sites that have pre-LGM dates such as the 38 ka Upper Swan (Pearce and Barbetti 1981) and 29 ka Helena River (Schwede 1983) sites. SCP sites containing stratified deposits are rare, however; the overwhelming majority of sites being surficial artefact scatters (Anderson 1984; Hallam 1986; Monks 2021; Strawbridge 1988).

Surface lithic artefact scatters, mainly comprising quartz and chert, are the characteristic archaeological site type recorded on the SCP, the vast majority of which are likely to date to pre-European Aboriginal occupation of the area (Dortch and Dortch 2019:18; Hallam 1986; Monks 2019:409, 2021:9; Schwede 2011:61). Of the region's 1653 recorded Aboriginal heritage sites, 59 percent (n = 979) are listed as artefact / scatter sites (DPLH 2022). In addition to quartz and chert, other raw material types used for lithic production include mylonite, quartzite, dolerite, and silcrete (Glover 1984). Quartz is, however, the most common material found in lithic assemblages in the SCP (Anderson 1984; Hallam 1986; Strawbridge 1988), in some instances accounting for over 70 percent of flaked artefacts found in surface assemblages, such as those found near the Greater Brixton Street Wetlands (Figure 8) (Monks 2019:412). Fragments of grinding material, made from granite or dolerite, have also been identified in many artefact scatter sites, particularly those close to swamps (Monks 2019:412–413). Other archaeological site types include fish traps, standing stones, engravings, built structures, and modified trees (DPLH 2022).

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Figure 8: Quartz fragments from the Greater Brixton Street Wetlands. Fragment b shows indications of bipolar crushing/percussion (Monks 2019:412).

Hallam (1972, 1986) developed a four-phase system to classify the 396 archaeological sites she had identified within her transect of the SCP (Figure 9):

Early: sites characterised by the presence of bryozoan fossiliferous chert and attributed to the period before 6.5 ka ago;

Middle: sites characterised by the presence of backed pieces, of a variety of material types, utilised over the last 4 ka and in particular during the Mid-Holocene;

Late: sites characterised by the presence of a 'high percentage of amorphous quartz pieces' (Schwede 2011:61) and a high ratio of debris; and

Final: sites characterised by the presence of post-contact, European material, such as glass and ceramic.

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Figure 9: Location of Hallam's SCP survey transect from the coast to the Darling Plateau (Monks 2018:92 after Hallam 1987).

Hallam's four-phase system proposed that the number and density of sites in the SCP increased through time. The highest density of sites in all the phases was associated with the lakes and wetlands of the eastern SCP and the alluvial soil systems at the foot of the Darling Escarpment (Hallam 1986, 1987). During this time, geological research hypothesising an offshore source for SCP bryozoan fossiliferous chert artefacts (Glover 1975a, 1975b, 1976), encouraged acceptance of Hallam's classification system. The presence of fossiliferous chert in assemblages on the SCP largely halts at 4–5 ka, matching sea-level stabilisation (Ferguson 1980; Pearce 1978).

The source of SCP fossiliferous chert continues to be debated (Bird et al. 2021; Ward et al. 2021). Whether the source is located on the now-submerged landscape of the Rottnest Shelf (Dortch and Dortch 2019:19; Glover 1975a; Glover and Lee 1984; Quilty 1978) or at a more distant location (Glover 1984; O'Leary et al. 2017; Ward et al. 2019), remains unclear. Regardless, it is certain that fossiliferous chert in the SCP does not naturally outcrop within the current terrestrial landscape and therefore must have been carried into the region.

The use of fossiliferous chert as a broad date-range indicator for the deposition of artefactual material in Hallam's four-phase system was critiqued by Schwede (1990), who argued that fossiliferous chert could not be used in isolation to date artefact assemblages, especially surface scatters. Additionally, in discussing the probable taphonomic impact of European agricultural activity on the SCP, Schwede (2011:66) suggests 'that apparently stratified sites in the SCP… should be interpreted with considerable caution' and that new approaches are required to assess surface sites in the SCP in lieu of Hallam's four-phase sequence. Despite these criticisms, Hallam's SCP survey 'provides some insight into people's use of the landscape' (Monks 2018:95) and the four-phase sequence is still used as a heuristic device for the classification of sites in the SCP.

Bowdler et al. (1991) have also noted the inherent problems in the assessment of artefact scatters in the SCP owing to the site formation processes of sandy soils. They highlight how the continual deflation of the mobile layer of sand, overlying the potentially artefact bearing dune systems, has led to artefacts being 'completely mixed on one level' (Bowdler et al. 1991:25). The lack of stratigraphic integrity, combined with the region's poor organic preservation, has meant that past patterns of landscape use on the SCP have often been deduced from the relationship between the distribution of assemblages across the landscape and their composition (Anderson 1984; Hallam 1987; Strawbridge 1988).

Hallam's survey of the SCP (Hallam 1972, 1986) also introduced the notion that the resources provided by the wetlands, lakes, and rivers of the SCP were more heavily used than littoral resources. Further, Hallam (1987:11) suggested that the 'widely accepted generalisation about "coastal economies" have been based on times and places which are atypical, or at least do not fully illustrate, the continental periphery through space and time.' Subsequent regional studies (Anderson 1984; Strawbridge 1988) concurred with Hallam's finding that SCP sites tend to be located near to water sources and on or near the Pinjarra or Bassendean soil systems. Analysis conducted by Dortch et al. (2007), following an archaeological survey of Peel, found that the landform features influencing stone artefact location in that area of the SCP were proximity to fresh water, the Pinjarra soil system, and certain vegetation complexes. The significance of water sources, such as wetlands, is highlighted by the absence of published reports of excavations producing artefacts in the Greater Swan Region that are further than one kilometre from water (Dortch and Dortch 2019:25).

Hallam (1972:15) suggested this concentration of sites around wetlands resulted from occupancy of 'the swamps and dunes of the sandplain' as a result of gradual population growth throughout the Holocene. Dortch et al. (2007:18) have argued that the 'more productive soils' of the Pinjarra and Bassendean systems would have supported diverse and abundant plant and animal food species, making them more attractive to Aboriginal people for occupation compared to other, less productive regions of the SCP.

The association between wetlands and site distribution may also be attributed to preservation bias; the wetland systems of the SCP were left relatively untouched by the impact of European development, which preferenced coastal areas and the banks of the Swan River (Bolleter 2015; Hallam 1991:48; Seddon 1972). This may partially account for the great size and density of artefact assemblages found at SCP wetlands, when compared to other areas affected by European development (Schwede 2011). Conversely, recent residential development on the Bassendean Dunes may account for the greater number of sites reported within this zone, resulting from a greater number of heritage compliance surveys (Bowdler et al. 1991).

More recently, Dortch and Dortch (2019:18) have emphasised how the traditional Noongar economy depended upon the seasonably available resources from both coastal and inland sources, particularly wetlands. Monks (2021:6) contends that marine resources need not predominate for an economy to be considered ‘coastal’, rather, ‘that seasonally important marine elements are equally transformative’, especially in biodiverse locations like southwestern Australia. During more productive periods, when resources were abundant, it is probable that the wetlands of the SCP served as seasonal gathering places (Dortch 2002a; Gibbs 2011; Hallam 1989; Monks 2019). The high diversity and density of surface artefact scatters, combined with sporadic sub-surface deposits and grinding tools at wetlands such as Munday Swamp, Beeliar Wetlands and the Greater Brixton Street Wetlands indicate long-term, repeated visitation to these sites (Dortch and Hook 2017; Monks 2019, 2021:20). This archaeological evidence corresponds with ethnohistorical records that describe how wetlands were used as congregation sites during warmer months, before dispersing into smaller family groups during autumn and winter (Gibbs 2011; Meagher 1974; Moore 1884). Monks (2021:14) notes how this seasonal sustenance strategy is ‘tentatively identified’ in archaeological records of some SCP sites, such as Yellabidde Cave (Monks 2018), where archaeofaunal assemblages demonstrate utilisation of both inland and coastal resources. Evidence of this diverse coastal economy is further provided by the small-scale utilisation of molluscan resources, demonstrated by a small number of modest shell middens spread along the southwest coastline (Figure 10 and 11) (Dortch et al. 1984; Meagher 1974; Monks 2021; Morse 1982).

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Figure 10: Example of a SCP shell midden site, Middle Head:1) Limestone caprock; 2) 'carbonate sediment with marine shells in situ'; 3) Cemented soil, or anthrosol, with shells and artefacts in situ; 4) Consolidated palaeodunes; 5) Modern dunes (Dortch et al. 1984:86).

It is possible that the environmental opportunities that supported this diverse economy persisted throughout much of human habitation in southwestern Australia (Backhouse 1993; Pickett 1997; Semeniuk and Semeniuk 2012). At Beeliar Wetlands, for example, flaked glass and other European materials were found in surface assemblages associated with sub-surface quartz artefacts and underlain by deposits containing artefacts made of fossiliferous chert (Dortch and Hook 2017). Such sequences imply recurring wetland occupation from the Mid-Holocene until at least the early 1800s. Much older dated sites have also been recorded in proximity to water sources. For example, the Upper Swan site, where charcoal associated with artefacts buried in a palaeosurface was radiocarbon dated to c.38,000 BP (Pearce and Barbetti 1981), or a site on the banks of the Helena River where quartz and chert artefacts are associated with charcoal dated to c.29,000 BP (Schwede 1990). These open-air sites are unlikely to preserve organic material, however, owing to the severely leached sands of the SCP, and limited vertebrate or faunal remains have been recovered to date. Dortch and Dortch (2019:26) highlight how the only piece of faunal remains in the Greater Swan Region 'having even provisional cultural associations' is a Pleistocene 'emu eggshell fragment' related to the occupation of Rottnest Island. This is representative of the wider SCP, except for the Northern SCP, where faunal assemblages provide evidence for past human exploitation of inland and littoral resources (Hallam 1974; Monks 2018; Monks et al. 2016; Thorn et al. 2017).

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Figure 11: Cemented sandy soil at Middle head. 'A fossilised *Leptopius* weevil pupal cases formed around the edges of two *Turbo Opercula* [shells], in situ.' This suggests these shells, and others at the Middle Head midden site, were in situ within this deposit when it cemented (Dortch et al. 1984:87).

2.3.1 The Northern Swan Coastal Plain

The northern section of the SCP is exceptional for its relatively high preservation of faunal remains compared to other parts of the SCP. Archaeologists working in the northern SCP have concentrated primarily on littoral midden sites (Dortch et al. 1984; Monks et al. 2015; Morse 1982) and cave systems (Figure 12) (Archer 1974; Baynes 1979; Hallam 1971, 1974; Monks 2018; Monks et al. 2016). Middens are often buried in sand dunes or situated in elevated locations, overlooking rocky platforms (Monks 2021:11). The caves represent a characteristic feature of the landscape, situated within low limestone ridges that are interspersed by sandplains and *kwongan* heathland (Beard 1976).

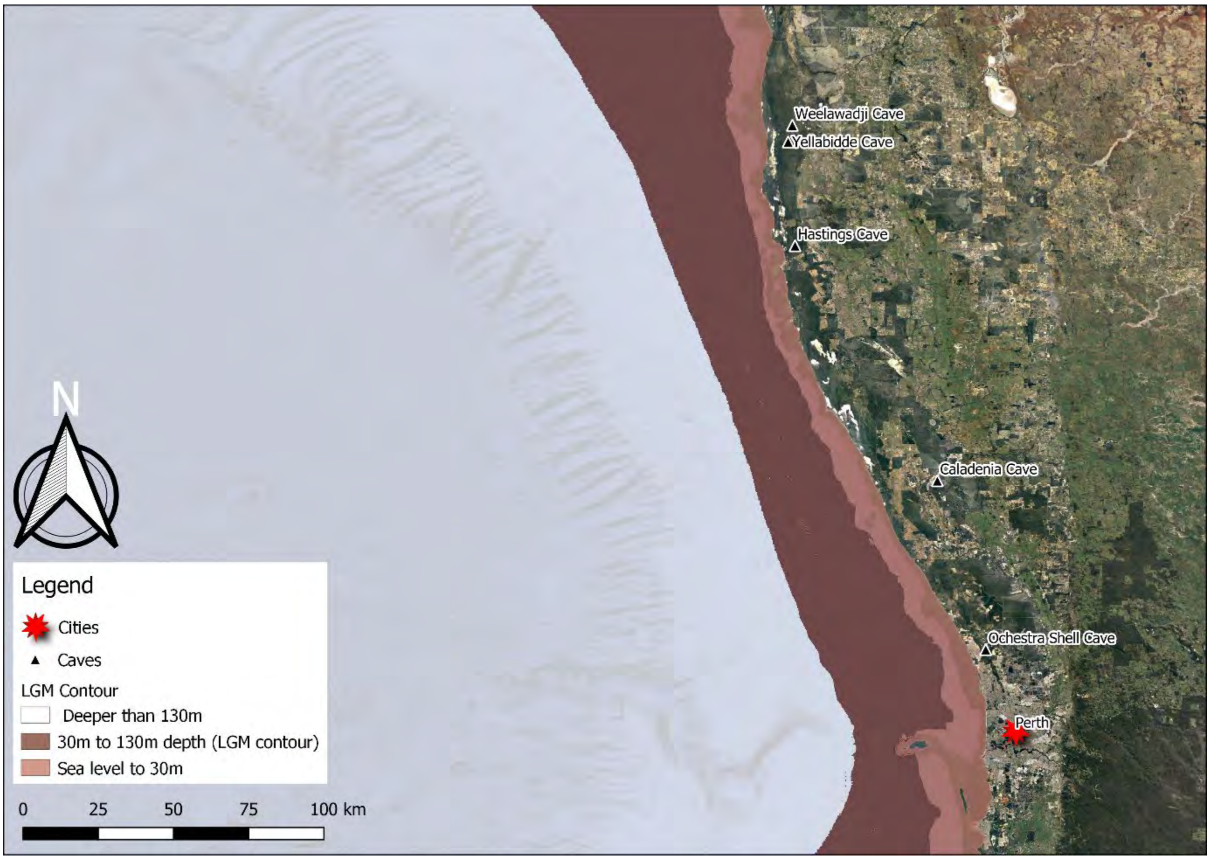

Figure 12: Location of caves mentioned in text. While these are located no more than 20 km from the present-day coastline, at the height of the LGM they would have been situated approximately 60 km from the shoreline, necessitating a crossing of the now submerged Rottnest Shelf to access marine resources. Satellite imagery: ©2022 Google.

Radiocarbon dates from Yellabidde Cave indicate periodic occupation of the site prior to the LGM through to the Late Holocene (Monks et al. 2016:277). A variety of fish and mollusc shells at Yellabidde Cave, found in association with cultural material (Figure 13), date to the Middle to Late Holocene when sea levels stabilised and the present-day shoreline formed (Dortch et al. 1984; Monks et al. 2015, 2016:278). The Yellabidde Cave assemblage demonstrates a series of sporadic occupation events that begin prior to the LGM, are most frequent during the Holocene and persist, gradually declining, until the Late Holocene.

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Figure 13: Backed quartz artefacts from Yellabidde Cave (Monks 2018:151).

Other caves in the northern SCP also have preserved archaeofaunal assemblages. These include Weelawadji Cave, where a single stone artefact was recovered along with faunal remains (Monks 2018) At Hastings Cave, 50 km south of Yellabidde Cave, mammal remains were found along with an Early Holocene baler shell fragment (Baynes 1979). Further south, at Caladenia Cave, a Mid-Holocene deposit was located including mammal remains, freshwater turtle and mussel shells (Roe 1971; Thorn and Baynes 2013; Thorn et al. 2017). In Orchestra Shell Cave, faunal remains include a variety of mammal, reptile, and amphibian skeletal material (Archer 1974; Hallam 1974). The northern SCP also contains coastal shell midden sites (Dortch et al. 1984; Monks et al. 2015; Morse 1982) that indicate the exploitation of rock shore gastropods.

While the faunal remains of the northern SCP are important for understanding people's use of its resources (Monks 2018, 2021), there are relatively few of them. As previously identified, a terrestrial analogue approach to predictive modelling in an offshore context requires a larger sample of terrestrial sites. Hence, the stratified sites of the northern SCP are used in this study in combination with the surficial archaeological sites that characterise the archaeology of the region.

2.3.2 Offshore: the Rottnest Shelf

The search for submerged landscape sites in Western Australia has, until now, been focused on the state's northern continental shelf, in particular, the offshore region of the Pilbara (Benjamin et al. 2020; Dortch 2002b; McCarthy et al. 2021; Veth et al. 2019; Ward et al. 2013; Wiseman et al. 2021). This ongoing programme of investigations led to the first, and only, confirmed submerged Aboriginal sites on Western Australia's continental shelf (Figure 14) (Benjamin et al. 2020).

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Figure 14: Submerged lithic recovered from Flying Foam Passage in the Dampier Archipelago (Benjamin et al. 2020:22).

Many of Western Australia's coastal islands have revealed artefacts attributable to a human presence prior to glacio-eustatic sea-level rise. In southwestern Australia, stone artefact assemblages were identified on the Houtman Abrolhos Islands (Marwick 2002), the Recherche Archipelago (Dortch and Morse 1984; Guilfoyle et al. 2019), Rottnest, Garden, and Carnac Islands (Bindon et al. 1978; Dortch 1991; Dortch and Hesp 1994; Dortch and Morse 1984; Ward 2016).

Rottnest, Carnac, and Garden Islands sit within the Rottnest Shelf and provide the only existing evidence of artefactual material offshore of the SCP. Six fossiliferous chert artefacts, three of them identified in situ, and four undated calcrete artefacts were found on Rottnest Island (Dortch and Dortch 2019:23–24). The in situ artefacts were located in 'Late Quaternary palaeosols intercalated within Tamala Limestone successions' and give a minimum c.17 ka age for the initial occupation of Rottnest Island (Dortch and Dortch 2019:23). These successions of Tamala limestone also continue offshore, presenting as submerged ridges and pinnacles (Figure 15). Two undated fossiliferous chert artefacts were recorded in a Rottnest palaeosol overlooking Fish Hook Bay, as well as an undated notched chert flake at Armstrong Bay that most likely had fallen from the aforementioned artefact bearing palaeosol (Dortch and Hesp 1994).

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Figure 15: Submerged Tamala Limestone pinnacle, 40 km north of Fremantle (Dortch and Dortch 2012:67).

Approximately 16 km south of Rottnest is Carnac Island; to date, no stone artefacts have been found there (Dortch and Dortch 2019). Four kilometres to the south of Carnac Island, on Garden Island, Dortch and Morse (1984) identified nine undated artefacts, including a single quartz flake. Dortch and Dortch (2019:24) discuss how this quartz flake is the only artefact from the Rottnest Shelf that demonstrates a link to the Darling Escarpment and its surrounds, where the closest source of naturally occurring quartz is known to be located (Glover and Lee 1984).

Garden Island is separated from the mainland by only 2.5 km at its southern tip. Despite this, there is no archaeological evidence that Aboriginal people made this, or any other, ocean crossing from the SCP after sea levels stabilised (Dortch and Dortch 2019:24). This finding is consistent with studies undertaken by Ronald Lampert and Norman Tindale that proposed Aboriginal populations along Australia's southwest coastline did not use ocean-going watercraft (Figure 16) (Guilfoyle et al. 2019:209–210). Evidence has emerged subsequent to Lampert's study which suggests oceangoing canoes may have been constructed using bark from culturally modified trees in South Australia; however, no such evidence contradicting Lampert's model has been observed in southwestern Australia (Guilfoyle et al. 2019:210). In a comprehensive review of ethnohistorical records relating to Noongar Aboriginal fishing techniques, Dortch (1997a) stated that there is 'no evidence' of Aboriginal people fishing along the coastlines of the South West. Gibbs' (2003:9) discussion of shore-based whaling in southwestern Australia suggests that, for the Noongar people, the ocean 'represented an unfamiliar and potentially terrifying environment', Gibbs notes that 'many other Nyungar songs speak of the anger of the seas… to move across them [on European whaling vessels] was obviously a courageous act.' Although the use of ocean-going watercraft by past iterations of Noongar culture cannot be ruled out, the ethnohistorical accounts, combined with the lack of Late Holocene, pre-European archaeological evidence on the offshore islands of the SCP, suggest it is highly unlikely Noongar people were using watercraft for ocean crossings following sea-level stabilisation.

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Figure 16: Map of watercraft usage around coastal Australia as recorded by Ronald Lampert (after Guilfoyle 2019:210). Note that the area where oceangoing watercraft were supposedly not in use encompasses the SCP and southwestern Australia more broadly.

2.4 Ethnohistorical Stories of Inundation

Ethnohistorical sources also provide an insight into sea-level change and the formation of islands on the Rottnest Shelf. 'Story, for Nyoongar people, is the most significant transmitter of cultural knowledge' (Robertson et al. 2016:42). Ethnohistorical accounts of these stories can provide further awareness into the submerged landscapes of Noongar *Boodjar* (Nunn and Reid 2015:20–23; Robertson et al. 2016). Many of these stories 'have an opening line that locates the story in a particular time' (Robertson et al. 2016:43). Three of these 'particular time' periods, and their related stories, are understood to be associated with sea-level change: the *Nyetting* 'the cold, dark time'; the *Koora* eras; and *Wardanaak Boodjar* 'the flood' times (Robertson et al. 2016).

There are two types of *Nyetting* stories: 'stories about what seem to be real people struggling with *nyidiny* (cold)' and those from an earlier time that relate to the creation of Noongar *Boodjar*. Mia (2000:1) for example, refers to a 'legend' relating to the creation of Noongar *Boodjar*:

> It is an area of almost 3,000,000 hectares with 1600 kilometres of coastline along which there are dotted a few islands … legend related that in the Dreaming of Aboriginal creation they formed part of the mainland and so belonged to Noongar people.

Both *Nyetting* stories about people surviving *nyidiny* 'cold' and those from the *Koora Koora* eras, when spiritual ancestors manifested and travelled across the landscape, describe 'ancient times' and have been linked to Noongar peoples' survival during the LGM (Robertson et al. 2016:43).

Wardanaak Boodjar 'the flood' stories, such as *Walyalup Dreaming*, have been associated with the drowning of the SCP and recount the creation of *Wadjemup* 'Rottnest Island', *Meeandip* 'Garden Island' and *Gnooroolmayup* 'Carnac Island' (Robertson et al. 2016:48–49). A Noongar traditional story recorded by the colonist George Fletcher Moore (1884) tells of how:

> Rottnest, Carnac and Garden Island, once formed part of the mainland, and that the intervening ground was thickly covered with trees; which took fire in some unaccountable way, and burned with such intensity that the ground split asunder with a great noise, and the sea rushed in between, cutting off these islands from the mainland.

Such ethnohistorical records indicate that these islands were known to Noongar people as being once a part of the emergent SCP. During periods of lower sea levels, it is feasible that a sea-level decrease of 5 m would have allowed access, perhaps wading at times, to Rottnest Island, while a sea-level decrease of 10 m would have allowed easy traversal of the Rottnest Shelf (Figure 17).

Figure 17: SCP offshore islands are accessible with a sea-level decrease of 5m, while a decrease of 10 m would have allowed people to easily walk to Rottnest Island. Satellite imagery: ©2022 Google.

2.5 Summary

Since people have occupied and lived in southwestern Australia, almost 50 ka ago, eustatic sea-level change has led to substantial changes to coastal environments and landscapes. The rise and fall of sea levels has seen ongoing changes to the topography and extent of the SCP; shifting the distribution of wetlands, waterways, and their resources (Baynes 1979; Dortch and Dortch 2019; Lewis et al. 2013; Lipar et al. 2017; Monks 2018, 2021; Pickett 1997; Semeniuk and Semeniuk 2012; Thorn et al. 2017). These changes created and then inundated water sources, moved intertidal zones, eroded away limestone headlands, and turned previously fresh water brackish or saline (Collins 1988; Kench 1999; Lewis et al. 2013; Ward 2016; Ward et al. 2015). As resource availability shifted within a dynamic environment, people adopted foraging strategies that supplemented terrestrial resources, with littoral resources such as turtle, shellfish, freshwater and estuarine fish (Monks 2021).

Many of these resources can be attributed to the archaeofaunal material found in the caves and middens of the northern SCP. These assemblages provide evidence of a foraging strategy that supplemented a primarily terrestrially based diet, particularly wetland resources, with a small, but consistent, variety of littoral resources (Archer 1974; Baynes 1979; Dortch et al. 1984; Hallam 1974, 1987; Monks 2018; Monks et al. 2015, 2016; Morse 1982). These findings align with ethnohistorical records which suggest 'that traditional Nyoongar economy was based on the systematic exploitation of largely seasonally available resources in coastal and adjacent inland districts, particularly in and around wetlands' (Dortch and Dortch 2019:18).

Dortch and Dortch (2019:26) have noted how the lack of evidence for past resource usage in many parts of the SCP 'is even more noticeable today than was observed [by Hallam] … half-century ago.' The region's poor organic preservation, combined with the lack of stratigraphic integrity (Bowdler et al. 1991; Schwede 2011), has meant that past patterns of occupancy and resource use on the SCP have been deduced from the relationship between the composition and distribution of assemblages in relation to landscape features (Anderson 1984; Hallam 1986, 1987; Strawbridge 1988).

The Bassendean and Pinjarra soil systems, as well as certain vegetation types, are landscape features that have also been identified for their relationship to SCP site distribution. However, the landform type identified as being most strongly correlated with the highest site densities is water sources (Anderson 1984; Dortch et al. 2007; Hallam 1987; Monks 2021; Strawbridge 1988). In the central SCP, for example, the most diverse and largest Middle to Late Holocene stone artefact sites are all located inland, near abundant freshwater wetland systems, at Perth Airport estate, Lake Monger, and Beeliar (Dortch and Dortch 2019:24–25). SCP Holocene site distribution, combined with the location of Pleistocene sites (Pearce and Barbetti 1981; Schwede 1990) adjacent to waterways, indicates an occupation pattern through time that was centred on persistent waterways and wetlands. This suggests that landscape features on the inundated continental shelf indicative of past waterways will have a higher potential for the identification of submerged landscape sites.

3 Methods

This chapter outlines the methods used in this thesis for the collection and analysis of the subaerial archaeology of the SCP and of data related to the physical landscape of the SCP and Rottnest Shelf. These methods included a desktop survey, landscape modelling, and GIS based predictive modelling.

3.1 Desktop Survey

The first method undertaken was a desktop survey. Primary and secondary sources were identified using a combination of search engines and databases. The desktop survey consisted of two main steps:

1) The search for and collection of data relating to the study area. Secondary sources were acquired using search terms that included:

- Western Australia
- SCP
- Rottnest Shelf
- Continental shelf
- Geology
- Geomorphology
- Sediment
- Submerged landscape
- Palaeoshoreline
- Bathymetry
- Oceanography
- Hydrology
- Last Glacial Maximum
- Holocene
- Pleistocene
- Sea-level Change
- Sea-level Data
- Sea-level Fall/Rise

2) The synthetisation and analysis of the data collected (Section 4.1 and Chapter 5). Sources were compiled into the citation management software Zotero, allowing for consistent data management. Evaluation of sources was conducted by assessing their relevance to the submerged continental shelf and the consistency of information across publications.

3.1.1 Sea Level

Analysis of sea-level change and its effect on prehistoric land use is central to this study, specifically the recreation of the palaeolandscapes of the SCP. The sea-level curve data used in this study is derived from a combination of four separate publications: Collins (2006), Eisenhauer et al. (1993), Lambeck (2004), and Lambeck et al. (2014). This data is utilised as an approximation of depth to age ratio of sea levels in the past (Benjamin 2010a:259–260).

All dates were produced by radiocarbon and/or uranium series dating (Collins et al. 2006:79–80; Eisenhauer et al. 1993:531–532; Lambeck et al. 2014:15297).

The collection of the sea-level data involved two methods. Firstly, the use of observational recording to establish the corresponding relative sea-level depths from Collins (2006) for periods of 1,000 years between 1,000 and 6,000 BP; from Eisenhauer et al. (1993) between 7,000 and 10,000 BP; and from Lambeck (2004) between 35,000 and 50,000 cal. BP. Secondly, data was gathered from the supplementary information provided by Lambeck et al. (2014 Supporting Information Appendix) for the years between 10,000 and 35,000 cal. BP.

To determine a sea-level curve, a line of best fit through the data was chosen as the best proxy for southwestern Australia as a region. To establish a line of best fit, the eustatic sea-level data from Lambeck et al. (2014) was averaged. Averages were used to establish singular data points for 500-year intervals (Appendix 1). This applied only to the publication data produced by Lambeck et al. (2014), relating to the period between 8,000 and 35,000 cal. BP. Ages younger than 10,000 BP and older than 35,000 BP were determined elsewhere. Data from Collins (2006) was corrected to account for the position of the measured pavement elevations being 0.4 m below the actual estimated sea level (Collins et al. 2006:82).

After averages were produced, the results were placed into Microsoft Excel to produce a graph detailing a line of best fit (Figure 18). The subsequent sea-level curve was produced by displaying the results as a scatter with smooth lines. For modelling purposes, where depth data was unknown, single age data was determined from the combined sea-level curve. Section 4.1.1 outlines the results of the sea-level curve construction and its relevance to study area in terms of geomorphological processes.

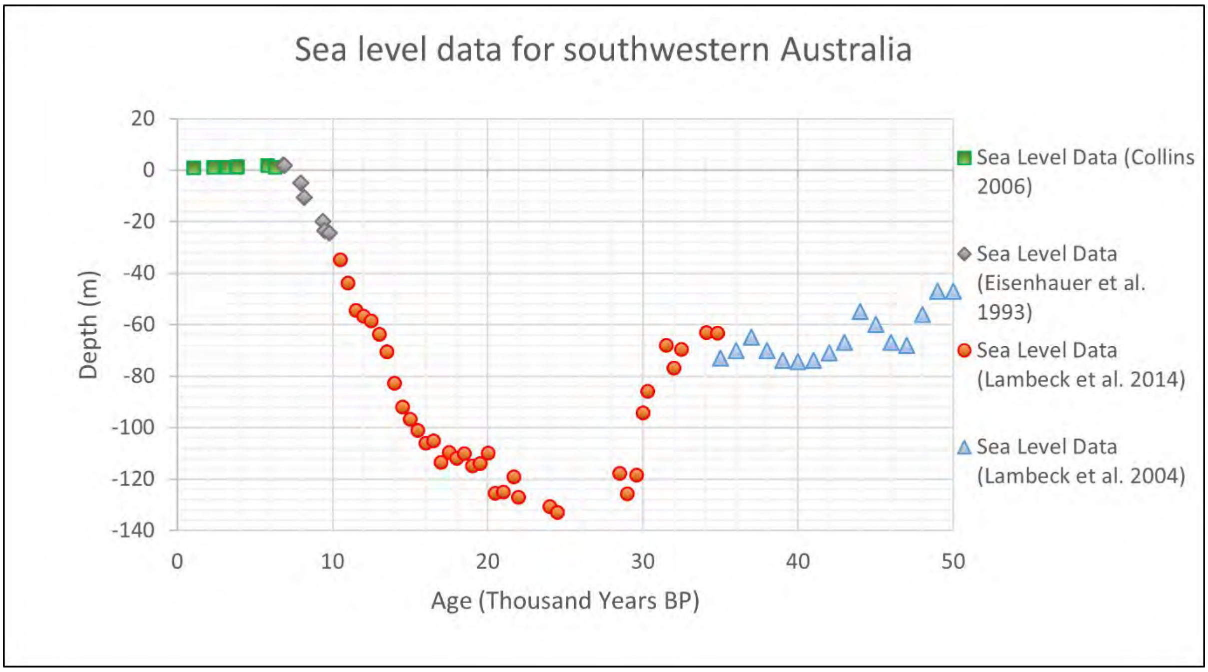

Figure 18: Sea-level data from Collins (2006), Eisenhauer (1993), Lambeck (2004), and Lambeck et al. (2014).

3.2 Landscape Modelling

Landscape modelling for this study involved the production of DRMs using topographic and bathymetric environmental geospatial layers. Resultant models represent the landscape of the SCP and the adjacent continental shelf over the past 50 ka, aligning with earliest known dates of occupation in the region (Turney et al. 2001). Geophysical sensing technologies have enabled detailed mapping of the seafloor (Firth 2010; Missiaen et al. 2017; Plets et al. 2013), allowing high resolution reconstructions of submerged landforms that can assist with the location of submerged sites (Benjamin et al. 2020; Braje et al. 2019; Duggins 2012; Müller 2010; O'Shea et al. 2014; Tizzard et al. 2014; Veth et al. 2019; Westley et al. 2011; Wiseman et al. 2021). Further, the process of modelling the submerged landscape can connect regional sea-level histories with the landscape in question; allowing the recreation of palaeoshorelines at specific time intervals (Benjamin 2010a:258–260). For this study, landscape models were constructed at 1,000-year intervals to demonstrate shoreline evolution and changes to the topography. Modelling was undertaken using the QGIS 3.16 and ESRI ArcGIS Pro 2.9.3 and the processes outlined below.

3.2.1 Data Acquisition

There is no available dataset that provides continuous resolution of combined bathymetric and terrestrial data for the study area; therefore, data was acquired from a variety of sources to describe the topography of the SCP and the adjacent submerged continental shelf. Terrestrial data was sourced from Geoscience Australia's (2011) Hydrologically Enforced Digital Elevation Model. Several bathymetric datasets were merged allow the creation of a raster representing the portion of the study area located on the Rottnest Shelf. These included the 50 m 'Multibeam Dataset of Australia 2012' and the 200 m 'Australian Bathymetry and Topography Grid, June 2009' from the AusSeabed (2022) portal. These datasets were provided as .tif files. Five metre aerial LiDAR datasets were acquired from the Western Australian Department of Transport, including the: 'Two Rocks to Cape Naturaliste Bathymetry & Seabed Survey' and 'Western Australia South West Inlets Peel, Harvey, Leschenault, Hardy & Wilson LiDAR Bathymetric Survey'. A total of 18 files were acquired for the LiDAR surveys: 12 files in raster format and 8 tiles in XYZ format.

Both multibeam and LiDAR data have been previously used in submerged landscape investigations (Benjamin et al. 2020; Westley et al. 2011; Wiseman et al. 2021). These bathymetry datasets are used as a proxy for past topography of the emergent continental shelf and interpreted in combination with the results of the desktop survey to account for physical environmental changes over time.

3.2.2 Study Area Extent

For modelling purposes, data that exceeded the boundaries of the study area was clipped so that it matched the boundaries of the study area and/or was contained by it. Onshore boundaries for the SCP are defined according to the IBRA (DAWE 2020). Offshore boundaries are identified in QGIS 3.16 by adjusting the symbology of the Australian Bathymetry and Topography Grid, June 2009 to display sea level at -131 m below mean sea level. This value was chosen to reflect the change in sea level and shoreline location during the height of the LGM (Lambeck et al. 2014). A new vector polygon matching the extent of the onshore and offshore area was then extracted using the export function in QGIS 3.16. All other data was clipped to the extent of the new SCP polygon.

3.2.3 Modelling Approaches

As a variety of different data sources and types are assembled, a significant component of this study involved the resampling and preparation of various data to allow for the creation of continuous DRMs.

This involved firstly combining the 12 LiDAR tiles that were provided as .tif files in ArcGIS Pro, using the Mosaic to New Raster tool. The datum of this raster was then reprojected to

EPSG 28350 GDA94/MGA Zone 50 (GDA94 Zone 50) at 100 m resolution. The LiDAR survey areas that were provided in XYZ format were loaded in QGIS 3.16 and exported as .tif files in GDA94 Zone 50 at 100 m resolution. Analysis was undertaken in this coordinate system to allow for measurement in kilometres. The reprojected data was then converted to point file format in ArcGIS Pro using the Raster to Point tool. The base point data was then merged using the Merge Vectors tool in QGIS 3.16 and clipped to the study area extent using the Extract by Mask tool in ArcGIS Pro. This base point data was used to create a DRM of the study area at a 100 m resolution, due to available computing power.

Hydrological analysis was undertaken on the newly created DRMs in ArcGIS Pro to allow for the prediction of drainage systems on the submerged continental shelf. Hydrological modelling followed the processes outlined by ESRI (2022a) for the creation of stream networks involving a seven-step process:

1. The input DRM was filled, removing raster elevation errors by filling in ‘sinks’ in the surface raster (ESRI 2022b).
2. The fill layer and the D8 flow modelling algorithm were used to create a flow direction layer (ESRI 2022c).
3. The number of upstream cells that flowed into each downstream cell of the flow direction layer was calculated, representing the stream network, thus allowing the output of a flow accumulation layer (ESRI 2022d).
4. To best identify drainages, a stream threshold was set on the flow accumulation layer using the ‘Con’ tool (ESRI 2022e).
5. Using the Strahler method (ESRI 2022f), the Stream Order tool was employed to ‘represent the order of each of the segments in the [stream] network’ (ESRI 2022g).
6. Using the Stream to Feature tool, the raster output of the Stream Order tool was converted to a feature (ESRI 2022h).
7. The feature output was filtered using the Definition Query function to show only those streams (line features) of a higher Strahler order (>5).

To effectively analyse the palaeolandscape of the SCP, sea-level curve data needs to be incorporated. Sea-level fluctuations were presented at 1,000-year intervals, corresponding with the sea-level records presented in section 4.1.1. Sea level was demonstrated at each 1000-year interval by creating a new DRM layer. To create each new layer, the Extract by Attributes tool was used in ArcGIS Pro, and values selected that were greater than or equal to the corresponding sea level. The symbology was changed so that values were stretched along a colour ramp and gamma changed to a value of 1.3 to assist with visualisation. To allow improved comparison between DEMs, the stretch type was set to ‘Minimum Maximum’; the statistics was set to ‘Custom’; and the ‘Min’ value for each DRM was set to -131 m (Figure 19). This ensured that elevation features above 0 m remained consistent, allowing easy comparison of shoreline position between DRMs. These modelling approaches allowed the creation and analysis of landscape models for the evaluation of the topography of the SCP and the adjacent submerged continental shelf.

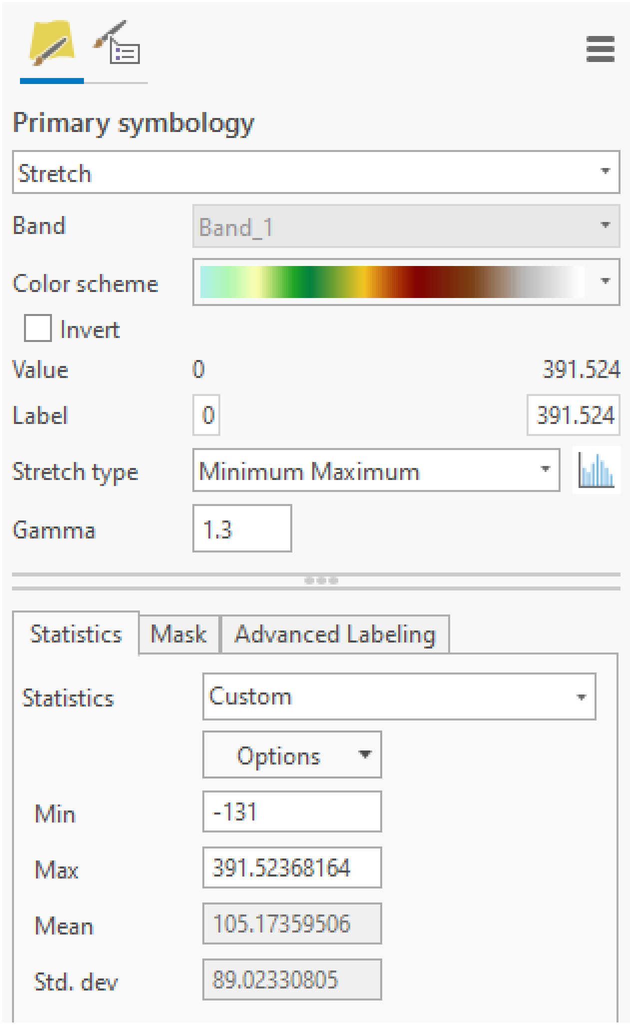

Figure 19: Discrete landscape model raster symbology.

3.3 Modelling Terrestrial Site Data

Kernel density analysis was undertaken to detect broad scale patterns within site distribution of the SCP (Bevan 2020:61–63). Proximity analysis (Kvamme 2020) was conducted to establish the relationship between terrestrial sites and landscapes features. This relationship can then be extrapolated to the offshore context, thus moving from the ‘known to the unknown’ (Braje et al. 2019).

3.3.1 Data acquisition

The register of Aboriginal Heritage Places, maintained by the Department of Planning, Lands and Heritage (**DPLH**), records the locations of possible Aboriginal sites reported under the *Aboriginal Heritage Act 1972* (WA) (Appendix 2). The dataset contains over 35,000 entries, representing Aboriginal heritage sites across Western Australia. This data is provided as a polygon shapefile and was converted into a point shapefile, each point located in the geometric centroid of the polygon, using the Polygon Centroids tool in QGIS 3.16. Each entry in the register is given one or more ‘type’ definitions, according to the use of the place and/or the materials identified there.

The Aboriginal Heritage Places dataset was filtered to extract only those sites that lay within the boundaries of the study area (n = 1653). This dataset was then further divided in new layers according to the following type definitions: ‘Artefacts’ (n = 991), ‘Scatter’ (n = 985), ‘Arch Deposit’ (n = 77), ‘Man-made Structure’ (n = 45), ‘Midden’ (n = 18), ‘Fish Trap’ (n = 14), ‘Quarry’ (n = 10), ‘Rockshelter’ (n = 10) and ‘Repository / Cache’ (n = 7). [1] These ‘type’ specific layers were merged to create a new dataset in QGIS 3.16 and duplicate entries deleted. The resultant dataset (n = 1,039) represented all entries in the original dataset that were located on the SCP and contained ‘Artefacts’, ‘Scatter’, ‘Arch Deposit’, ‘Man-made Structure’, ‘Midden’, ‘Fish Trap’, ‘Quarry’, ‘Rockshelter’, or ‘Repository / Cache’ as a ‘type’ definition.

The ‘Artefacts’ and ‘Scatter’ type definitions were selected as lithic scatters and are the characteristic site type of the SCP and are therefore deemed essential to any analysis of local sites. Further, surficial artefact scatters have been demonstrated to be identifiable in a submerged context on the Western Australian continental shelf (Benjamin et al. 2020; Wiseman et al. 2021) as well as at Lake Jasper (Dortch 1997b; Dortch and Godfrey 1990)

[1] Note, each entry in the register of Aboriginal Heritage Places dataset may be assigned more than one ‘type’ definition.

and Broke Inlet (Dortch 1997a:28). The other included ‘type’ definitions, such as fish traps, quarries, and shell middens, have been highlighted by Nutley (2014:268–269) for their potential to survive inundation and are thus more likely to be preserved in an offshore context.

3.3.2 Site Distribution

Kernel density analysis has often been used in archaeological applications (Bevan 2020) and for home range analysis (Baxter et al. 1997; Duggins 2012; Seaman and Powell 1996). Kernel density analysis operates by assigning each point a given search radius, where more points sit within this search radius, a higher density is allocated (Bevan 2020:61). Kernel density analysis is an appropriate choice for summarising the first-order intensity of a point pattern when there are too many points in the study area to ‘eye-ball easily’ and when there are numerous lots of nearly superimposed points (Bevan 2020:63). Given the number of points (n = 1,039), kernel density analysis was selected for this study to allow for regional hotspots to be more easily determined.

When undertaking kernel density analysis, the search radius entered by the user can greatly vary the output (Bevan 2020:61–63). User defined bandwidths are often the best strategy for choosing a search radius, assuming that the choice is appropriately justified, such as a ‘meaningful behavioural scale for the pattern and process under study’ (Bevan 2020:63). For this study, the home range data for warm climate, non-equestrian foragers from Marlowe’s (2005) analysis of documented hunter-gatherer populations, was used as a behavioural scale for the study area. Site density analysis was conducted using the maximum (4,500 km^2) and median (175 km^2) home range values (Marlowe 2005:63). This equated a search radius for kernel density analysis of 38 km and 7.5 km, respectively.

3.3.3 Site Proximity

The exact spatial relationship between site location and features was quantified using graduated buffer distances. Analysis was undertaken in ArcGIS Pro using the Buffer Feature Proximity Tool. Each feature included in the analysis was assigned incrementally increasing buffers to determine the most probable search radius. Buffer distances of 0.1 0.2, 0.3, 0.4, 0.5, 1, 2, 3, 4, and 5, kilometres for all wetlands, rivers, and stream layers with the resultant distances to Aboriginal sites on the SCP graphed. Proximity analysis focused on the relationship between sites and water sources, these being the landform identified in the literature review as having the strongest correlation to site distribution and are also identifiable in a submerged context.

These methods provided the measurements used to quantify site distribution and identify broad scale patterning of sites in relation to certain landform features which could then be extrapolated to the offshore context.

3.4 Identifying High Preservation Potential Areas

High preservation potential areas are defined as those areas on the continental shelf that have a higher probability of containing submerged landscape sites. Areas of high preservation potential can be identified by considering that submerged sites have a higher probability of having been deposited near to attractive subaerial landscape features (Braje et al. 2019; Veth et al. 2019). Assuming terrestrial site patterning continues onto the inundated continental shelf, submerged landscape features with a demonstrated association to site location can provide a marker for areas that, when combined with favourable environmental (taphonomic) conditions, have a realistic potential for submerged archaeological sites to exist and be preserved in situ. These high preservation potential areas are discussed in Section 5.3.

4 Results

This chapter presents the results of the desktop survey, landscape modelling, and distribution analysis outlined in the previous chapter. The results for the desktop survey present geomorphological evolution of the SCP and the Rottnest Shelf. The landscape modelling results present visual representations of this evolution. The distribution analysis results present the patterns of site distribution on the SCP.

4.1 Desktop Survey

The desktop survey identified three geomorphological processes affecting the topography of the SCP and Rottnest Shelf over the last 50 ka. These are marine, fluvial, and aeolian processes. Marine and fluvial processes are the two primary factors relating to sediment production and transport on the submerged continental shelf. As this study focuses on the submerged continental shelf, the desktop survey focused on only the marine and fluvial processes. The impact of aeolian processes on sediment production during periods of subaerial exposure is acknowledged, however, this impact is deemed relatively negligible, such sediment having since been reworked by marine processes (Collins 1988; James et al. 1999).

4.1.1 Marine Processes

Marine processes have had the greatest impact on continental shelf morphology and shoreline location. Marine processes were found to be the product of 1) eustatic sea-level fluctuations, and 2) physical processes of current circulation, wave, and tidal action.

4.1.1.1 Sea-Level Fluctuations

There are two types of sea-level change that occur because of the formation and deterioration of glaciers: eustatic and isostatic (Lambeck 2009; Lewis et al. 2013). Eustatic sea-level is a worldwide phenomenon, resulting from glacially induced shifts in the volume of global ocean water (Grant et al. 2012). Isostatic sea-level change results from glacier induced regional variations to the structure of the lithosphere. The weight of a glacier can cause the Earth’s surface to deform; as a glacier melts, the lithosphere rebounds to its pre-glacier position (Lambeck 2009; Lambeck and Chappell 2001:681). This cycle of isostatic depression and uplift can cause sea-level variation at a regional scale in addition to any glacio-eustatic effects. Regions closely affected by isostasy are known as near-field areas, while those locations situated furthest from glaciated areas are known as far-field areas (Lambeck et al. 2014:15297).

Southern Western Australia is considered a far-field region (Collins et al. 2006; Eisenhauer et al. 1993). Given the region's tectonic stability (Brooke et al. 2010:6231), sea-level fluctuations can be said to result primarily from eustatic impacts. As such, studies relating to global glacioeustasy, specifically far-field locations, were used to produce a record of sea-level oscillations for the SCP. The applicability of global sea-level curves for regional models has been critiqued due to the regional variability caused by hydro-isostasy (Lambeck et al. 2002:350; Murray-Wallace and Woodroffe 2014:364). To account for these effects, where possible, sea-level data for southwestern Australia has been taken from local sources.

The selected far-field studies relating to the Late Pleistocene are Lambeck (2004), and Lambeck et al. (2014). This data was acquired from far-field areas (where possible). Data from Lambeck (2004) was used for the period 50,000 to 35,000 cal. BP. From 35,000 to 10,000 cal. BP, data from Lambeck et al. (2014:15296–15298) was utilised. The absence of potential outliers, primarily between 15,000 to 10,000 cal. BP, represents a potential limitation of this dataset (Lambeck et al. 2014) but is deemed acceptable for this study. There are four distinct trends illustrated by this data. The first is gradual regression period from 50,000 to 35,000 BP. Second is a rapid regression period seen between 34,000 to 31,000 BP. The third is a period of stabilisation between 30,000 to 17,000 BP. The final trend is the rapid transgression of sea level following 16,000 BP.

West Australian Holocene sea-level data is presented by Collins et al. (2006) and Eisenhauer et al. (1993). Samples were collected from emergent coral platforms throughout the Houtman Abrolhos Islands. Combination of the datasets allows for a composite sea-level curve that reflects the Holocene sea-level high stand in southwestern Australia that is 'not seen in better known sea-level records elsewhere at the time' (Collins et al. 2006:78). Using data acquired from southwestern Australia for this period also helps to account for 'geographical variability in relative sea-level change during the Holocene' (Murray-Wallace and Woodroffe 2014:364). Sea-level data and the associated curve are shown in Figure 20. Landscape models visualising sea-level fluctuations are presented in Section 4.2.

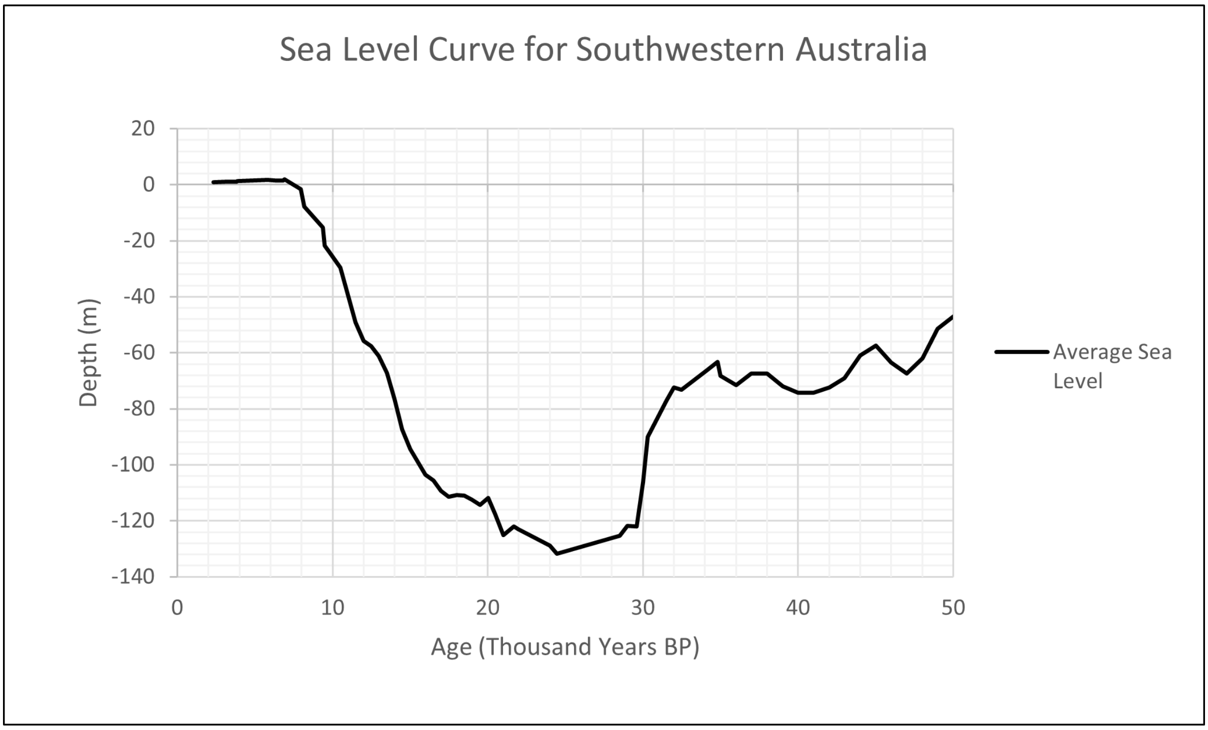

Figure 20: Sea-level curve produced using data from Collins (2006), Eisenhauer (1993), Lambeck (2004) and Lambeck et al. (2014).

The morphology of the Rottnest Shelf southward of Perth has been described by Collins (1988), who summarised its sedimentary evolution in four stages (Figure 21). James et al. (1999:1299) have described the Rottnest Shelf north of Perth and found that it has 'the same geomorphic elements' as the southern shelf. Across the Rottnest Shelf Pleistocene substrate was subject to prolonged meteoric diagenesis (subaerial exposure to freshwater inputs) and not inundated until about 10,000 BP, leading to primarily Holocene sediment that overlies Pleistocene limestone (Collins 1988; James et al. 1999; Richardson et al. 2005:14–21).

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Figure 21: The four stages of Late Pleistocene-Holocene Rottnest Shelf sedimentary evolution (Collins 1988:40–41): 1) A period of lower sea levels, 27,000–17,000 BP when Outer Shelf and Upper Continental Slope deposits were reworked and affected by wave abrasion, while subaerial weathering affected the emergent shelf; 2) A period of rapid marine transgression, 17,000–10,000 BP, when sea levels rose from a depth of -130 m to -25 m. This transgressive event stripped pre-Holocene deposits and resulted in an erosional morphology, also forming barrier islands that were progressively submerged; 3) A period of slow transgression, 10,000–6,000 BP, as erosional shoreface retreat gradually expanded landward. By the middle of Stage 3, 'modern environments and processes were established [in] all but the shallowest parts of the shelf.' On the Inner Shelf, lag sands continued to be deposited and were colonised by contemporary biota, contributing skeletal material, which were then occupied by sea grass communities. On the Outer Shelf, shelf erosion and bevelling gradually stopped due to its progressive submersion below the maximum wave abrasion depth, leading to the deposition of the Rottnest Blanket; 4) The period between 6,000 BP to present, saw the continued evolution of the contemporary sedimentary system, established in the second half of Stage 3, with the increased production of skeletal sands. Sediment deposition nearshore during this stage is controlled by wave climate, the littoral transport system, and seagrasses, which stabilise substrate.

This Pleistocene Tamala Limestone was deposited during subaerial exposure and forms a series of shore-parallel ridges, of up to 16 m relief, extending 30 km offshore and 10 km inland (Brooke et al. 2010, 2014, 2017). Brooke et al. (2017:49) have described these landforms as remnant palaeo-sand dunes, which were then 'partially eroded and drowned' by post-glacial sea-level rise (Figure 22 and 23). These remnant coastal barriers appear to have at least partially resisted the effects of erosion during the periods of transgression (Brooke et al. 2014). Based on this, Brooke (2014:121) proposed 'a conceptual model of Quaternary continental shelf carbonate deposition and aeolianite landform evolution' (Figure 24).

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Figure 22: Combined bathymetric and topographic DRM of the SCP and Rottnest Shelf (Brooke et al. 2010:6225). Major onshore ridges are marked 1,2,3. Offshore ridges in the nearshore zone are marked a, b,c. The white box indicates where smaller ridges occur; subtle ridges also occur south of Cockburn sound at H. Lines (T1–T4) indicate location of land surface and seabed profiles (Figure 23).

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Figure 23: Land surface and inner shelf (a) and outer shelf and slope profiles (b) as outlined in Figure 21 (Brooke et al. 2010:6230).

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Figure 24: Model of the submerged landform evolution of the Rottnest Shelf. Note, the submerged palaeo-barrier depicted in section E (Brooke 2014:122).

Changing sea levels also impacted the formation of the terrestrial dune systems of the SCP (McArthur and Bettenay 1974:25; Semeniuk 1985, 1996; Tonk and Withagen 1999). As shown in Figure 25, the accumulation of the Spearwood Dune System began approximately 85,000 BP, during the Early Würm I interstadial, and continued until the Würm II interstadial, 45,000 BP, approximately 10 ka after the earliest dated evidence of the arrival of humans in southwestern Australia. The Quindalup Dune System probably covers a range from Flandrian times, 6,000 BP, to the present. McArthur and Bettenay (1974) suggest that these associations demonstrate that soil formation occurred during lower sea-level periods; each fluviatile deposition can be correlated to a period of higher sea level; and dune formation can be tied to periods of marine regression. Many of the lake, inlet, and estuary complexes of the SCP also show a distinct lineation parallel to the existing shoreline. Most of these features occur within the limits of the three major dune systems and their boundaries lie primarily between the adjacent systems, which is interpreted by McArthur and Bettenay (1974) as demonstrating how each dune system formed independently.

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Figure 25: Chronology of SCP dune system formation (after McArthur and Bettenay 1974:26).

4.1.1.2 Current Circulation

The Western Australian Current is the largest water mass off the Western Australian Coast. It is part of the Indian Ocean circulation that flows northward, bringing cold water from higher latitudes (Cresswell and Golding 1980; Pattiaratchi and Buchan 1991). The second major current is the Leeuwin Current (**LC**). Volumetrically much smaller than the Western Australian Current, it flows southward, bringing warmer, less-saline, water from equatorial regions and has a substantial impact on sediment production (Cresswell 1991; Cresswell and Golding 1980; Pattiaratchi and Buchan 1991).

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Figure 26: Northern Rottnest Shelf cross section, showing 'the smooth inner-shelf plain, ridge complex, outer shelf' and periodic upwelling over the upper slope that occurs during summer months (Richardson 2005:16 after James et al. 1999).

The LC generally inhibits large-scale upwelling in the region (Godfrey and Ridgway 1985; James et al. 1999; Thompson 1984), although downwelling can be locally important for sediment transport (Richardson et al. 2005:22–26). When the LC weakens in summer, periodic increased upwelling of nutrient-rich waters enhances precipitation of sediment carbonates (Figure 26) (Hatcher 1991; McGowran et al. 1997:30–35). If the LC was weakened during glacial low stands, as many studies suggest (Feng et al. 2003; Spooner et al. 2011; Wyrwoll et al. 2009), then the area 'would have been one of cool-water carbonate sedimentation, with reefs confined to local shoreline refugia' (James et al. 1999:1320). In addition to currents, waves and non-tidal sea-level changes are the main oceanographic processes that affect Holocene sedimentary processes and resultant depositional landforms in southwestern Australia.

4.1.1.3 Tidal Regimes and Surface Waves

Swell and storm waves are the dominant physical processes on the Rottnest Shelf. Waves primarily come from the west and southwest, with swell waves reaching 2 m high and storm waves of up to 10 m (Collins 1988; James et al. 1999; Semeniuk 1996). Wave currents cause erosional mixing of shelf sediment and wave-formed structures. Near shore, they have been demonstrated to transport sediment (Godfrey et al. 2005). Swell waves can rework sediment to depths of 60 m; as over 90 percent of the shelf is under 50 m depth, sediments experience ongoing reworking (Collins 1988; James et al. 1999). The Outer Shelf has sat below wave abrasional depth since the Mid-Holocene, allowing a depositional regime to be established based on seaward transport of fine sediment via downwelling (Collins 1988:41).

Maximum wave energy on the shelf decreases from south to north, with some protection offered to nearshore areas by Cape Naturaliste and the offshore islands (Figure 27). The complex bathymetry of the Rottnest Shelf has led to the creation of a variety of coastal habitats, influenced by the amount of exposure to ocean swells. Up to 60 percent of wave energy can be prevented from reaching the coast by offshore features such as reefs. Where these structures limit wave action from affecting the coast, protected beaches and estuaries can form (Valesini et al. 2003).

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Figure 27: Mean (a) and maximum (b) wave energy for the Inner Rottnest Shelf. Physical wave energy gradually decreases to the north (Richardson et al. 2005:25).

Sanderson (2000) notes how the protection provided by offshore reefs causes a dynamic interaction between currents and waves. These processes greatly affect the evolution of depositional landforms, for example, ‘cuspate forelands and tombolos typically form behind offshore islands, patch reefs, and limestone headlands’ (Sanderson et al. 2000:78). These patterns of sediment deposition and shoreline configuration can alter quickly in response to evolving inshore wave patterns as coastal barriers become degraded. The reef systems of the Rottnest Shelf, for example, were likely more extensive in the past, with fewer gaps and higher elevation. Wave attack has eroded the reefs over time, creating more gaps and lower elevation, in doing so, changing the erosional and depositional processes (Figure 28) (Geoscience Australia 2021; Sanderson et al. 2000:78).

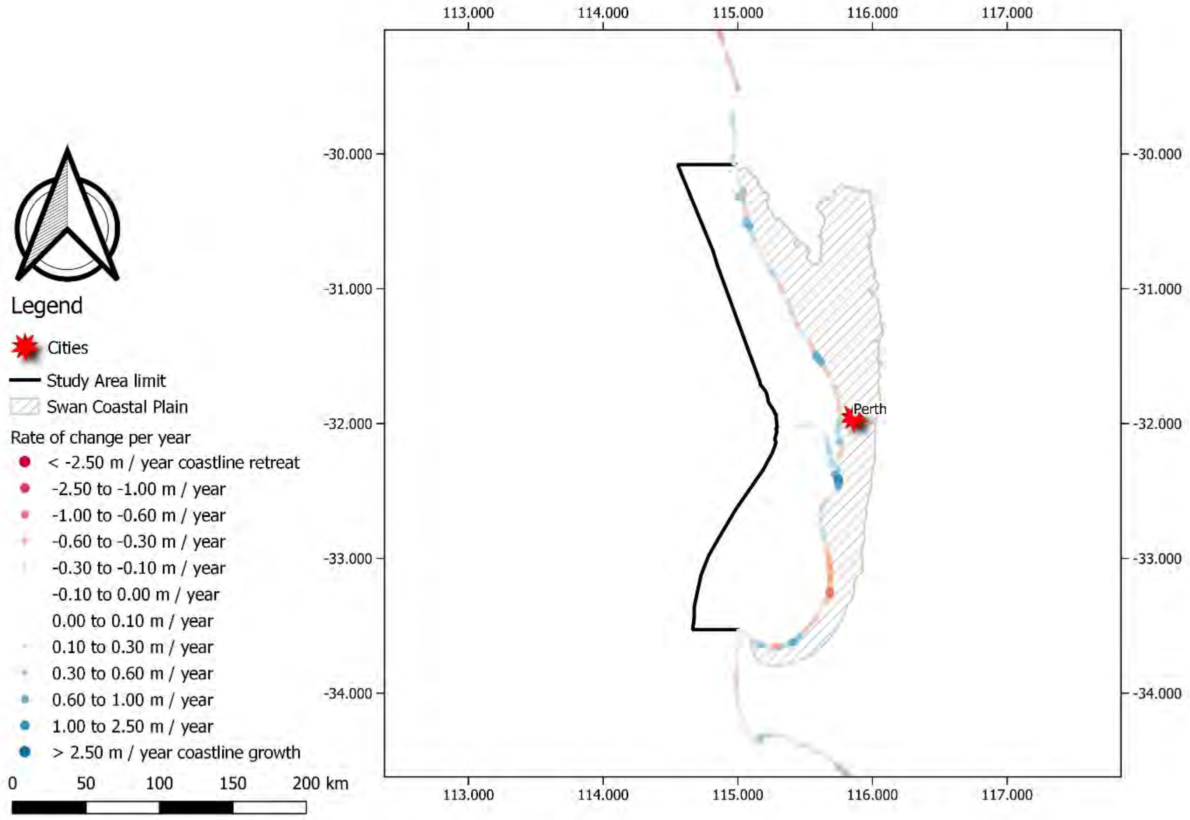

Figure 28: Digital Earth Australia CoastLines tracks the rate of coastal change around Australia (Geoscience Australia 2021). This figure presents coastal erosion on the SCP. Where the coastline is sheltered from wave energy, it can be seen the rate of coastline retreat is lessened.

Rottnest Shelf tides are microtidal, with a range of <0.5m, and thus have a limited effect on sediment transport (Sanderson et al. 2000; Searle and Semeniuk 1985). However, non-tidal sea-level variations, such as cyclones, can result in high sea-level peaks of 1–2 m when they travel along the coast, while a stronger LC can also induce increased sea level along the west coast (Pattiaratchi and Buchan 1991; Provis and Radok 1979).

4.1.2 Fluvial Processes

The rivers of the SCP occur either in wide channels with vast floodplains or as narrow steep-sided, straight channels (McArthur and Bettenay 1974). The Swan and Collie, and to a lesser degree, the Dandalup, are of the former type, while all other streams are of the latter type. McArthur and Bettenay (1974) suggest that wide channels and floodplains formed in Middle to Late Pleistocene times whereas the narrow channels formed in the Holocene. Major rivers are significant not only due to their extended age but also as a means for ‘wetland and alluvial resources to extend inland’ across the SCP (Hallam 1987:14).

Various studies have shown that development of fluvio-estuarine depositional environments is primarily controlled by sea-level change (Blum et al. 2013; Blum and Törnqvist 2000; Lambeck et al. 2002). Cycles of cutting and filling resulted in riverine deposits of different ages on the SCP that are representative of past drainage systems. Other past drainage systems are shown by lines of swamps, for example in the Waroona district, where earlier streams are revealed by thin depressions oriented north and south and containing fine-textured deposits (McArthur and Bettenay 1974).

The Swan River is the central river system on the SCP. Playford (1983:14) identified how the palaeo-Swan River would have cut across the exposed Rottnest Shelf during glacial periods. Beginning from the Late Pleistocene, the sedimentological history of the Swan River can be described in three phases, each resulting in a distinct palaeochannel (Bufarale et al. 2017). From the oldest to most recent, these are the: A) Perth Formation, B) Swan River Formation, and C–D) Holocene deposits (Figure 29). Several surficial and buried palaeochannels have also been detected south of the Swan River Estuary, in Geographe Bay, off the southern coast of the SCP (Bufarale 2019). Some of these palaeochannels directly align with the modern Capel River mouth, demonstrating that a palaeo-Capel River flowed in the past. Bufarale (2019:92) suggests these channels indicate that the 'palaeoriver might have been more significant, in terms of dimensions, discharge and flow than the modern one.'

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Figure 29: Late Quaternary development of the morpho-stratigraphy of the Swan River Estuary. A) Formation of deep inset valley during the Last Glacial period. B) Sea-level fluctuations 70–50 ka ago led to the alternation of erosion and deposition and subsequent filling of channel with sediment. C) During the LGM the most recent palaeochannel was formed. D) This channel was filled with Holocene fluvial deposits. Elevation/depth values are in metres and refer to present sea level; 'orange lines represent the width of active valley' (Bufarale et al. 2017:137).

Regarding the contemporary landscape, drainage from the SCP is generally by consequent streams extending seaward from the Darling Plateau. McArthur and Bettenay (1974:14) identify how these streams, upon entering the Pinjarra Plain, are diverted north or south, merging, and thus entering the sea at only a few main points. While Fremantle Blanket sediments are mainly formed from erosion and biotic assemblages, near to these exit points fluvial sediment can accumulate and can exceed 50 percent of surface sediment (Collins 1988:29; James et al. 1999:1302; Richardson et al. 2005).

4.2 Landscape Modelling

4.2.1 Submerged Landscape Reconstruction

The landscape modelling results present the evolution of the SCP over the last 50 ka. The results of the landscape modelling are presented in Appendix 3. These changes are presented in 1,000-year intervals, according to the sea-level data recorded in Section 4.1 and are discussed further in Section 5. All maps were produced at a scale of 1:15,000 m.

The creation of a single DRM that encompassed the SCP and the Rottnest Shelf, at a sufficient resolution to enable hydrological modelling, was a significant element of this study. A variety of disparate data was assembled, from which base point elevation data was extracted. With this extracted data, a DRM was produced at 100 m resolution. Resolution was limited by the processing capabilities of available computer hardware. This method (Section 3.2) successfully demonstrated proof of concept and can be replicated using the same method and data, with improved processing capabilities, to produce a DRM of the same area of up to 50 m resolution. The use of 100 m resolution DRMs for hydrological analysis on the submerged continental shelf, however, has been successfully demonstrated by Conti and Furtado (2009), who identified palaeo-drainage networks using GIS before groundtruthing their location using a sub-bottom profiler.

The landscape model shown in Figure 30 displays the current terrestrial component of the SCP and the extent of the continental shelf exposed at the height of glaciation. At this time, an additional 20,000 km^2 of land would have been available; ranging between 30 km, in the north, and 90 km, in the south, from the current coastline. Rottnest, Garden and Carnac Islands were all connected to the mainland and the shore-parallel ridges, interpreted by Brooke et al. (2014) as cemented palaeo-sand dunes, are visible along the extent of the coastline.

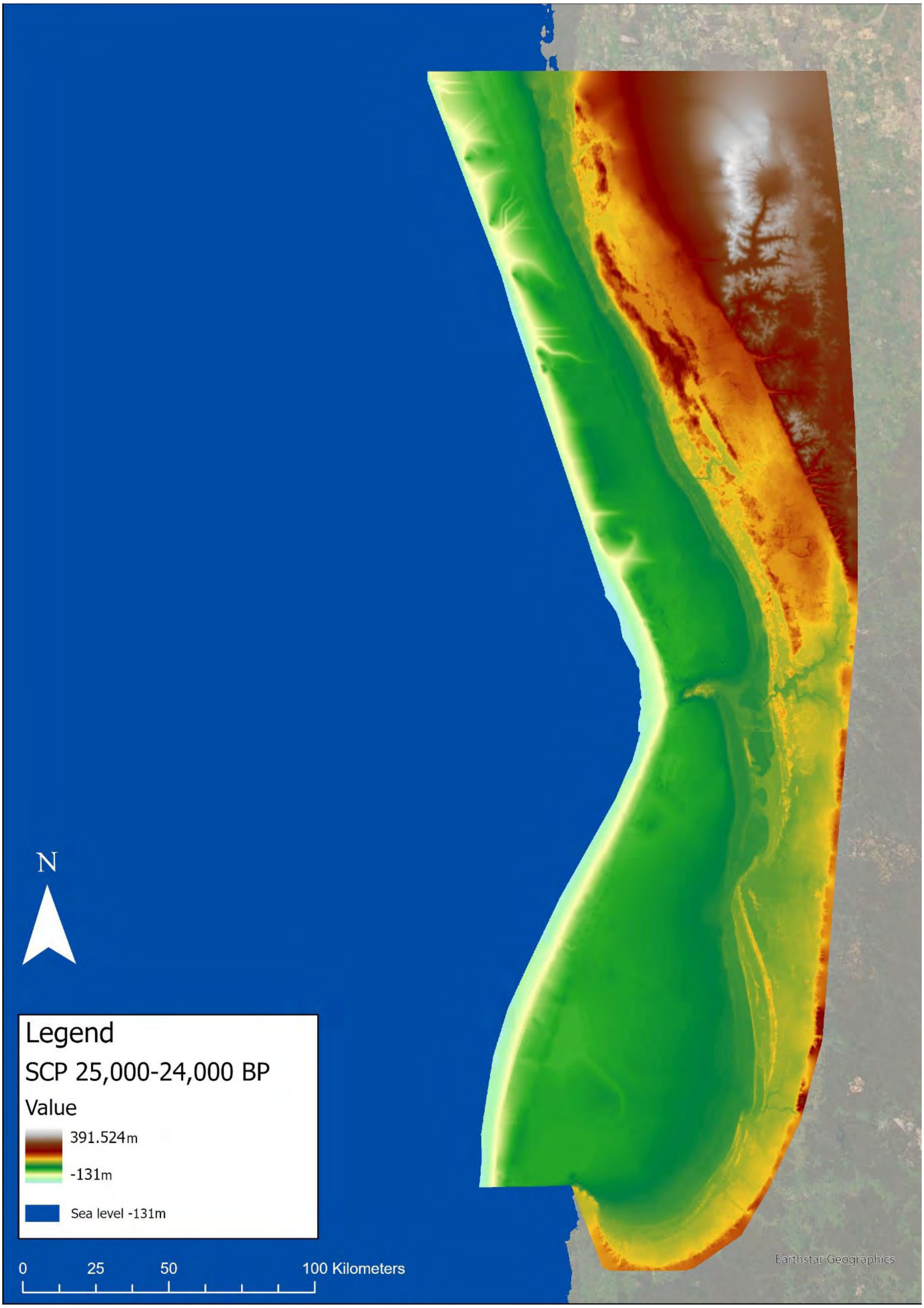


Figure 30: SCP landscape extent and features at 25,000 to 24,000 BP, overlain on imagery of the contemporary landscape. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

4.2.2 Hydrological Analysis

Figure 31 presents the results of the hydrological analysis and shows the stream network laid across the SCP and the adjacent continental shelf. Figure 32 shows the similarities between the Department of Water and Environment Regulation (**DWER**) Linear Hydrography dataset (DWER 2018) and predicted drainage channels resulting from hydrological analysis. To validate the effectiveness of hydrological analysis a comparison was made in the currently terrestrial area with modern river channels and, although no quantitative measure was taken, the correlation was found to be high. No other hydrological analysis models of this resolution, which encompass both the current onshore and offshore landscape, have been published.[2]

According to the results of the hydrological analysis, most SCP river channels can be seen to discharge offshore and are the continuation of modern channels, however, several channels represent palaeorivers that would have only existed on the continental shelf. The location and extent of the modelled drainage channels result from a calculated stream threshold (Section 3.2.3). Implementing a higher stream order threshold diminishes the likelihood of false positives and results in larger channel features that will be easier to identify during potential groundtruthing activities (Duggins 2012:106–107). Only those line features (streams) of a weighting of 6 or more, according to the Strahler method, were displayed. In the Strahler method, first order streams are allocated an order of 1; whenever a stream of the same order intersects, stream order increases. As such, higher order streams represent greater upstream concentrated flow and are thus more likely to create channels within the landscape (ESRI 2022f). Higher order streams are also more representative of wide channels; those that formed during the Late Pleistocene (McArthur and Bettenay 1974), and so, are likely to have been present for the entire span of human occupation of southwestern Australia. These 'major rivers' also influenced the distribution of wetland and alluvial resources on the SCP, unlike 'lesser and less permanent streams' (Hallam 1987:14). Where modelling results have delineated in straight lines suggests that higher rates of sedimentation in these areas have obscured the seabed sufficiently to bury such features. In these locations palaeochannels and other formally subaerial low-lying landforms may have been infilled instead of preserved.

[2] Crabtree (2021) have produced a hydrologically modelled stream network of Sahul, however, limited only to Strahler order 9 and using a DRM of coarser (~250 m) resolution.

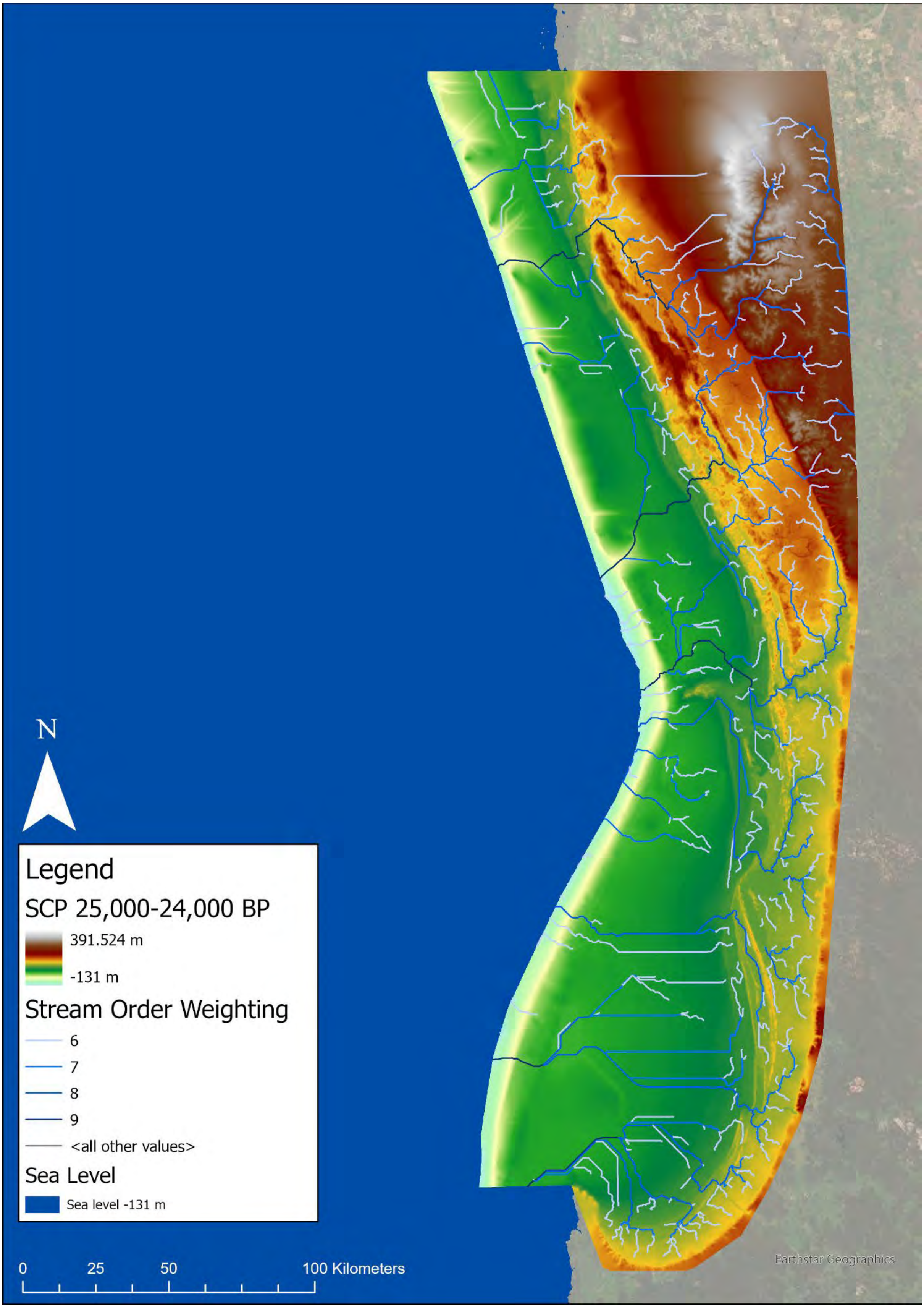


Figure 31: SCP Hydrological Analysis overlain the DRM of combined SCP and Rottnest Shelf. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

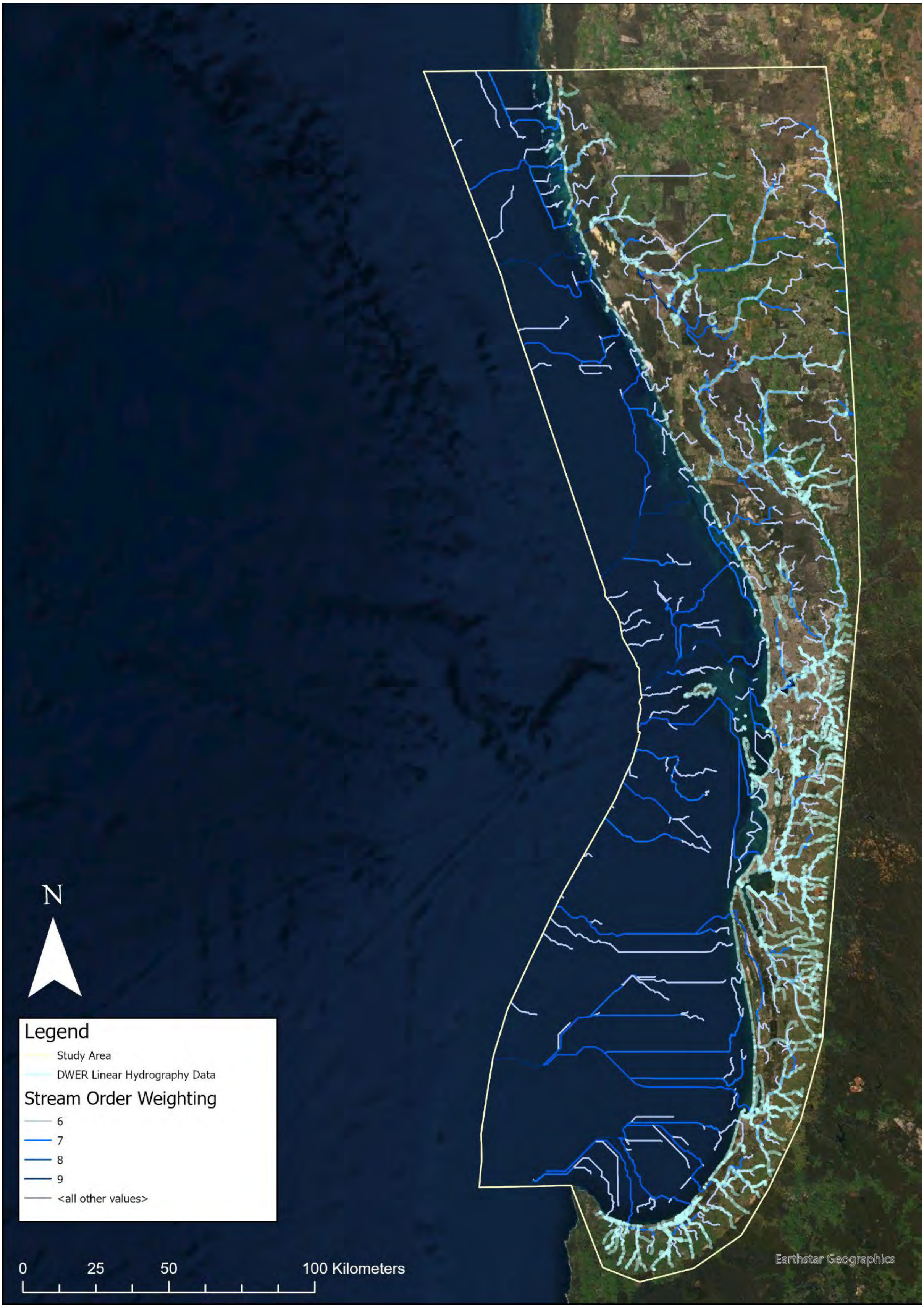


Figure 32: SCP Hydrological Analysis overlain on the DWER Linear Hydrography dataset. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

4.3 Site Distribution Analysis

This study incorporated 1,039 separate sites from the DPLH Aboriginal Heritage Places register. All sites were given a unique vector point and treated equally for the purpose of analysis. Initial observation shows that Aboriginal sites extend across the extent of the SCP but are not evenly dispersed (Figure 33). Sites appear to be clustered primarily around the Swan River Estuary and at large, southern estuaries. When site distribution is overlain on the Department of Biodiversity, Conservation and Attractions (**DBCA**) Geomorphic Wetlands dataset (DBCA 2022) or a filtered layer of DWER (2018) Linear Hydrography dataset, so that only 'Major Rivers' are displayed, it appears that sites are distributed near to these landforms (Figure 34 and 35).

While plotting the distribution of sites is informative, site patterning can be better visualised by utilising density analysis (Bevan 2020). Kernel density analysis was undertaken using a search radius of 7.5 km and 38 km, as informed by Marlowe's (2005) analysis of the home range of warm climate non-equestrian foragers. Figure 36 shows the density of sites with an estimated home range of 175 km^2, representing the median home range taken from Marlowe's ethnographic data. Previous archaeological studies and ethnohistorical records suggest that Aboriginal people were highly mobile as they moved across the SCP in search of seasonally available coastal and inland resources (Dortch 2002a; Dortch and Dortch 2019; Gibbs 2011; Hallam 1987; Moore 1884; Monks 2021). Therefore, the maximum-recorded home range value from Marlowe's ethnographic data of hunter-gatherers, 4,500 km^2, is likely more representative of Aboriginal peoples' mobility on the SCP than the lower median number (Figure 37). Density analysis shows an area of highest density centred on the Swan River Estuary. Density gradually decreases as distance from this central point increases.

Figure 33: Distribution of Aboriginal sites on the SCP (n = 1,039) and location of major urban centres. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

Figure 34: Distribution of Aboriginal sites on the SCP in relation to wetland location. The DBCA Geomorphic Wetlands dataset was filtered according to physical classification to exclude drylands, artificial wetlands, and non-assessed wetlands. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

Figure 35: Distribution of Aboriginal sites on the SCP in relation to the filtered 'Major Rivers' layer. The Major Rivers layer was filtered from the DWER (2018) hydrography dataset to include only mainstreams, rivers, and significant streams. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

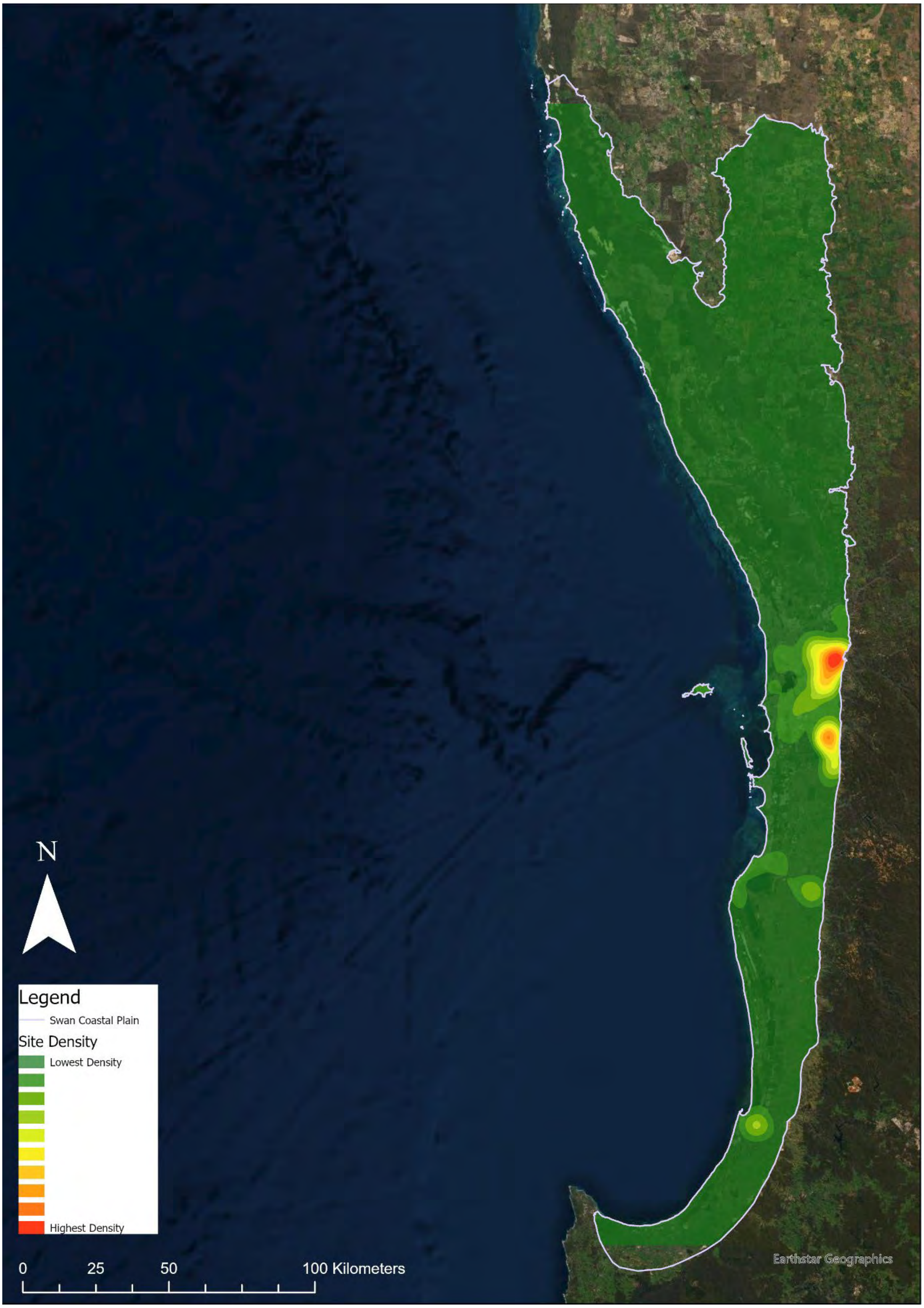


Figure 36: SCP Aboriginal site density home range 175 km^2. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

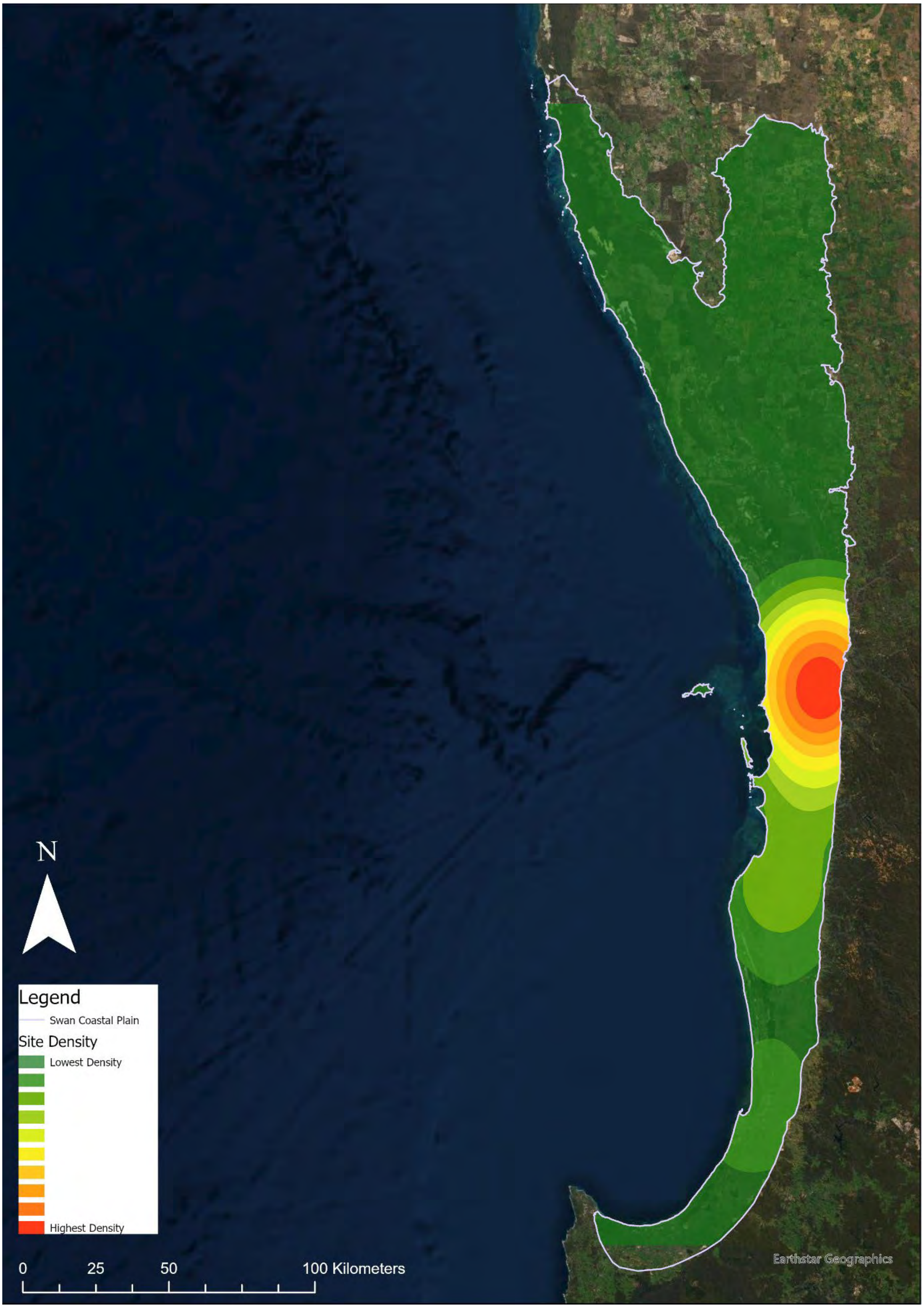


Figure 37: SCP Aboriginal site density home range 175 km^2. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

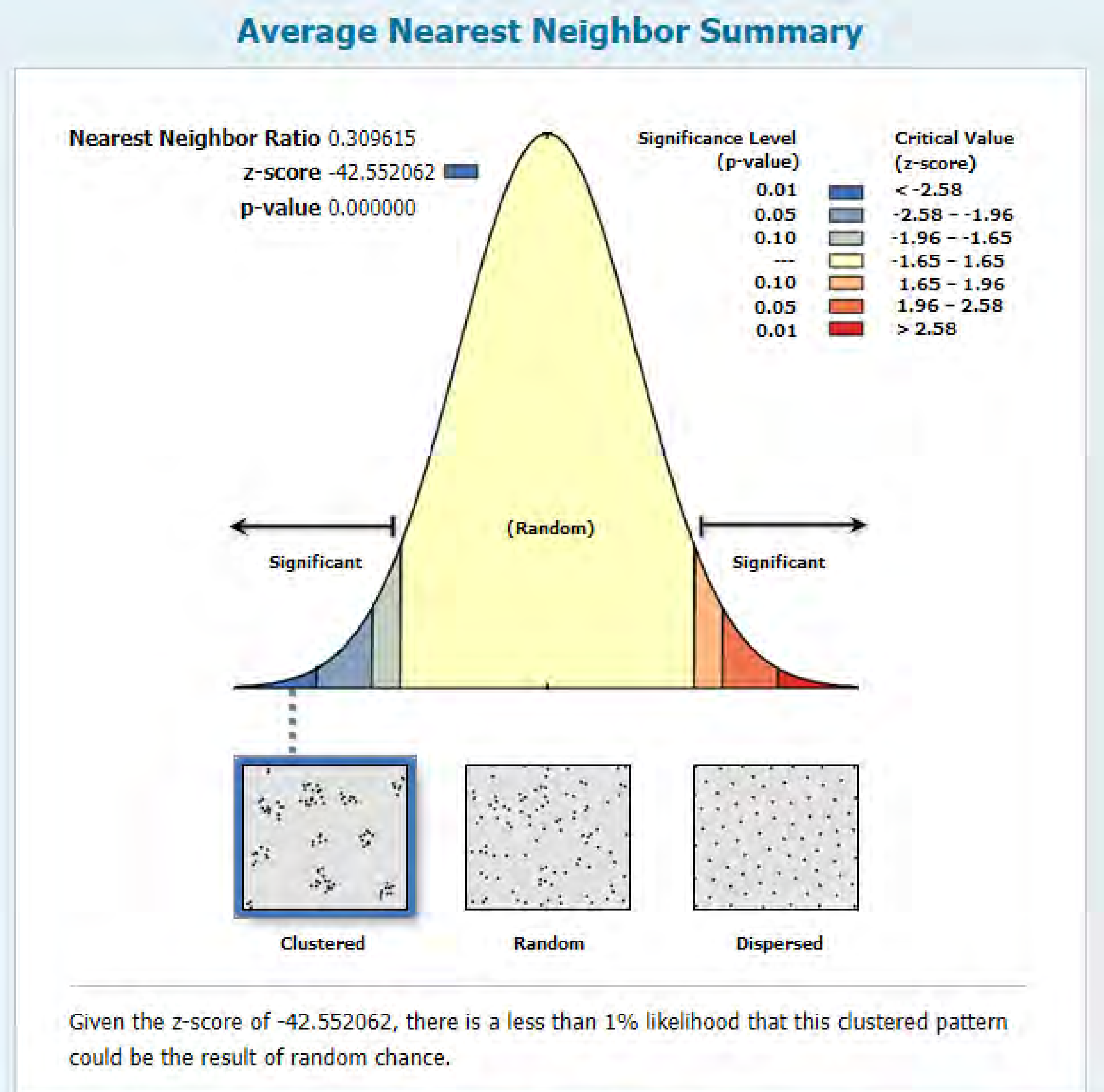
4.3.1 Site Proximity

Understanding the distance between sites provides additional insight into patterns of land use of the SCP and is also useful in guiding future survey work. When a new site is found, knowing the average distance between sites helps to guide the survey distances in an onshore and offshore context. Measuring distances between Aboriginal heritage sites on the SCP (Table 2) provides a different approach to kernel analysis. The median distance between sites is 416 m, suggesting a concentration of sites in nearby areas.

Table 2: Nearest neighbour site proximity for SCP sites (m) (n=1,039).

Median	416.9
Average	940.3
Minimum	0.001
Maximum	19,095.8

This analysis is further supported by the use of the Average Nearest Neighbour tool in ArcGIS Pro. The Average Nearest Neighbour tool averages the ‘distance between [site points] and its nearest neighbour’s location. If the average distance is less than the average for a hypothetical random distribution, the distribution… [is] considered clustered’ (ESRI 2022i). Accordingly, if the Nearest Neighbour index is less than 1 the pattern exhibits clustering, while if it is greater than 1 it exhibits dispersion. The 1,039 SCP sites were found to have a Nearest Neighbour ratio of 0.309615, demonstrating that the sites are clustered (Figure 38). This result aligns with the findings of the distribution analysis and previous archaeological studies detailing the high density of surface artefact scatters on the SCP, often identified near to wetlands and waterways (Dortch 2002a; Dortch and Dortch 2019:24–25; Dortch and Hook 2017; Hallam 1987; Monks 2019).



Average Nearest Neighbor Summary

Observed Mean Distance	940.3414 Meters
Expected Mean Distance	3037.1265 Meters
Nearest Neighbor Ratio	0.309615
z-score	-42.552062
p-value	0.000000

Figure 38: Average Nearest Neighbour output demonstrates that site patterning on the SCP exhibits significant clustering (n = 1,039).

Further site patterning can be established when comparing the relationship between sites and different water features. The median distance between sites and wetlands is 311 m, while the median distance between sites and Major Rivers is 1062 m (Table 3), suggesting a stronger relationship between sites and wetlands, than between sites and rivers. When comparing these distances with distances between random points and wetlands/rivers (Table 4 and Figure 39), the site-water distances are significantly closer than the random point-water distances. While this association is truer of wetlands features, the relationship between sites and major rivers is also significantly closer than the distance between random points and rivers.

Table 3: Distance between SCP sites and Wetlands, Major Rivers, or Hydrological Analysis results (m).

	Sites-Wetlands	**Sites-Major Rivers**
Median	311.6769	1062.285
Average	1722.683	1824.034
Minimum	0	2.917227
Maximum	68293.4	14325.06

Table 4: Distance between random points and Wetlands, Major Rivers, or Hydrological Analysis results (m).

	Random Points-Wetlands	**Random Points-Major Rivers**
Median	1188.899	2296.068
Average	7560.692	3338.97
Minimum	0	0.976425
Maximum	70192.14	16957.82

Figure 39: Position of random points generated on the SCP for distance analysis (n = 1,039). Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

4.3.2 Sites and Water Features

There is a clear relationship between Aboriginal sites on the SCP and water features, particularly wetlands. Figures 40–42 show the relationship between sites and distance from wetlands. Figure 40 demonstrates how site numbers decrease with increasing distance from wetlands. The upward trend seen at the middle-distance interval (0.5–1 km) is potentially misleading; this, and subsequent, buffer intervals are larger (0.5–1 km each) than the initial five buffer intervals (0.1 km each). Additionally, higher buffer ranges may also encompass other attractive landforms besides wetlands, such as other water sources, soil types, or vegetation, that influence catchment numbers. Yet, it may also suggest a deliberate occupation choice; Dortch et al. (2007:18) records how Noongar people preferred not to camp immediately adjacent to 'fresh water to avoid insects and to not pollute the source.' This trend in the data is seen for all analysed water sources. Almost 30 percent of sites lie within 0.1km wetlands and a cumulative 75 percent of sites lie within 1 km of wetlands. Frequency change data shows diminished returns after 0.1 km, and then again after a 0.5km buffer. There is a strong negative correlation (R = -0.72833) between site frequency and distance from wetlands.

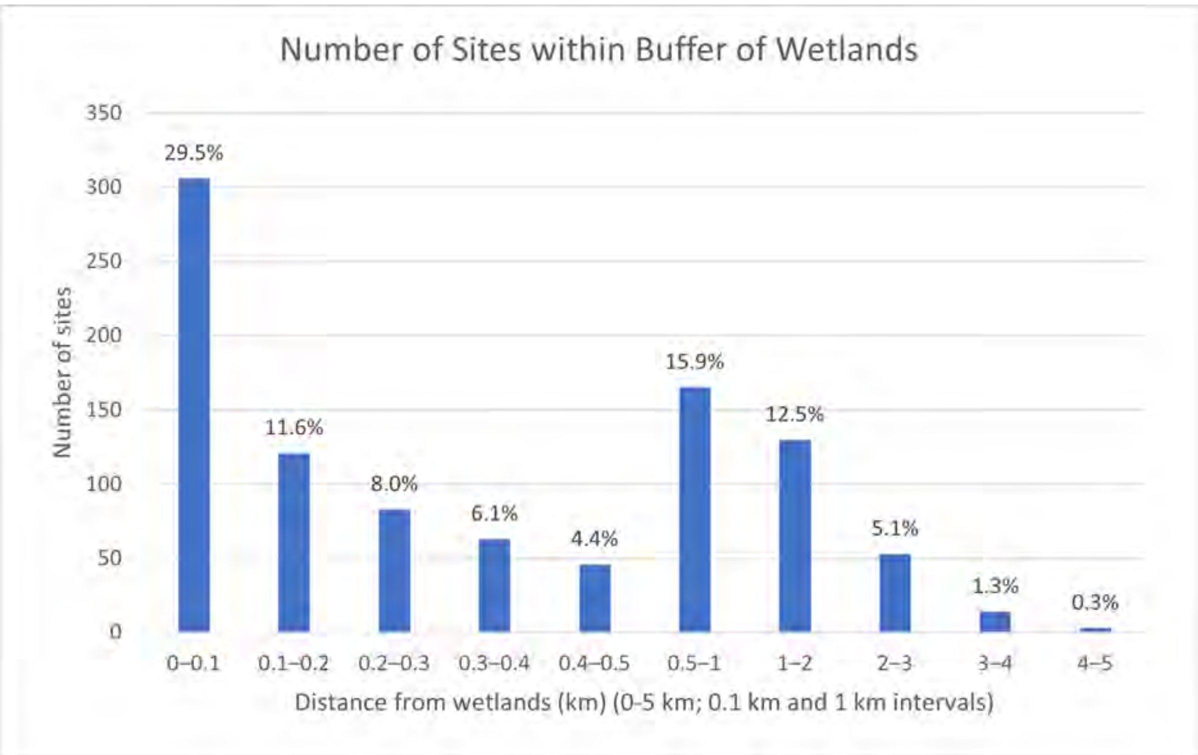


Figure 40: Distribution of Aboriginal sites on the SCP relative to distance from wetlands. 0.1 km distance intervals between 0.1–0.5 km buffers; 1 km intervals between 1–5 km buffers.

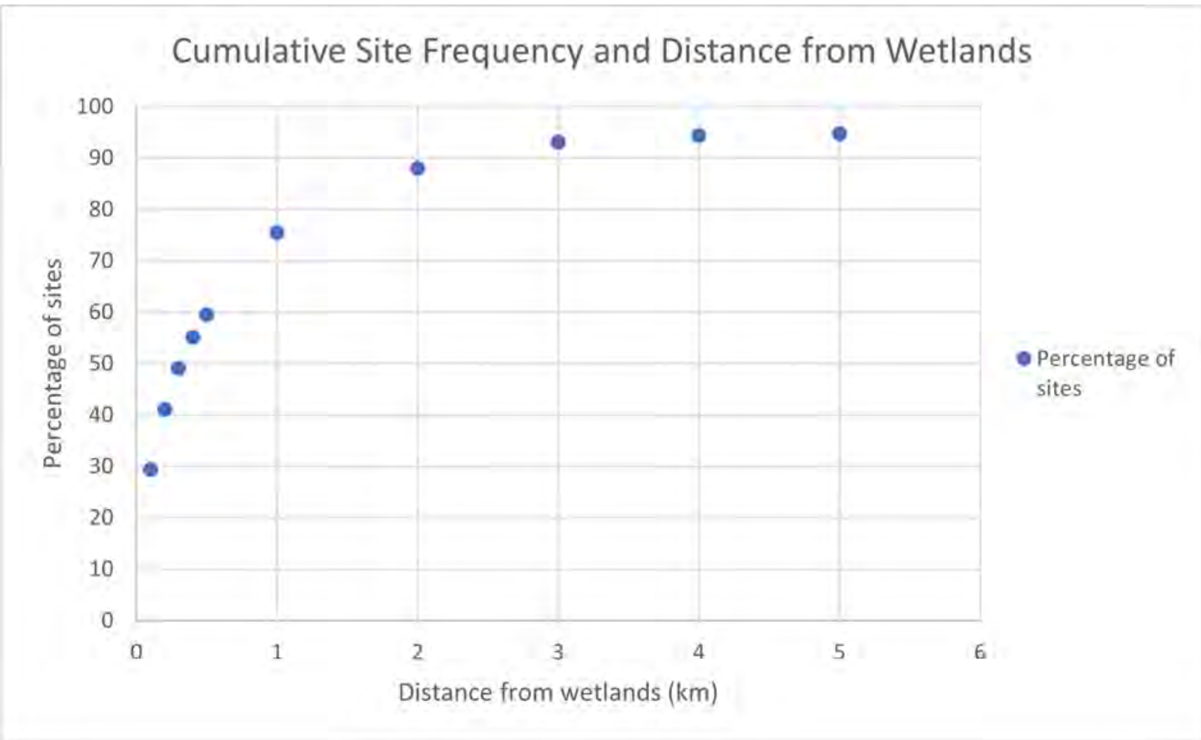


Figure 41: Cumulative Aboriginal site frequency relative to buffer distance from wetlands.

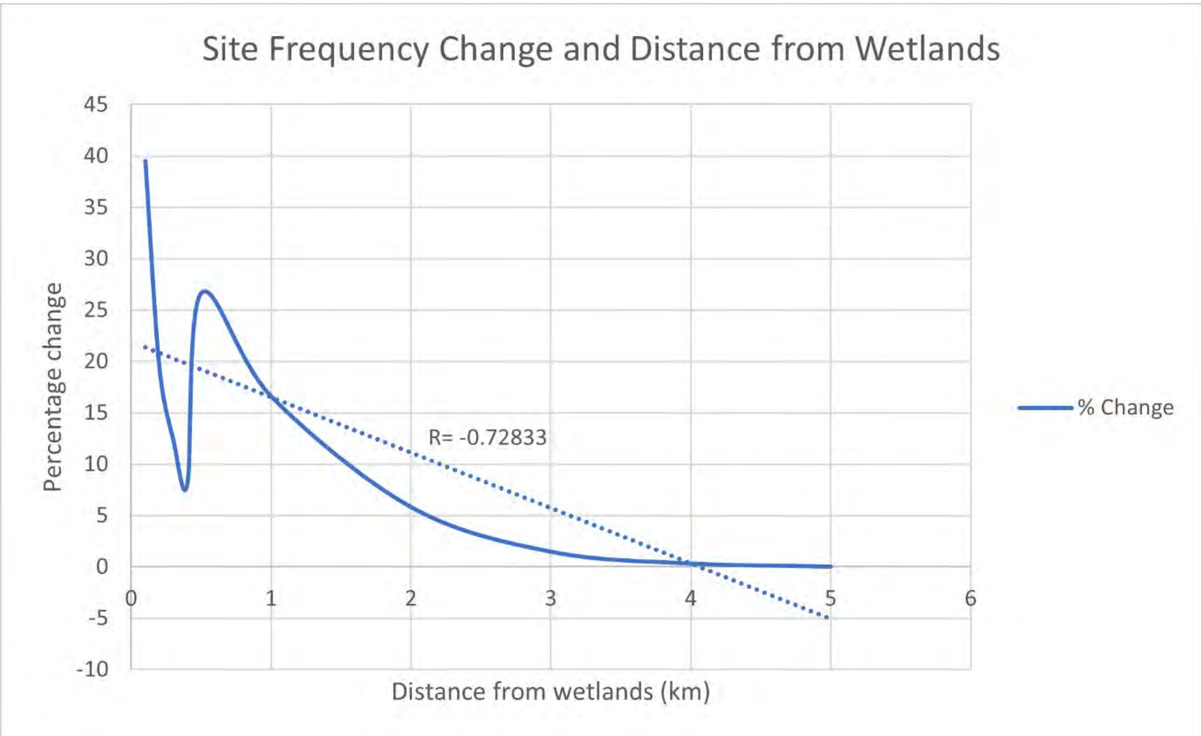


Figure 42: Aboriginal site frequency change and distance from wetlands.

There is a relationship between site location and the features contained in DWER Linear Hydrography dataset (Figure 43–45). Sixteen percent of sites lie within 0.1 km of these features and cumulative 73 percent of sites are within a 1 km buffer. Frequency change data shows diminished returns after 0.1 km and 0.5km. There is a strong negative correlation (R = -0.67029) between site frequency and distance from all rivers, streams, and tributaries. These data indicate an association between site location and river landforms and suggest Aboriginal people were utilising resources near a variety of water sources.

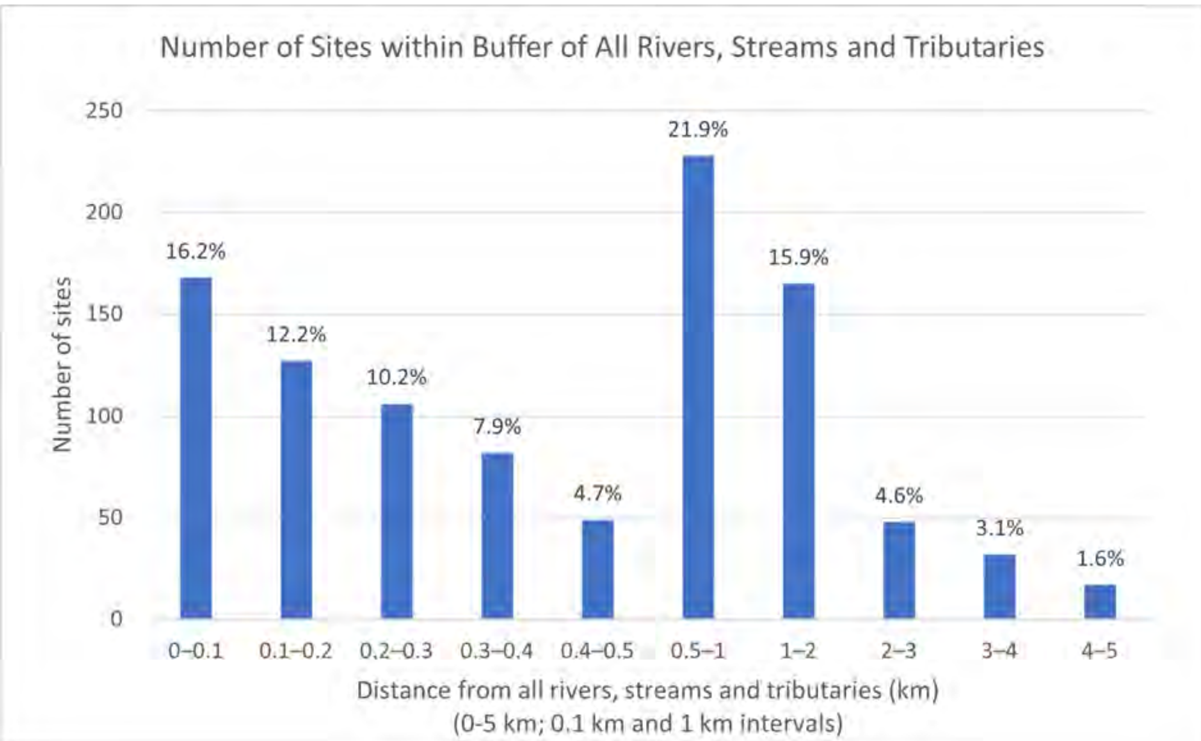


Figure 43: Distribution of Aboriginal sites on the SCP relative to distance from all rivers, streams, and tributaries. 0.1 km distance intervals between 0.1–0.5 km buffers; 1 km intervals between 1–5 km buffers.

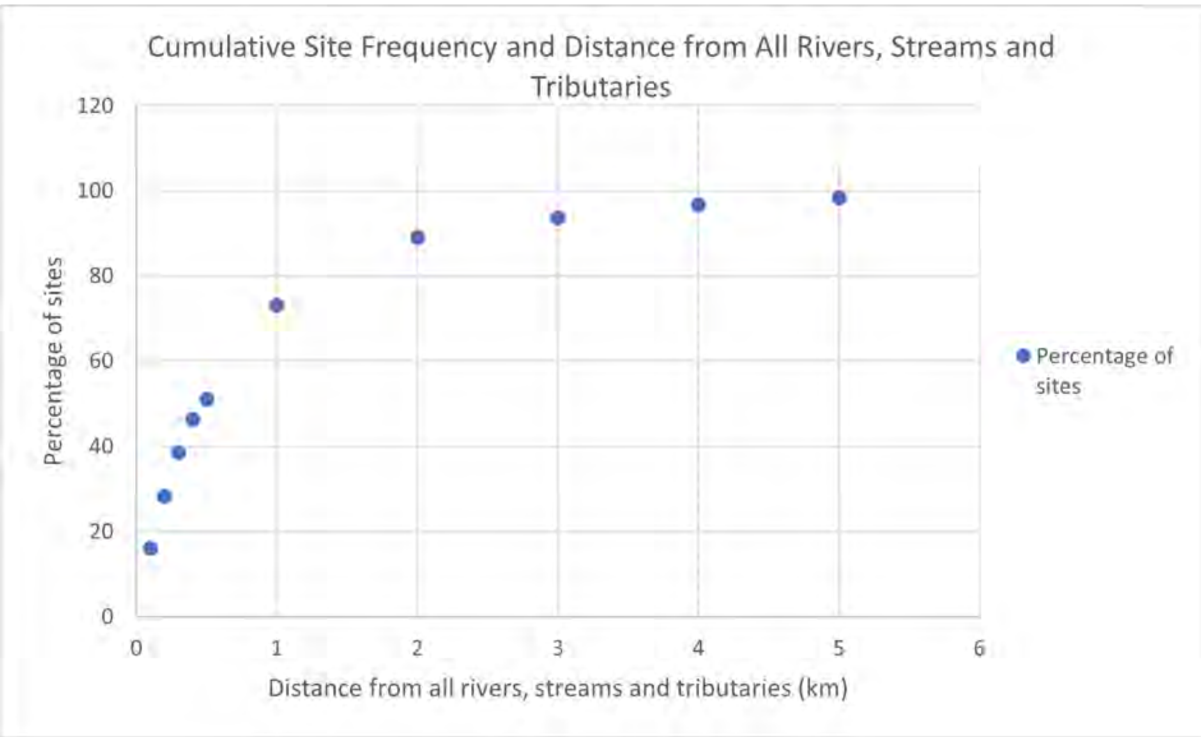


Figure 44: Cumulative Aboriginal site frequency relative to buffer distance from all rivers, streams, and tributaries.

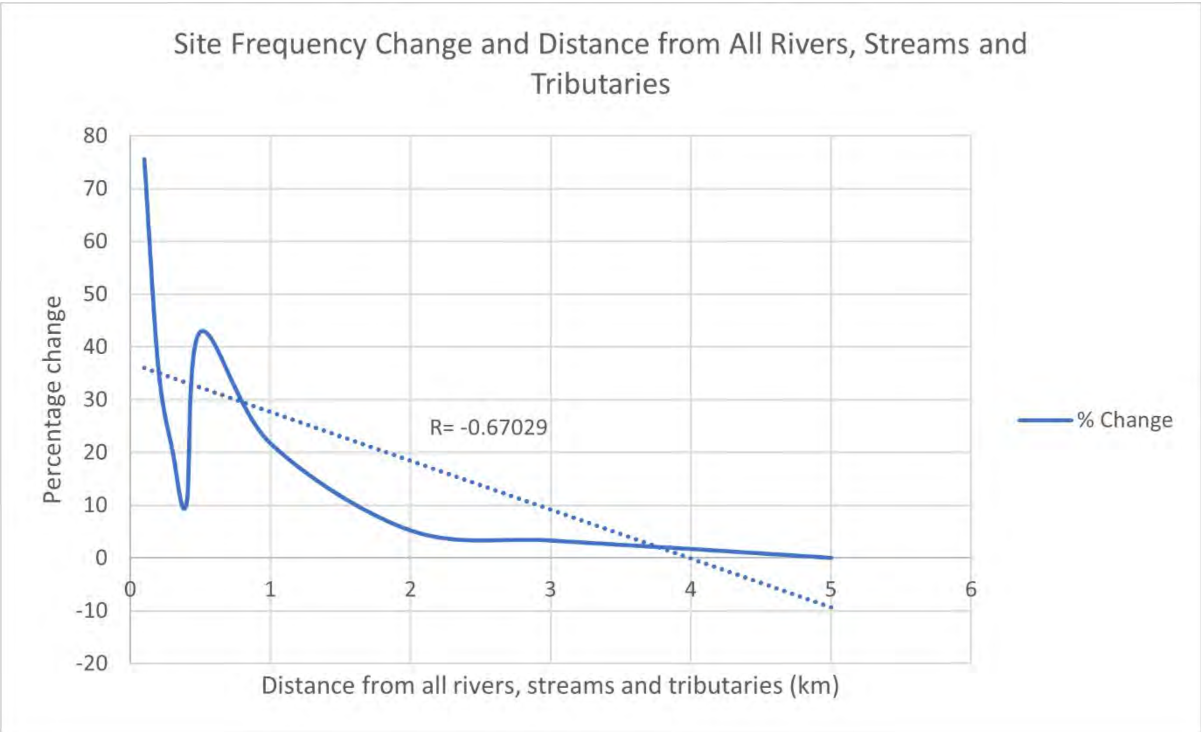


Figure 45: Aboriginal site frequency change and distance from all rivers, streams, and tributaries.

When smaller streams and tributaries are removed from the DWER Linear Hydrography dataset, and only mainstreams, rivers, and significant streams included, there is a reduction in site numbers contained within buffers (Figure 46–48). Despite this reduction, a negative correlation (R = -0.54512) between site frequency and distance from mainstreams, rivers and significant streams exists. Frequency change data shows a drop in return after 0.1 km and 0.5 km. A cumulative 26 percent of sites lie within 0.3 km of major rivers and a cumulative 48 percent of sites sit within 1 km of major rivers. This demonstrates that even with a reduced dataset, lacking smaller streams and tributaries, a relationship still exists between sites and major rivers.

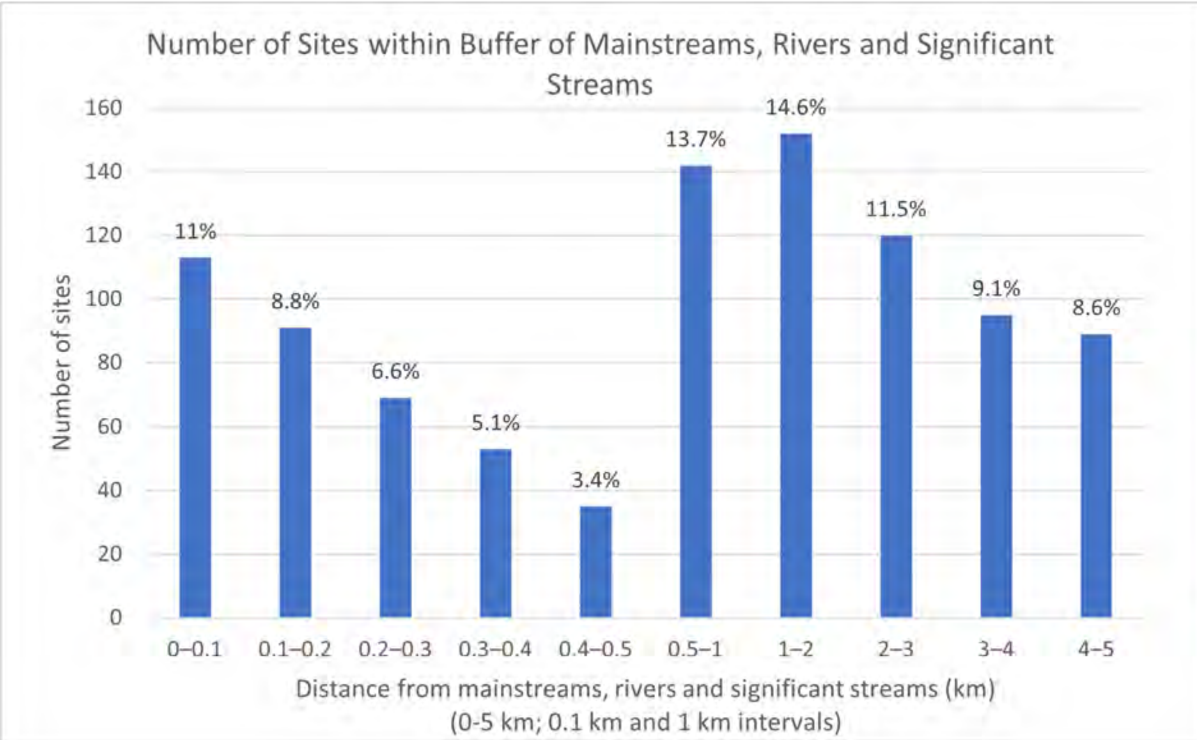


Figure 46: Distribution of Aboriginal sites on the SCP relative to distance from mainstreams, rivers, and significant streams. 0.1 km distance intervals between 0.1–0.5 km buffers; 1 km intervals between 1–5 km buffers.

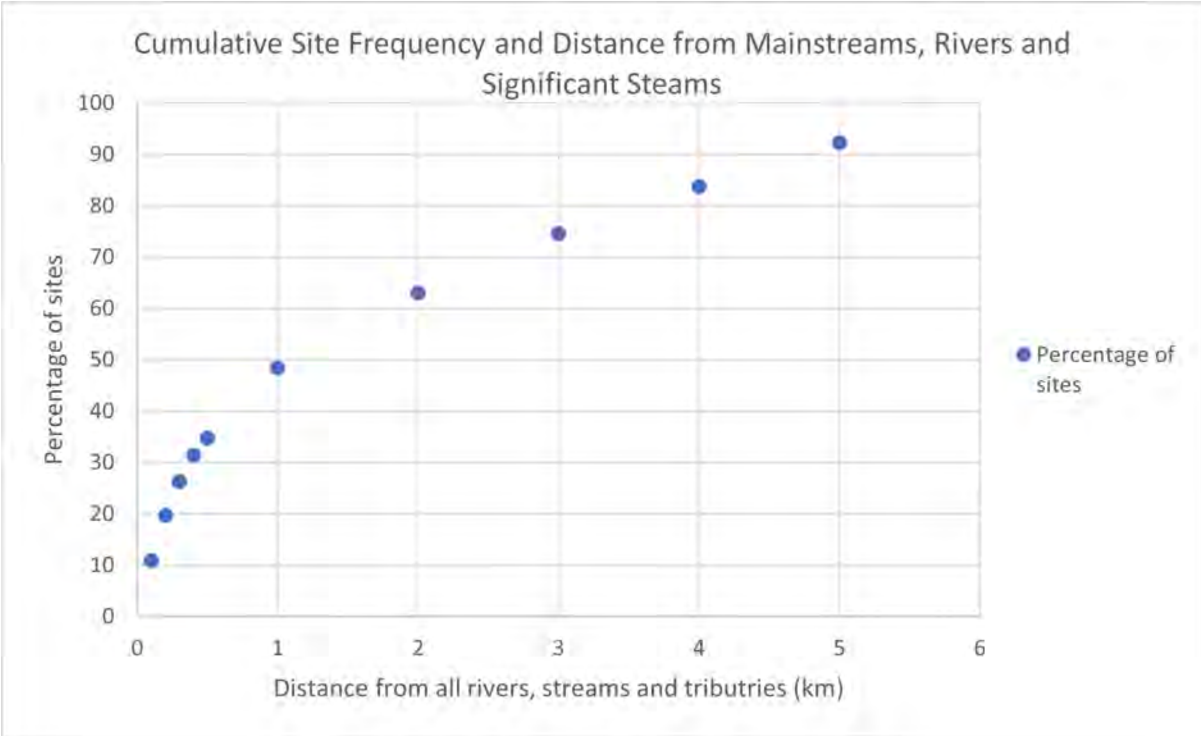


Figure 47: Cumulative Aboriginal site frequency relative to buffer distance from mainstreams, rivers, and significant streams.

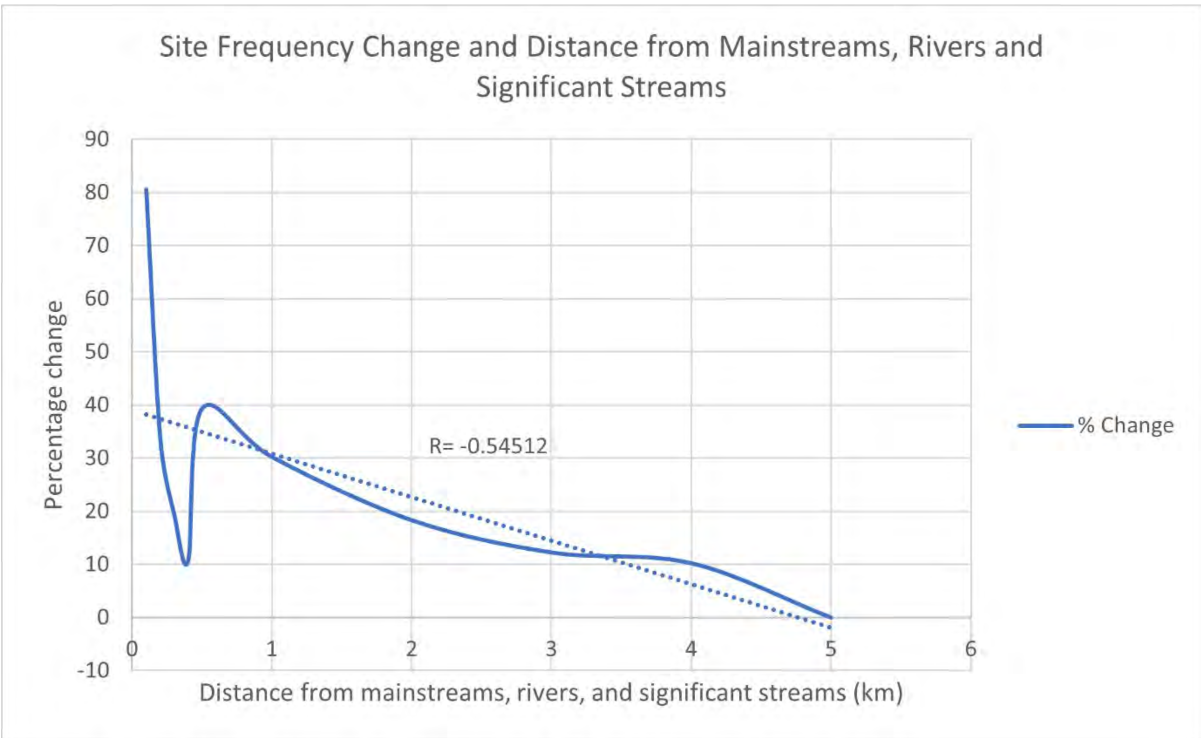


Figure 48: Aboriginal site frequency change and distance from mainstreams, rivers, and significant streams.

A relationship can also be seen between sites on the SCP and the drainage channels produced via the hydrology analysis (Figure 49–51). Frequency change data shows a drop in return after 0.1 km and 1 km. A negative correlation (R = -0.60858) between site frequency and hydrological modelling results also exists. A cumulative 13 percent of sites are situated within 0.3 km of a drainage channel and a cumulative 33 percent of sites lie within 1 km of a drainage channel. These results reveal an association between site location and the results of the hydrology analysis. While the percentage of sites contained within individual sub-kilometre buffer catchments is lower than that of previously analysed water sources, it is worth noting the imposed limits of the Stahler order to ensure only higher order streams resulted from modelling. This means there are less data points on the terrestrial extent of the study area; modelling outputs on the continental shelf, however, are more likely to have survived and be identifiable.

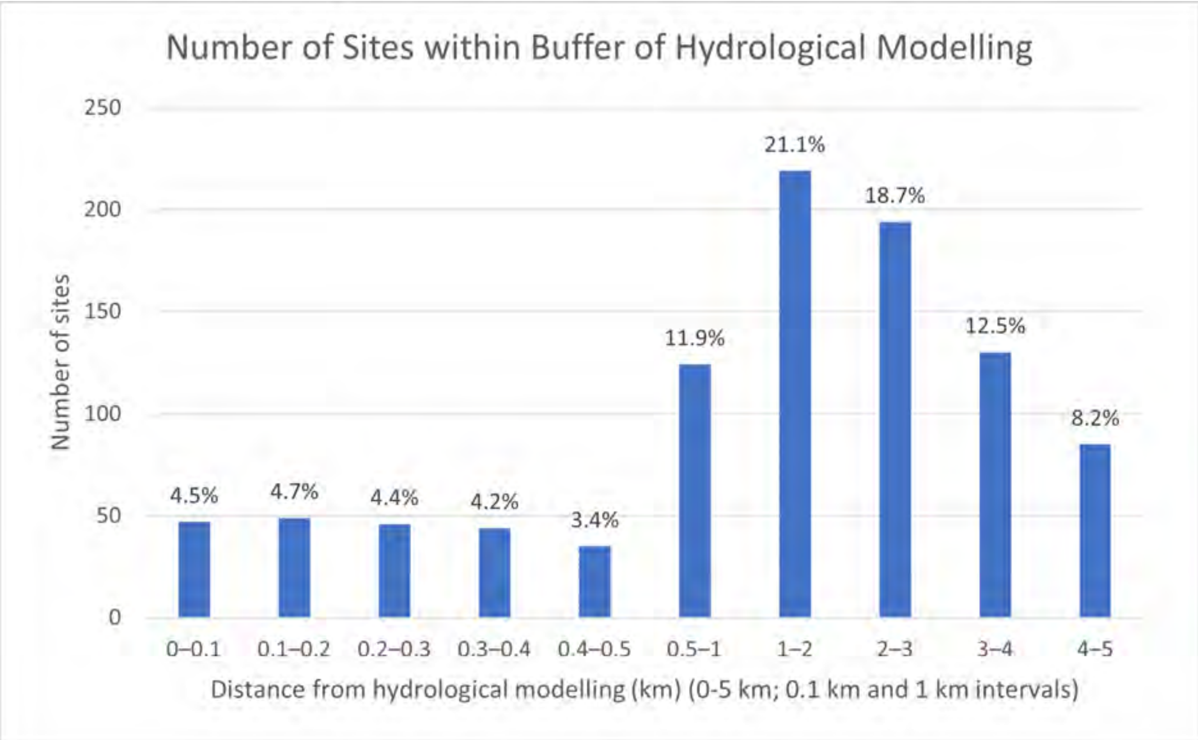


Figure 49: Distribution of Aboriginal sites on the SCP relative to distance from hydrological modelling. 0.1 km distance intervals between 0.1–0.5 km buffers; 1 km intervals between 1–5 km buffers.

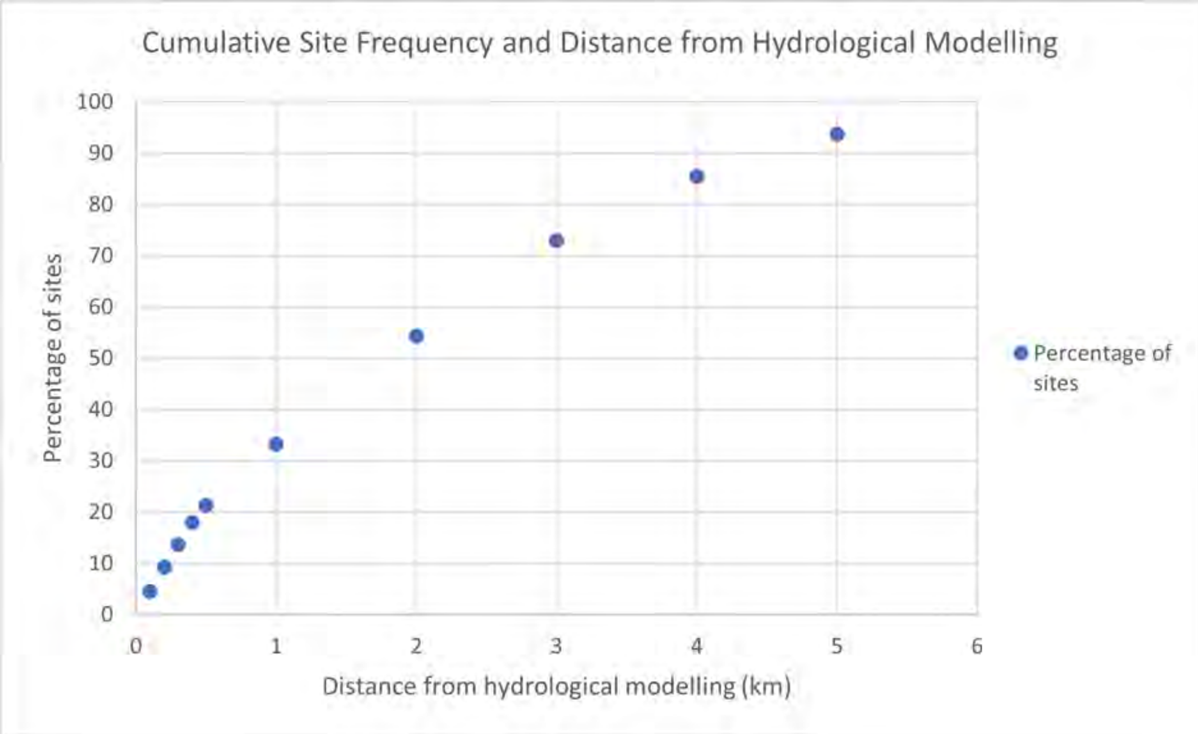


Figure 50: Cumulative Aboriginal site frequency relative to buffer distance from hydrological modelling.

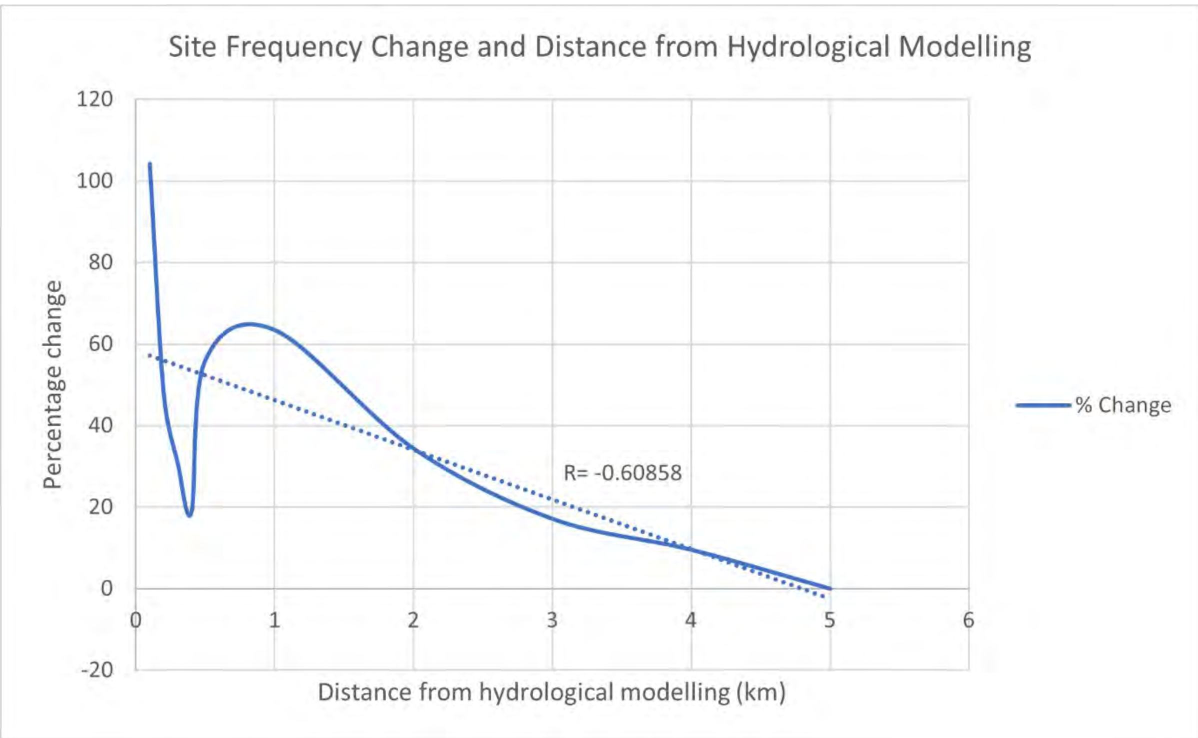


Figure 51: Aboriginal site frequency change and distance from hydrological modelling.

5 Discussion

This chapter presents the analysis and interpretation of the results of this study (Chapter 4). Patterns of site distribution in relation to landscape features are discussed in relation to previous theories of occupance and resource usage on the SCP and southwestern Australia more broadly. The submerged landscape reconstruction produced in this study is evaluated and discussed, together with the results of the desktop survey. High preservation potential areas for submerged landscape sites on the Rottnest Shelf are identified. Finally, this chapter discusses recommendations for future submerged landscape investigations on the SCP and Rottnest Shelf.

5.1 Site Distribution and Proximity: Strategies of Occupance and Resource Usage on the Swan Coastal Plain

This section will discuss the results of the site distribution and proximity analysis produced by this study within the context of existing theories of occupance and resource usage on the SCP. This study has quantified the relationship between SCP sites and water features, specifically wetlands. Such analysis of subaerial site distribution can provide insight into past strategies of occupance and resource usage on the SCP.

One of the first things to consider when analysing site distribution is survey bias. The greatest density of sites can be seen around the Swan River Estuary, and south, surrounding the Mandurah Estuary and Peel Inlet, the Leschenault Estuary, and the Vasse-Wonnerrup Estuary. These water features also situate major urban centres: Perth, Mandurah, Bunbury, and Busselton. The Perth metropolitan area alone represents one of the most concentrated areas of intensive and repeated heritage surveying in Western Australia. Compounding this, Hallam’s (1986) survey transect across the SCP also overlays the Perth metropolitan area. Hence, the potential for bias, owing to commercial and residential development of these areas and subsequent heritage surveys, is acknowledged. Ethnohistorical observations of early European colonists, however, indicate that the use of waterways and wetlands as meeting places and for resource exploitation at the time of European arrival was widespread across the SCP (Dortch 2002a; Gibbs 2011; Meagher 1974; Moore 1884).

Open water bodies such as rivers, wetlands, and lakes were not only economically significant, they also had/have important cultural and spiritual importance for Noongar people (Hughes-Hallet 2010:43–44). This is exemplified by the *Waugal*, a Dreamtime spirit believed by the Noongar people to be responsible for the creation of all waterways also being responsible for creating and preserving both the natural and cultural law (Bolleter 2015:1; Hughes-Hallet 2010:20). These beliefs, along with the resources provided by waterways, help explain their relationship to site distribution on the SCP.

The universality of rivers as a recognisable reference point upon a perhaps otherwise unfamiliar landscape was espoused by Bowdler (1977, 1990), who argued that, after occupying the coastline of Sahul, Aboriginal people travelled inward, utilising the continent's river systems. This coastal theory of colonisation is one of three distinct arguments relating to the colonisation of Sahul, the other two being based on inland routes or water availability (Figure 52) (O'Connell and Allen 2004:835). Bowdler (1990) re-examined her coastal colonisation theory to account for the increasing number of inland Pleistocene sites being identified, suggesting a faster adaption to unfamiliar environments, but maintained her theory of initial coastal expansion. Bowdler's coastal colonisation hypothesis was a response to Birdsell's (1953) model of colonisation that proposed an inland route and argued that population was a function of precipitation, with people expanding downwards across the continent as population increased (Birdsell 1977). Birdsell's model was also contested by Hallam (1977:173), who suggested 'it was not rainfall as such, but specific resources… in and around estuaries, lakes, rivers and swamps, which supported the highest populations.' Further, Hallam (1977) argued that patterns of resource usage were dynamic and changing, not static, as suggested by Birdsell (1977) and Bowdler (1977), the result of Aboriginal peoples' impact upon the landscape.

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Figure 52: Colonisation theories depicted as models: a) Inland routes; b) coastal colonisation; c) water availability (after Nutley 2006:2–3).

Hallam's (1987) model of occupancy and resource usage on the SCP was a direct response to Bowdler's (1977) littoral model of colonisation and expanded upon her own 'Topographic' model (1977), incorporating the results of her (1986) survey across the SCP and elements of Horton's (1981) colonisation model of Sahul. Horton's (1981:23–24) model asserted the colonisation of Sahul relied upon the availability of fresh water and adaptable subsistence strategies that could be applied to a variety of environments. Hallam (1987:10–11) developed this position, suggesting that the first people to enter Sahul from Sunda would have brought with them 'generalised subsistence patterns' applicable to the shared ecology of both continents, with the marine component having 'dropped out of the diet' as the colonists expanded across Sahul and adapted their subsistence strategies. Hallam (1987:10, 19) suggested that the most intensive resource usage on the SCP, in all periods, lay adjacent to lakes and swamps and their associated resources, and that the landscape was actively managed, via burning, to 'manage and increase those resources'.

The association between sites and wetlands proposed by Hallam (1986, 1987) on the SCP has been quantified in this study. Twenty-nine percent of sites are located within 0.1km of wetlands. The percentage of site frequency change is at the highest at the 0.1 km wetland buffer and reduces as the distance away from a wetland increases. The high percentage of sites found near wetlands supports a pattern of repeated occupance and resource usage around wetlands. This data concurs with Hallam's (1987) hypothesis that the distribution of wetlands, and their associated resources, are vital to understanding patterns of site distribution across the SCP.

Twenty-six percent of sites are within 0.3 km of a major river. When smaller streams and tributaries are included, 38 percent of sites are within this buffer. The percentage of site frequency change is highest at 0.1 km and reduces as the distance away from rivers increases. This suggests that rivers, as well as wetlands, played in important part in resource usage on the SCP and agrees with the findings of Anderson (1984) and Strawbridge (1988) that SCP sites tend to be located near to water sources more generally. Indeed, Hallam (1987:23) also acknowledged the utilisation of estuarine resources, notably fish, as part of an adaptive subsistence strategy. Monks (2021:15) has also observed that fish and shellfish are 'common elements of what is ultimately a sparse regional subsistence record' otherwise dominated by terrestrial foods. That Aboriginal people on the SCP were using rivers, whether for fishing, travel to and from the coast, or otherwise, is supported by the results of this study which quantify the relationship between SCP site distribution and rivers.

The importance of water sources for strategies of occupance across the continent, including southwestern Australia, has been reaffirmed by Crabtree et al. (2021), whose empirical study of the peopling of Sahul proposed a series of colonisation ‘superhighways’ (Figure 53). This superhighway model incorporated landscape prominence and least-cost pedestrian travel modelling to suggest an initial inland expansion southward into Sahul that relied on the discovery of water sources and ‘then travelling among them, all the while navigating prominent landscape features’ (Crabtree et al. 2021:1306). How people migrate, Crabtree et al. (2021:1307) argue, has ‘not changed in the hundreds of generations since the first people entered Sahul’. The way in which people adapt to a landscape is always guided by ‘fundamental rules’ of human movement: the use of visual cues, searching for freshwater, and minimising caloric expenditure. Previous settlement theories stressed the importance of one resource or landform type over another; Crabtree et al. (2021) framework accounts for a multi-component model of occupance. Further, the model incorporates the palaeolandscape of Sahul and its past coastline and ancient lakes. This acknowledgement of a past environment that was not static but dynamic, in relation to human dispersal, is lacking from previous conceptual models of dispersal.

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Figure 53: Model averaged superhighway probability across Sahul. Areas coloured green never or seldom selected; yellow paths have a 50% probability of being chosen; red areas represent areas with the highest probability of being chosen. Black dots show the location of archaeological sites predating 35 ka (Crabtree et al. 2021:1307).

In discussing the pre-transgression site distribution of the SCP, Dortch (1991, 2002a) proposed that the emergent western continental shelf would have displayed a similar distribution to that recorded in the present coastal plain, where occupation was concentrated around the wetlands and alluvial soils of its eastern margins (Hallam 1987). By extension, the western parts of the emergent shelf were less used. The archaeological record contained on the SCP offshore islands is interpreted by Dortch (2002a:14–15) as evidence of this occupation strategy and of wide-spread group movement across the emergent coastal plain. Large, repeatedly re-used, and maintained, sites are considered ‘congregative sites’, primarily located around modern estuaries or fresh water bodies. These inferences are based, in part, on the ‘extremely sparse’ archaeological record of Rottnest and Garden Islands (Dortch 1991:41). However, this extremely sparse record may be attributed to the lower extremities of the island being inundated during the Mid-Holocene high stand (Collins et al. 2006; Dortch and Hesp 1994; Eisenhauer et al. 1993). Indeed, an absence of evidence does not mean a lack of presence, rather, that the evidence relating to a presence either does not exist or has not yet been found. Without fully understanding and accounting for the nature of a past landscape, interpretations of past strategies of occupance and resource usage are inherently limited.

In the case of the western portion of the emergent Rottnest Shelf, for example, the Rottnest locality would have provided access to a system of freshwater lakes and wetlands at least for several hundred years prior to its separation from the mainland (Backhouse 1993). Hydrology analysis has demonstrated that palaeorivers would have flowed across the emergent shelf, creating chains of wetlands and alluvial systems around the topographic highpoint of Rottnest and in other, now submerged, locations. These environments would have been attractive to early populations as they occupied the SCP, perhaps even more so than the eastern margins of the coastal plain, due to their improved proximity to maritime and estuarine resources. These western parts of the shelf may have also provided additional habitat for macropods, and consequently additional hunting territory for human populations (Dortch and Wright 2010:1063). Further, the palaeorivers on the Rottnest Shelf identified via hydrology analysis may have supported yam patches in their alluvial soils attractive to past populations; the banks of the Swan River were known to have contained large occupation complexes resulting from yam exploitation (Hallam 1989). Whether these habitats extended onto the emergent shelf is hypothetical; continued research into the southwestern Australia’s submerged landscapes has the potential to provide the answers to these questions and reveal much about paleoenvironments in southwestern Australia.

Analysing patterns of site distribution and proximity on the SCP allows the relationship between sites and water features to be quantified. While this data is consistent with the findings of past studies (Anderson 1984; Hallam 1987; Strawbridge 1988) that have identified the relationship between sites and water sources on the SCP, it does not suggest that areas where those water sources are now most heavily concentrated, on the SCP eastern margins, would have been the most attractive throughout all periods of time. The results of the hydrology modelling have demonstrated that numerous water sources would have been accessible on the emergent shelf prior to transgression. Given the potential of this submerged landscape to support past populations, the paucity of archaeological material identified on the islands of the Rottnest Shelf to date should not be interpreted as evidence of these areas being less attractive for occupation. Answers to these questions of occupance and resource usage may now lie on the submerged landscape.

The results of the landscape modelling and hydrology analysis provide a foundation for further investigations into the submerged sites of the SCP. While there are other factors that are associated with the distribution of sites on the SCP, such as the location of alluvial soil systems and vegetation, the water features analysed in this study have been shown to have a significant relationship to site location and are identifiable on the submerged continental shelf. Assuming terrestrial site patterning extends onto the continental shelf, these results provide a hypothetical model for submerged landscape site potential on the Rottnest Shelf that may be tested.

5.2 Submerged Landscape Reconstruction and Hydrological Analysis

This study employed a new method to create high-resolution DRMs that model the SCP and adjacent submerged continental shelf. These landscape models, when combined with the results of the desktop survey, identify the physical landscape process that has affected the topography of the SCP and Rottnest Shelf throughout the last 50 ka. The landscape models shown in Appendix 3 represent a visual display of these topographic changes. The changes are summarised into four main periods: 1) A period of gradual regression; 2) a period of relative stabilisation; 3) a period of rapid transgression; and 4) a final period of stabilisation. Topography can be seen to have varied between periods, particularly in relation to the extent of habitable land on the coastal plain. During the height of the last glacial period, 24,000–

25,000 BP, approximately 20,000 km^2 of the continental shelf would have been exposed. The most rapid changes occurred during the transgressive period 17,000–6,000 BP, when the entirety of the exposed continental shelf was inundated. Transitioning from 9,000 to 8,000 BP Rottnest Island was separated from the mainland, while Garden and Carnac Island were formed at 7,000 BP.

The submerged landscape reconstruction and results of the hydrological analysis represent the most comprehensive map of submerged river channels ever created for the Rottnest Shelf. Previous attempts to identify submerged channels have relied upon remote sensing operations (Bufarale 2019). The methods developed in this study provide focus for future investigative operations, reducing time required in the field and any associated costs. The data resulting from this study can be entered into Global Positioning Systems (**GPS**) to allow easy navigation to identified areas for groundtruthing.

A limitation of creating DRMs of the submerged landscape is that they are based on current submerged bathymetry. Sea floor morphology, particularly at shallower depths, is reworked and affected by wave abrasion. While such sediment movement can impact elevation data, particularly near to fluvial discharge points (Collins 1988:29), at a macrolevel, low-lying drainage areas should remain constant regardless of changes to surficial morphology (Duggins 2012:123). Generally, where sediment load is decreased, elevation data and resultant hydrological modelling will be more accurate (Section 1.4).

The identification of well-preserved submerged palaeochannels in Geographe Bay (Bufarale 2019) suggests that, despite the high-energy coastline of the southern west coast, inundated archaeological sites may be preserved in situ in a sub-sediment context. That these palaeochannels were identified on the southern part of the Rottnest Shelf, where swells and storms are the strongest, suggests the relatively calmer northern waters may contain similar features. The potential for sub-surface site preservation in localised areas is further supported by the survival of cemented palaeo-sand dunes that have endured the erosional effect of marine transgression (Brooke et al. 2014:122).

The sub-surface potential of the Rottnest Shelf is also highlighted by the identification of reddish cemented palaeosols, matching the soils formed in the Spearwood Dune System, and of decayed tree wood within Cockburn Sound carbonate shell and sand tailings extracted during commercial dredging operations (Dortch 1991:41–42; Dortch and Dortch 2012:67–68). This suggests that the palaeo-land surface, which may contain cultural material, is preserved under Holocene sediment accumulations. The preservation potential of these accumulations is strengthened by the presence of seagrass communities overlying the sediment (Collins 1988:41); seagrass sedimentary deposits have been shown to function as 'security vaults' for submerged sites in a sub-surface context (Krause-Jensen et al. 2019). Dortch (1991) has stated that the sediment-cover of the Rottnest Shelf 'is probably the most limiting factor of underwater survey offshore the Swan Region', however, as identified by Benjamin (2010a:259), 'Holocene sedimentation and "undesirable" seabed composition do not necessarily imply that archaeological discovery is impossible.' Indeed, Holocene sediment units on the nearshore Rottnest Shelf are, in places, only one or two metres deep (Collins 1988; James et al. 1999).

Sedimentation across the Rottnest Shelf is regularly reworked by wave currents (Collins 1988:31, 40–41; Godfrey et al. 2005). The transport of sediment has the potential to uncover and rebury submerged sites or palaeolandforms in a cyclical manner. Cycles of sediment exposure and reburial have been recognised in Mediterranean submerged landscape studies for their potential to erode land surfaces and reveal cultural material, particularly following storm events (Galili et al. 2018, 2019). Better understanding of local patterns of sediment transportation could enable a similar potential within nearshore areas of southwestern Australia. Despite the generally high energy coastline of southwestern Australia, intact submerged trees have been identified at a number of sites along the southern coast (Dortch 1991:42, 1997a:17–18; Merrilees 1979:120), suggesting localised areas may exist across southwestern Australia that have been resistant to the erosional morphology of the region. Given the presence of decayed tree material in offshore sub-surface palaeosols, it is possible that submerged trees also exist within remnant terrestrial land surfaces on the Rottnest Shelf and are intermittently exposed by shifting sediments.

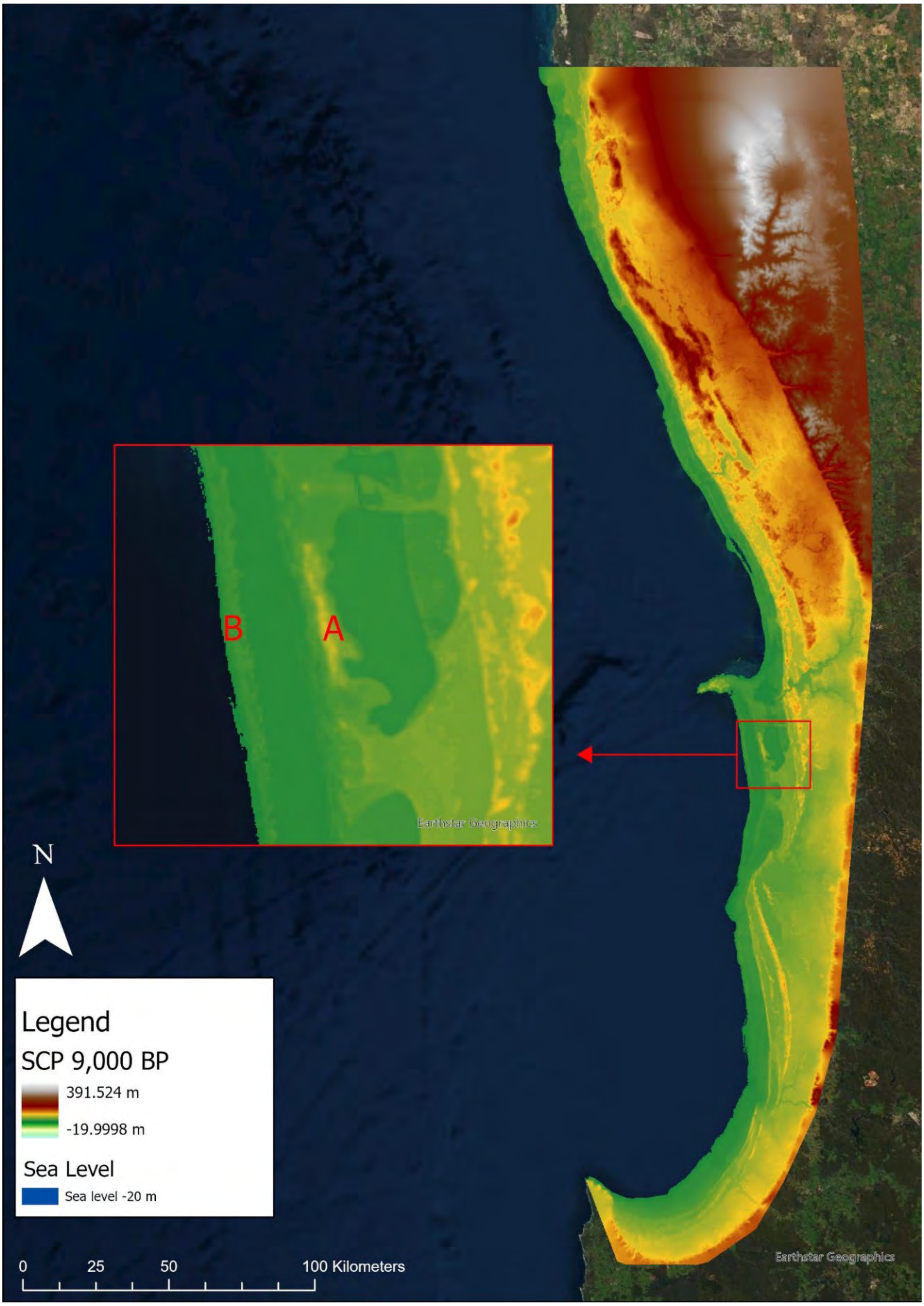

Figure 54: Wetlands and/or estuaries may have existed in Cockburn Sound and the west of Garden Island (A), in the deeper water between the submerged ridge of Tamala limestone (B). Both ridges A and B extend north-south, parallel to the modern coastline, representing the position of past palaeoshorelines. In this Figure, ridge B represents the position of the shoreline at 9,000 BP, 20 m below modern sea level. The inset shows an area around Garden Island at 1:300,000 scale. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

It is possible that cultural material may be preserved in situ above the sea bed. Previous, albeit unsuccessful, attempts to identify submerged terrestrial sites on the Rottnest Shelf have identified upstanding calcrete roots or ‘pinnacles’ in outcrops of Tamala Limestone on the sea floor (Dortch and Dortch 2012:67). These Tamala limestone formations have demonstrated their potential for the in situ preservation of artefacts on Rottnest Island (Dortch and Dortch 2019:23; Ward 2016:21–22) and on the mainland (Price et al. 2001). These limestone formations extend along the extent of the submerged shelf as a series of shore-parallel ridges, as described by Brooke et al. (2010, 2014, 2017), and are visible in the landscape models produced for this study. Such ridges may have preserved cultural material deposited there during periods of lower sea level. Locations where these palaeo-ridges occur adjacent to troughs of deeper water are likely to be the most promising for site preservation. Such bathymetric depressions represent possible fresh water bodies that existed on the emergent shelf and formed behind barrier dunes now preserved as cemented palaeodunes. Given the concentration of SCP terrestrial sites around water sources, it is reasonable to assume these offshore locations, if they were water bodies, would have also been congregative sites, with repeated use, and associated artefact deposition, over an extended period. This interpretation demonstrates how the terrestrial archaeological record and modern landscape of the Swan Coastal Plain can inform the search for submerged archaeological sites on the adjacent continental shelf. By considering the results of hydrology analysis search areas for submerged sites can be further refined.

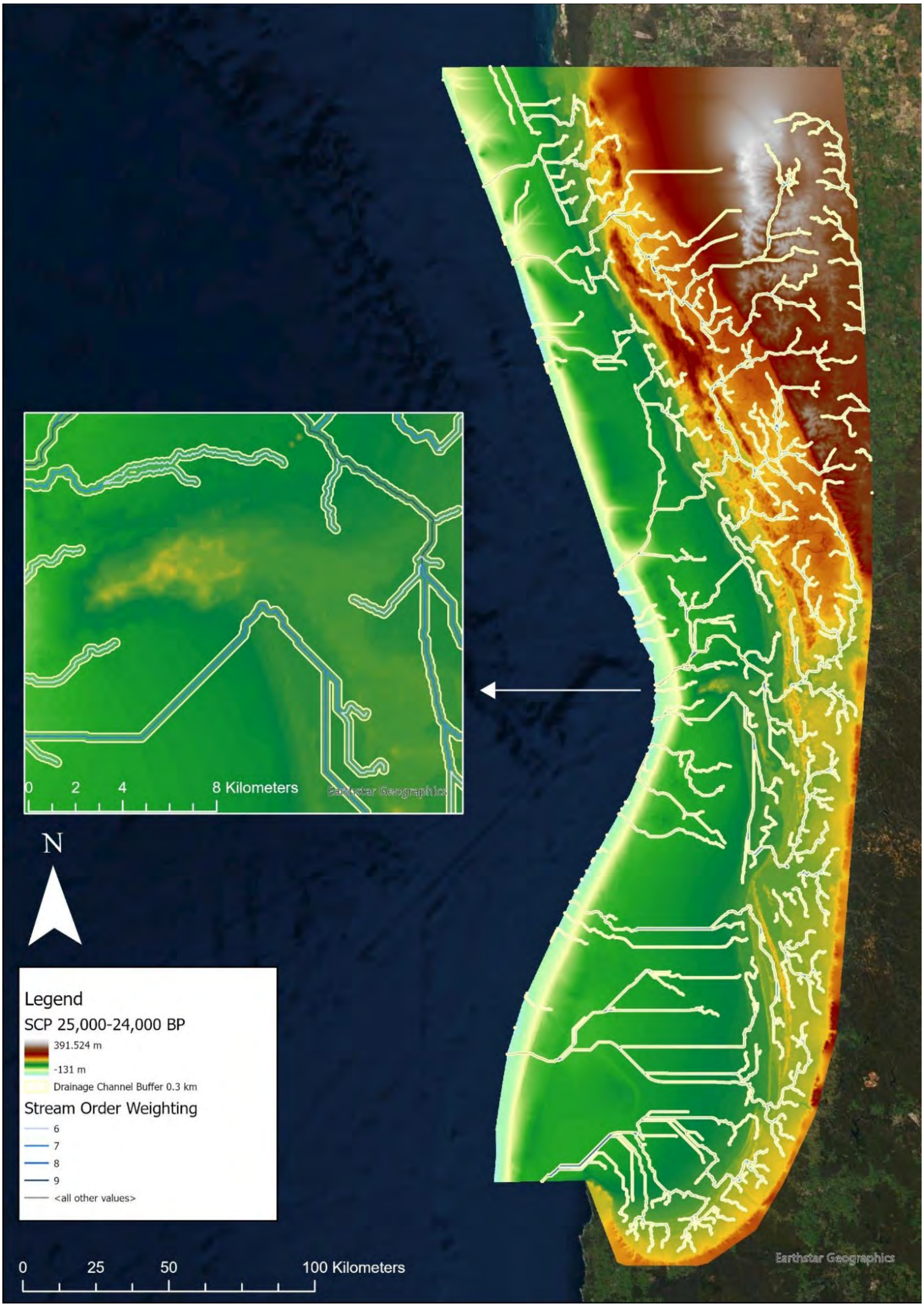

Figure 55: Drainage channels of Strahler stream order 6 or higher displayed with a 0.3 km buffer (yellow). Proximity modelling suggests 13 percent of offshore sites would have been deposited in in this buffer. The inset shows an area around Rottnest Island at 1:300,000 scale. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

A relationship exists between the location of sites on the SCP and the location of water features. The identification of these features on the submerged continental shelf can help guide further investigations for submerged sites. The results of the hydrological analysis provide a hypothetical map of palaeoriver channels, flowing from the SCP across the continental shelf. By limiting the results of the hydrological modelling to Strahler order 6 or higher, the resultant drainage channels better replicate major rivers.

Thirteen percent of sites are situated within 0.3 km of a drainage channel and 33 percent of sites lie within 1 km of a drainage channel, after which frequency change data shows a drop in return. If terrestrial site patterning continues offshore, these results suggests that 13 percent of offshore sites will have been deposited within 0.3 km of a drainage channel (Figure 55) and 33 percent of submerged sites will have been deposited within 1 km of drainage channels (Figure 56). The successful identification of palaeochannels in Geographe Bay (Bufarale et al. 2019) provides further evidence that areas adjacent to palaeoriver channels on the submerged shelf have the potential to preserve sub-surface sites with a high integrity. Considering this, and accounting for the taphonomic effects of the shelf morphology, areas with an improved likelihood of high preservation potential for submerged landscape sites can be identified.

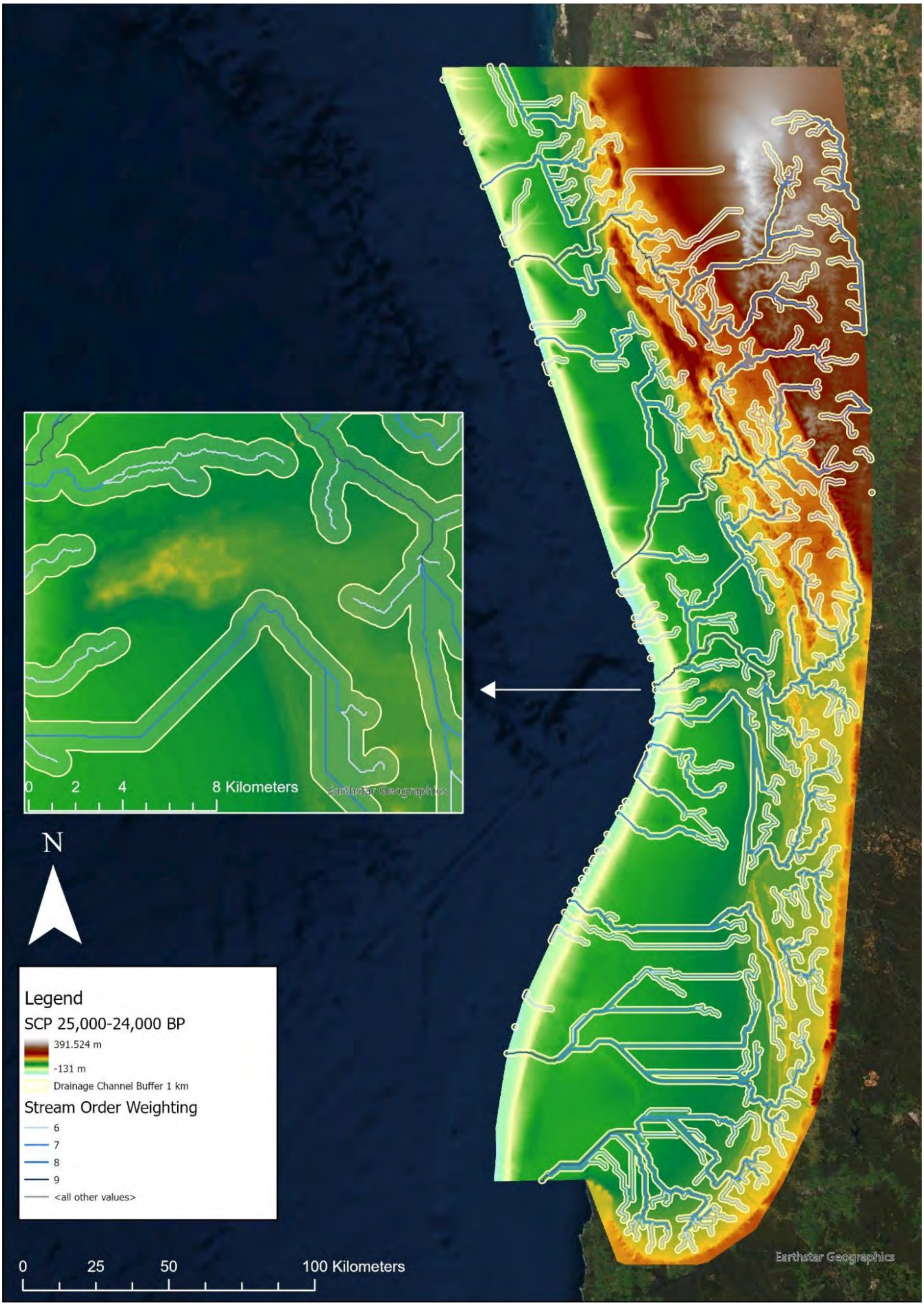

Figure 56: Drainage channels of Strahler stream order 6 or higher displayed with a 1 km buffer (yellow). Proximity modelling suggests 33 percent of offshore sites would have been deposited in in this buffer. The inset shows an area around Rottnest Island at 1:300,000 scale. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

5.3 Areas of High Preservation Potential

The terrestrial site data analysed in Section 3.3 demonstrates the relationship between the location of terrestrial sites and landscape features. Assuming terrestrial site patterning continues onto submerged areas, these landscape features provide a marker for areas that may have higher potential for submerged archaeological sites to exist and be preserved in situ (Duggins 2012:122–128; Veth et al. 2019). By also considering the results of the desktop survey outlined in Chapter 4, in combination with the results of the proximity modelling and hydrological analysis, it is possible to further isolate areas with high preservation potential for submerged sites.

Pleistocene-Holocene sea-level transgression was not constant. Nutley (2006, 2014) has highlighted the importance of rapid, singular inundation events as providing the best conditions for site survival, particularly when sites are quickly buried in sediment. It has been long understood that 'gradual inundation usually does not result in good preservation' conditions (Stewart 1999:572). The shallow slope of the SCP is beneficial in this regard; transgression occurs much quicker on shallowly sloping coasts than on steep coasts (Gifford 1990:115). The period of most rapid transgression began at approximately 17,000 BP and saw sea levels rise from -131 m to -25m by 10,000 BP. The period between 11,500 BP and 10,000 BP saw the rapid inundation of much of the inner continental shelf (Collins 1988:41). Based on this, three time slices (Figure 57) have been selected to cover the rapid drowning of the inner shelf: 12,000–11,000 BP; 11,000–10,000 BP; and 10,000–9,000 BP. The areas that were submerged during these periods of transgression were done so rapidly and without periods of shoreline retreat, thus representing areas that have a higher potential for positive taphonomic conditions. The combined area of land inundated during this period is shown in Figure 58.

Areas of high preservation potential can be narrowed further using SCP terrestrial site-landform associations. The results of the terrestrial proximity analysis indicate that 33 percent of sites are contained within 1 km of a drainage channel. Assuming this terrestrial site patterning is consistent in an offshore context suggests that this buffer will contain 33 percent of submerged Aboriginal sites deposited on the Rottnest Shelf adjacent to the SCP. Accordingly, areas of high preservation potential are identified in Figure 59, where 1 km drainage channel buffers overlay areas of rapid transgression from 11,500–9,000 BP.

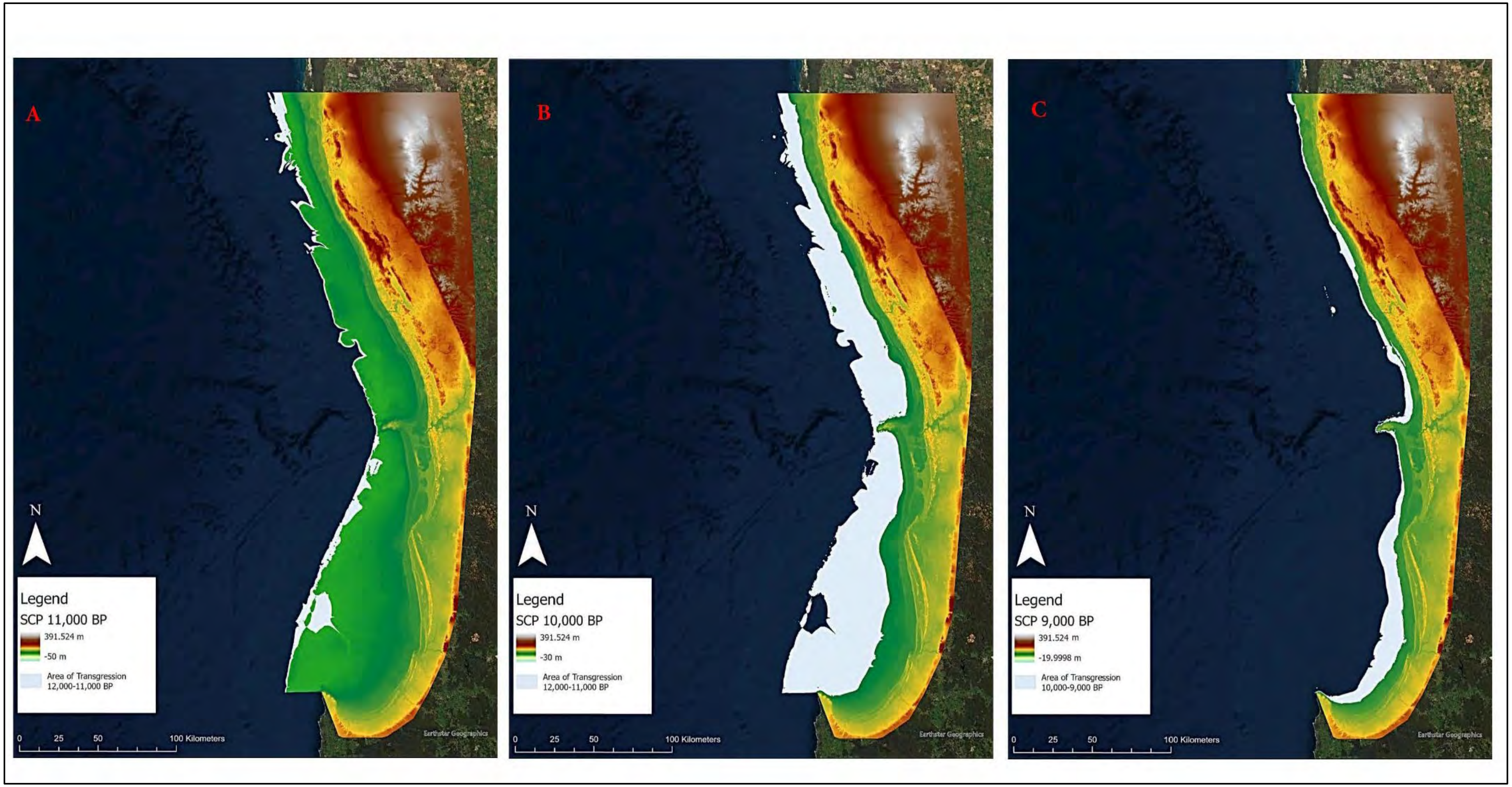

Figure 57: A) Inundated land 12,000–11,000 BP; B) Inundated land 11,000–10,000 BP; C) Inundated land 10,000–9,000 BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

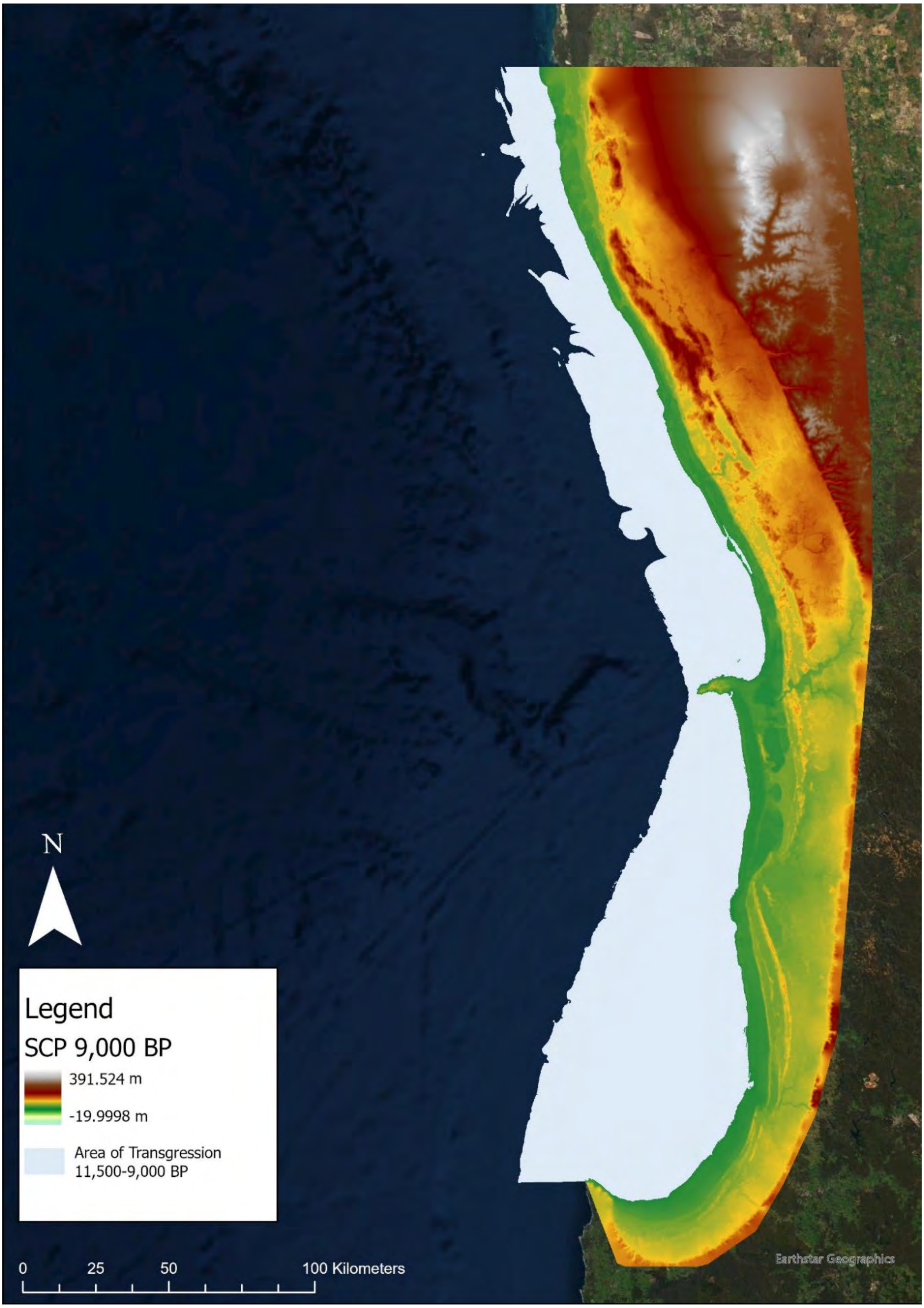

Figure 58: Cumulative area of land inundated between 11,5000–9,000 BP. Sites found in this area will not necessarily date from the period of inundation, rather any sites that existed prior to the inundation period may have been better preserved than in other areas. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

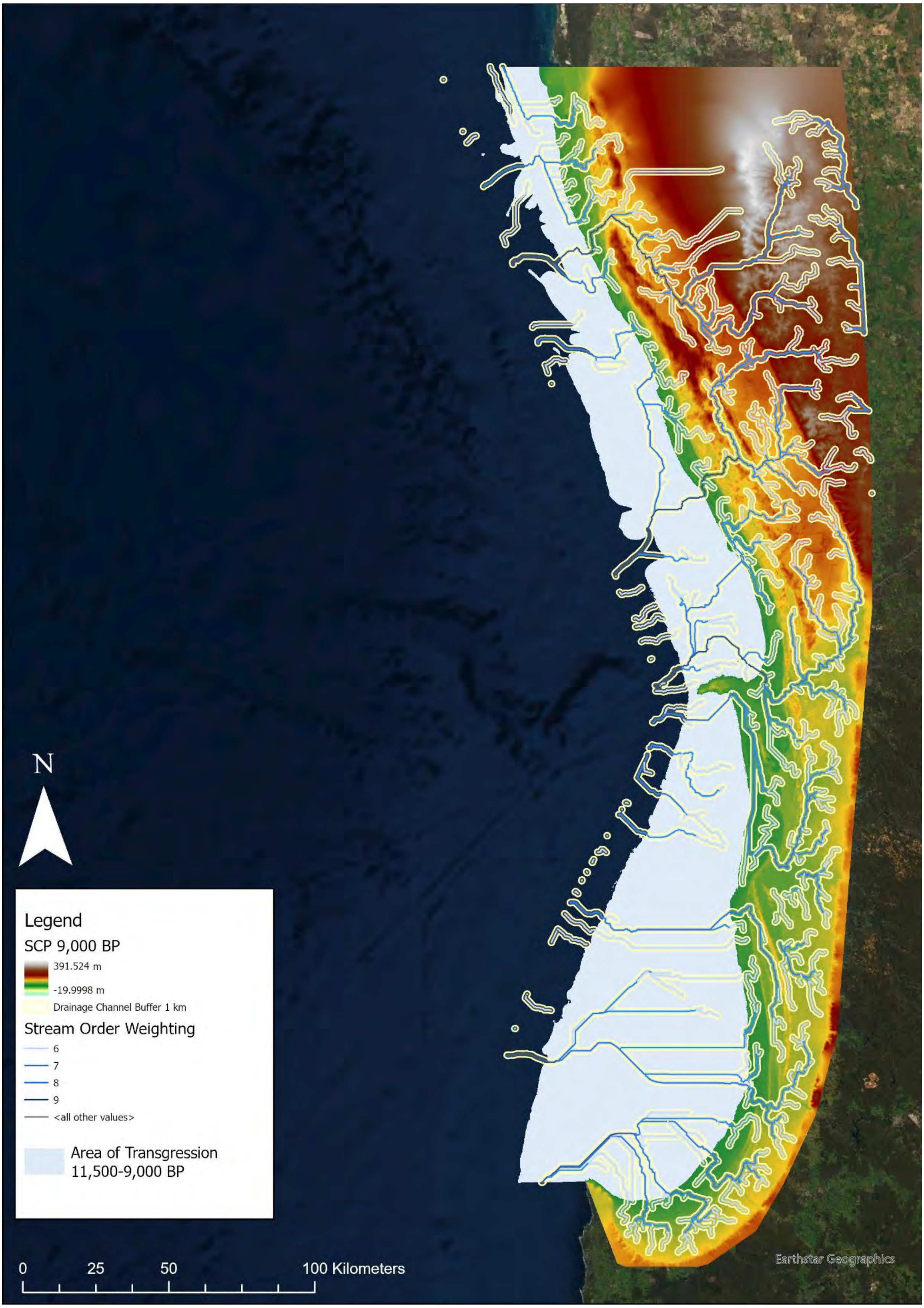

Figure 59: Areas of high preservation potential exist where 1 km buffers from drainage channels overlay areas of rapid transgression from 11,500–9,000 BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

Areas within the near shore of the inner shelf, despite being submerged relatively slowly and displaying characteristically high-energy environment, may also contain localised areas of high preservation potential. As Benjamin (2010a:259) notes, 'localized [sic] areas may exist as exceptions to an otherwise unlikely region of study.' The Rottnest Shelf is bathymetrically complex, resulting in a variety of coastal environments. On the inner shelf, shore-parallel cemented palaeodunes are visible along the extent of the coastline, the modern offshore islands representing high points of these ridges. These types of cemented dunes have been identified on other parts of the continental shelf for their potential to preserve middens and artefacts (Veth et al. 2019:494; Wiseman et al. 2021:164) and offer a similar prospect here. These ridges, along with other offshore features, can shelter the coast from wave action, leading to the creation of sheltered estuarine lagoons. Given that many of these offshore features have eroded over time (Sanderson et al. 2000:78), it stands that these estuarine environments would have been even more so protected in the past. These types of environments can enhance the survivability of sites that have been deposited within them (Nutley 2006:44).

In a coastal setting, the 'depositional sites with the greatest potential to survive inundation' are those that were deposited in swamps and wetlands (Nutley 2006:45–46). As the water table rises during transgressive events, it can create 'swamps behind a barrier of coastal dunes… sealing archaeological deposits' (Figure 60). The cemented ridges of the Rottnest Shelf would have provided such coastal barriers, behind which rising water tables could have led to the formation of coastal wetlands. This suggests that areas where cemented ridges were quickly inundated and/or overlap with drainage channels will contain areas of high preservation potential, even in a nearshore context (Figure 61).

This study has identified hypothetical areas of high preservation potential, that is, those locations which have a higher probability of containing submerged landscape sites. These locations can be targeted in future underwater surveys guided by the results of this study. The identification of these areas does not mean that potential is absent from other areas of the continental shelf. The limitations and potential biases of this study have been outlined in detail; the results of the study are therefore intended as a starting point, based on current knowledge and available methods.

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Figure 60: Process of wetland creation behind coastal barrier dunes owing to sea-level rise (Nutley 2006:45).

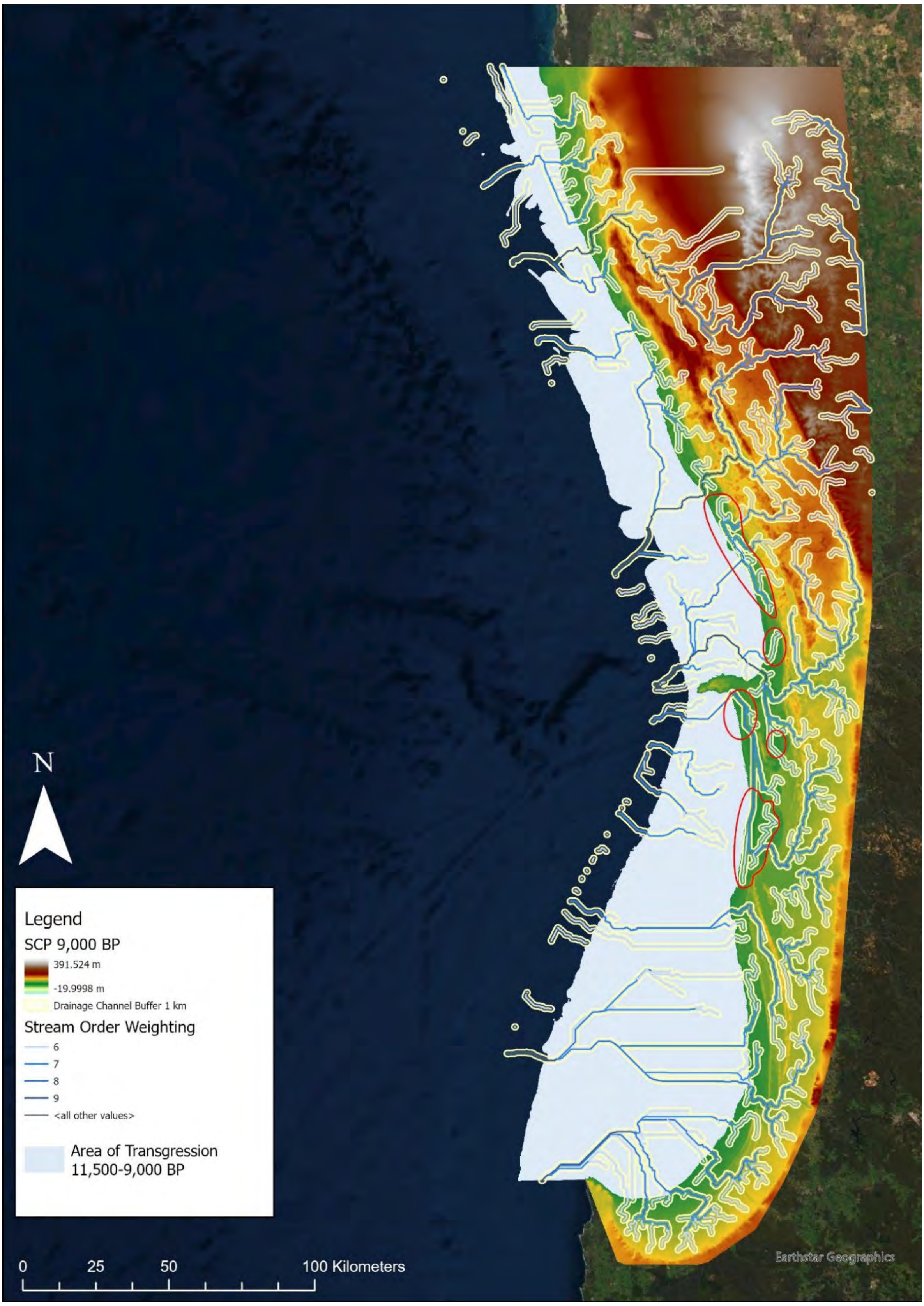

Figure 61: Areas of high preservation potential exist where 1 km drainage channel buffers intersect shore-parallel palaeo-barrier dunes. These areas are circled in red, according to the location of cemented ridges as outlined by Brooke et al. (2010). Other, similar, areas are likely to exist along the coast. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

5.4 Recommendations for Future Work

Future research into the submerged landscapes of the SCP has the potential to answer questions concerning regional strategies of occupance and resource usage, which, in turn, can be incorporated into continental models relating to the colonisation of Sahul. Alongside the identification of submerged site location, this research can focus on what submerged landscapes can communicate about the people who inhabited them; moving beyond the false dichotomy presented by contemporary shorelines and fully integrating the archaeology of land and sea. Understanding that research need not necessarily start with questions relating to the earliest dates of occupation or theories of colonisation is key. Objectives can be limited to improving the understanding of the subaerial archaeological record or of localised geomorphological processes on the submerged shelf. With this in mind, recommendations for future work are presented below.

5.4.1 Incorporating Additional Data

This study has used publicly available data to create a continuous high-resolution DRM of the SCP and Rottnest Shelf. The methods presented provide a framework for further early-stage investigation of submerged sites on the Rottnest Shelf. The results of this study demonstrate proof of concept for the application of the outlined methods. With access to improved hardware processing capabilities and by replicating this method, and using the same dataset, a DRM of up to 50 m resolution can be produced. This method can also be applied to other areas on the continental shelf where sufficient bathymetric data is available. Future work relating to the Rottnest Shelf could include new datasets to expand the area covered by the DRM and/or improve resolution.

The results of the desktop study can also be added to with a focus on local micro-environments, rather than regional, data. Micro-environments should be selected from within the areas of high presentation potential identified by this study. Modelling the erosion impacts for these micro-environments will help to improve the understanding of the taphonomic effects of marine inundation.

5.4.2 Maxent: Eco-Cultural Niche Modelling

The DRM produced by this study can be used for additional GIS analysis. Maxent modelling is commonly used in environmental sciences and uses a machine learning algorithm to create a probability distribution based on site occurrence location data and environmental data (Phillips and Dudík 2008; Warren and Seifert 2011). When used with archaeological data, this process is referred to as Eco-Cultural Niche modelling and 'can be used to explore the relationships between archaeological cultures and their paleoenvironments [sic], as well as examine them across periods of climate change' (Banks 2017:4). As demonstrated in several studies, Eco-Cultural Niche Modelling aims to predict culture distribution based on known environmental variable and constraints (Banks et al. 2009, 2011, 2013; Gillam et al. 2007). Using the DRMs produced for this study, new raster layers can be calculated for aspect, hillshade, slope, besides the existing elevation and drainage layers. These rasters can be the environmental input used in conjunction with the geographic coordinates of archaeological sites required for Eco-Cultural Niche Modelling. Duggins (2012:135–142) has shown that Eco-Cultural Niche Modelling in a submerged landscape context can identify high probability areas of occupation and artefact deposition on the continental shelf. This mode of analysis represents a promising opportunity for GIS-based assessment of site distribution on the SCP and can help to further narrow the location of high preservation potential areas for submerged sites on the continental shelf.

5.4.3 Remote Sensing and Groundtruthing

This study has produced a new method for the identification of areas of high preservation potential for submerged archaeological sites on the Rottnest Shelf. The continuation of these investigations should be multi-scalar, continuing to narrow the location of zones that are identified as priority areas for targeted survey (Wiseman et al. 2021). Using the results of this study, it is possible to navigate a vessel within the area of the outlined 1 km drainage channel buffers to carry out targeted remote sensing activities.

Multibeam and sidescan sonar systems allow the production of a map of seafloor morphology for large zones of seabed and with a high precision (Missiaen et al. 2017:25). These technologies have been recently utilised for the successful identification of target landscape features on the seafloor adjacent to submerged palaeochannels (Benjamin et al. 2020; Wiseman et al. 2021) and would help identify targets for diver survey within the buffer areas provided by this study. There is also the potential for the improved identification of submerged freshwater sources (Faught and Donoghue 1997; Tizzard et al. 2014) and of worked flint in geophysical sensing techniques (Grøn et al. 2021; Hermand et al. 2011; Ren et al. 2011). Enhanced detection of these acoustic signals would have useful application in this study area given site association with water features and the frequency of lithic scatters in the terrestrial context.

The application of a sub-bottom profiler is also recommended for investigation of high preservation potential areas. Seismic data was successfully collected from Geographe Bay using an acoustic boomer system that allowed the characterisation of stratigraphic features, including palaeochannels, to a depth of approximately 30–40 m below the sea floor (Bufarale 2019). This method can be applied to areas of high preservation potential, as identified by this study, for the detection of palaeosols, palaeochannels, shell middens, and other sub-surface features (Missiaen et al. 2017:27). Sub-bottom profiler survey has contributed to the identification of the size, shape, and depth of a submerged midden at Hjarnø, Denmark. The presence of shell middens along the northern reaches of the SCP (Dortch et al. 1984; Monks et al. 2015; Morse 1982) suggests that these types of sites will also have been deposited in an offshore context. Seismic survey can be targeted where shore-parallel ridges intersect with drainage channel buffers; these cemented dunes being representative of past palaeo-shoreline locations (Brooke et al. 2010, 2014) and are more likely to preserve subsurface features.

Diver survey can be used to visually confirm the interpretation of acoustic data and to collect sediment cores for the analysis of sub-surface material. Coring can help provide localised morphological information that can contribute to improved understanding of Holocene sedimentological and erosional processes, as well as palaeoenvironmental data (Nutley 2014:270). Coring can also be used to detect the distinct sedimentological profile of shell midden sites across a range of differing environmental and preservation contexts (Cook Hale et al. 2021).

5.4.4 Reviewing the Approach to Underwater Cultural Heritage Management

The submerged landscape archaeology of Australia's continental shelves is not adequately protected by Western Australia's underwater cultural heritage legislation, the *Maritime Archaeology Act 1973* (WA). The legislation was drafted with a focus on the historical wrecks and associated early maritime infrastructure of the first European visitors to the coastline. The nearshore area of the Rottnest Shelf is under State jurisdiction and falls under the *Maritime Archaeology Act 1973* (WA), however, outer areas of the shelf are under Commonwealth jurisdiction (Figure 62). While the *Underwater Cultural Heritage Act 2018* (Cth) recognises Australia's Aboriginal and Torres Strait Islander Underwater Cultural Heritage in Commonwealth waters, the state-based legislation does not. Western Australian maritime heritage legislation needs to be brought in line with the Commonwealth standard to acknowledge that the archaeology of submerged landscapes is as much a part of Western Australian cultural heritage as historical shipwrecks are. The new *Aboriginal Cultural*

Heritage Act 2021 (WA) allows Aboriginal people to apply to have important heritage places on the seabed listed as protected areas though it provides no specific provision for submerged landscape sites. This legislative context illustrates how the legal regimes set up to protect Australia's cultural heritage were done without accounting for dynamic palaeoenvironments and coastlines, nor the submerged archaeological records they may now hold.

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Figure 62: Division of jurisdiction between State and Commonwealth maritime areas. State jurisdiction areas are coloured blue; Commonwealth jurisdiction areas are coloured white. Red represents sea level during the LGM (after Anderson and Morrison 2020).

Improved collaboration with industry should be prioritised to facilitate improved access to data and raise awareness of submerged Aboriginal archaeology. This may lead to better outcomes for submerged site identification, recording, and management of underwater cultural heritage. Importantly, collaborative efforts with industry should provide space for Traditional Knowledge Holders to be involved with, or lead, investigations into the archaeology of Australia's continental shelf. On the Rottnest Shelf, the proposed WA Offshore Windfarm (2021) development offers a suitable target for collaborative efforts.

6 Conclusion

This study has presented the results of a new method for the identification of areas of high preservation potential on the continental shelf adjacent to the SCP. Specifically, it has applied a four-step desktop-based approach: 1) a desktop survey; 2) landscape modelling; 3) modelling SCP terrestrial site data; and 4) identifying high preservation potential areas. The desktop survey identified the geomorphological processes affecting the topography of the SCP and Rottnest Shelf. The landscape modelling combined bathymetric and topographic data to reconstruct past landscapes of the SCP. Terrestrial site modelling used the distribution, geographic setting, and archaeology of 1,039 subaerial SCP sites to identify relationships between sites and landforms on the SCP. Finally, using these results, areas of high preservation potential for submerged archaeological sites were identified on the Rottnest Shelf.

Whilst the archaeological potential of the Rottnest Shelf has been recognised since the confirmation of Aboriginal artefacts on Rottnest and Garden Islands (Dortch and Morse 1984), this study represents the first investigation of its kind on the SCP and adjacent continental shelf. It has presented a new method for the identification of areas on the Rottnest Shelf that have a high preservation potential for submerged archaeological sites, and the resultant data can be used for the continuation of SCP submerged landscape investigations. By incorporating the submerged shelf into future archaeological investigations, on the SCP or otherwise, archaeologists can contribute to a more holistic approach to the study of occupance and resource usage on the SCP and across Australia.

Previous investigations into the terrestrial archaeological record of the SCP have proposed an association between Aboriginal sites and water sources (Anderson 1984; Hallam 1987; Dortch et al. 2007; Dortch and Dortch 2019; Strawbridge 1988; Monks 2021). The distribution and proximity analysis conducted in this study has quantified the relationship between SCP sites and water sources. This analysis has relied heavily on the characteristic site type of the SCP: surficial lithic scatters. Too often smaller sites and surface scatters can be discounted because of their lack of vertical context, thus preventing their contribution to theories of landscape use. This study has shown otherwise; the location where sites are deposited upon the landscape represents a direct choice made by a past individual. Although these sites may lack vertical context, their horizontal context can provide valuable data and insights. Patterns in regional site deposition represent the accumulation of repeated behaviours and/or preferred environments through time. While such an approach could also be applied elsewhere, the uncertainty relating to the stratigraphic integrity of SCP sites (Bowdler et al. 1991, Schwede 2011) presents the region as a particularly appropriate study for the spatial analysis of site distribution and proximity to landforms. Understanding these site-landform associations is also vital to the successful application of a predictive modelling process underpinned by terrestrial analogues (Veth et al. 2019). On the Rottnest Shelf, where the archaeological record is extremely sparse, such predictive strategies are an important first step 'for beginning the challenging task of locating prehistoric sites underwater' (Benjamin 2010a:262).

This study set out to answer the research question: how can the terrestrial archaeological record and modern landscape of the SCP inform the search for submerged archaeological sites on the adjacent continental shelf? Through the fulfillment of the aims and objectives of this study, it has been demonstrated that the terrestrial archaeological record and modern landscape of the SCP *can* inform the search for submerged archaeological sites. The method presented in this study demonstrates one way of 'how' such a search can be undertaken. This method can be revised, or improved, for example through the adoption of the recommendations outlined in Section 5.4. However, fundamental to any future submerged landscape investigation of the SCP will be the requirement to understand past patterns of occupance and resource usage as reflected in the archaeological record; to understand the physical landscape processes that have affected topography during the period of human habitation and how this might affect submerged site taphonomy; and to create a visual representation of landscapes, past and present, to allow for the identification of submerged landforms and other features associated with hunter-gather occupation. These findings are consistent with the multi-scalar '"Australian Model" of practice for submerged site detection' (Wiseman et al. 2021:168).

Like the 'Australian Model', this study has begun investigations into the submerged landscape using regional environmental and cultural data; future work should continue to narrow the focus of SCP submerged landscape investigations through geophysical survey and groundtruthing of identified high preservation potential areas. In adapting the Pilbara-centric 'Australian Model' to a specific area of southwestern Australia, one with different environmental and cultural contexts, this study has contributed to the emerging discourse of submerged landscape studies in Western Australia and more broadly, Australia.

7 References

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8 Appendix

Appendix 1: Sea-Level Data

Table A below displays the 500-year averages determined from methods presented in Section 3.1.1. Data is combined from Collins (2006), Eisenhauer et al. (1993), Lambeck (2004), and Lambeck et al. (2014):

Table A: Sea-level averages for 500-year periods.

Age Averages	Age Mean (BP)	Average Sea Level
0	0	0
1058	1.058	0.86
2335	2.335	1.13
3226	3.226	1.07
3831	3.831	1.18
3867	3.867	1.43
5825	5.825	1.86
6323	6.323	1.2
6832	6.832	2.02
6919	6.919	1.82
7962	7.962	-5
8189	8.189	-10.7
9374	9.374	-19.8
9489	9.489	-23.6
9809	9.809	-24.4
10.250–10.749	10.5	-34.909
10.750–11.249	11	-43.78
11.250–11.749	11.5	-54.585
11.750–12.249	12	-56.838
12.250–12.749	12.5	-58.6
12.750–13.249	13	-63.864
13.250–13.749	13.5	-70.443
13.750–14.249	14	-82.68

14.250–14.749	14.5	-91.932
14.750–15.249	15	-96.867
15.250–15.749	15.5	-101.133
15.750–16.249	16	-106.033
16.295	16.5	-105.2
16.750–17.249	17	-113.42
17.580 17.580	17.5	-109.6
17.750–18.249	18	-112.017
18.250–18.749	18.5	-110.033
18.750–19.249	19	-114.86
19.250–19.749	19.5	-113.875
20.042	20.042	-110
20.250–20.749	20.5	-125.4
21.000	21	-125
21.690	21.69	-119.1
21.750–22.249	22	-127
23.750–24.249	24	-130.7
24.476 24.476	24.476	-133
28.250–28.749	28.5	-117.85
28.750–29.249	29	-125.8
29.580	29.58	-118.4
29.750–30.249	30	-94.275
30.298	30.298	-86
31.250–31.749	31.5	-68.15
31.997 31.997	31.997	-76.8
32.250–32.749	32.5	-69.65
34.1	34.1	-63
34.800	34.8	-63.4
35.000	35	-73
36.000	36	-70
37.000	37	-65
38.000	38	-70

39.000	39	-74
40.000	40	-74.5
41.000	41	-74
42.000	42	-71
43.000	43	-67
44.000	44	-55
45.000	45	-60
46.000	46	-67
47.000	47	-68
48.000	48	-56
49.000	49	-47
50.000	50	-47

Sea-level modelling was undertaken using the 1000-year sea level averages displayed in the Table B below. These averages were calculated from the data in the previous table.

Table B: Sea-level averages at 1000-year intervals.

Age (years BP)	**Depth (m)**
0	0
1000	1
2000	1
3000	1
4000	1
5000	2
6000	1
7000	2
8000	–8
9000	–20
10,000	–30
11,000	–50
12,000	–57
13,000	–64

14,000	–83
15,000	–97
16,000	–106
17,000	–113
18,000	–112
19,000	–115
20,000	–110
21,000	–125
22,000	–127
23,000	–129
24,000	–131
25,000	–131
26,000	–127
27,000	–123
28,000	–119
29,000	–126
30,000	–94
31,000	–75
32,000	–77
33,000	–67
34,000	–63
35,000	–73
36,000	–70
37,000	–65
38,000	–70
39,000	–74
40,000	–75
41,000	–74
42,000	–71
43,000	–67
44,000	–55
45,000	–60

46,000	–67
47,000	–68
48,000	–56
49,000	–47
50,000	–47

Appendix 2: Aboriginal Heritage Place Attribute Definitions

Table C: Aboriginal heritage place attribute definitions

Attribute	**Definition**
Place_ID	Aboriginal Place Identifier (mandatory)
Place_Name	Name of Aboriginal Place (not mandatory)
Legacy_ID	Old Aboriginal Place Number (not mandatory)
Status	Lodged, Registered Site, Stored Data / Not a Site
Status_Reason	e.g. Exclusion - Relates to a portion of an Aboriginal site or heritage place as assessed by the Aboriginal Cultural Material Committee (ACMC). e.g. such as the land subject to a section 18 notice
Origin_Place_ID	Used in conjunction with Status Reason to indicate which Registered Site this Place originates from
Type	A list of one or more of the following types: Artefacts / Scatter, Ceremonial, Engraving, Fish Trap, Grinding Patches / Grooves, Historical, Man-Made Structure, Midden / Scatter, Modified Tree, Mythological, Painting, Quarry, Repository / Cache, Rockshelter, Skeletal Material / Burial, Arch Deposit, Birth Place, BP Dating, Camp, Hunting Place, Massacre, Meeting Place, Mission, Named Place, Natural Feature, Ochre, Plant Resource, Shell, Water Source, Other
Region	Indicative regional location of Place

Restrictions	Female Access only Initiated Female Access only Male Access only Initiated Male Access only No Gender Restrictions Other Restrictions
File Restricted	Yes / No (mandatory)
Location Restricted	Yes / No (mandatory)
Boundary_Reliable	Yes/No (not mandatory)
Protected_Area	Yes / No, Yes if Place is a protected area
Protected_Area_Gazetted_Date	Date protected area was gazetted, blank if Place is not a protected area
National_Estate_Area	National Estate Area Number, blank if Place is not a national estate area

Appendix 3: Discrete Landscape Models

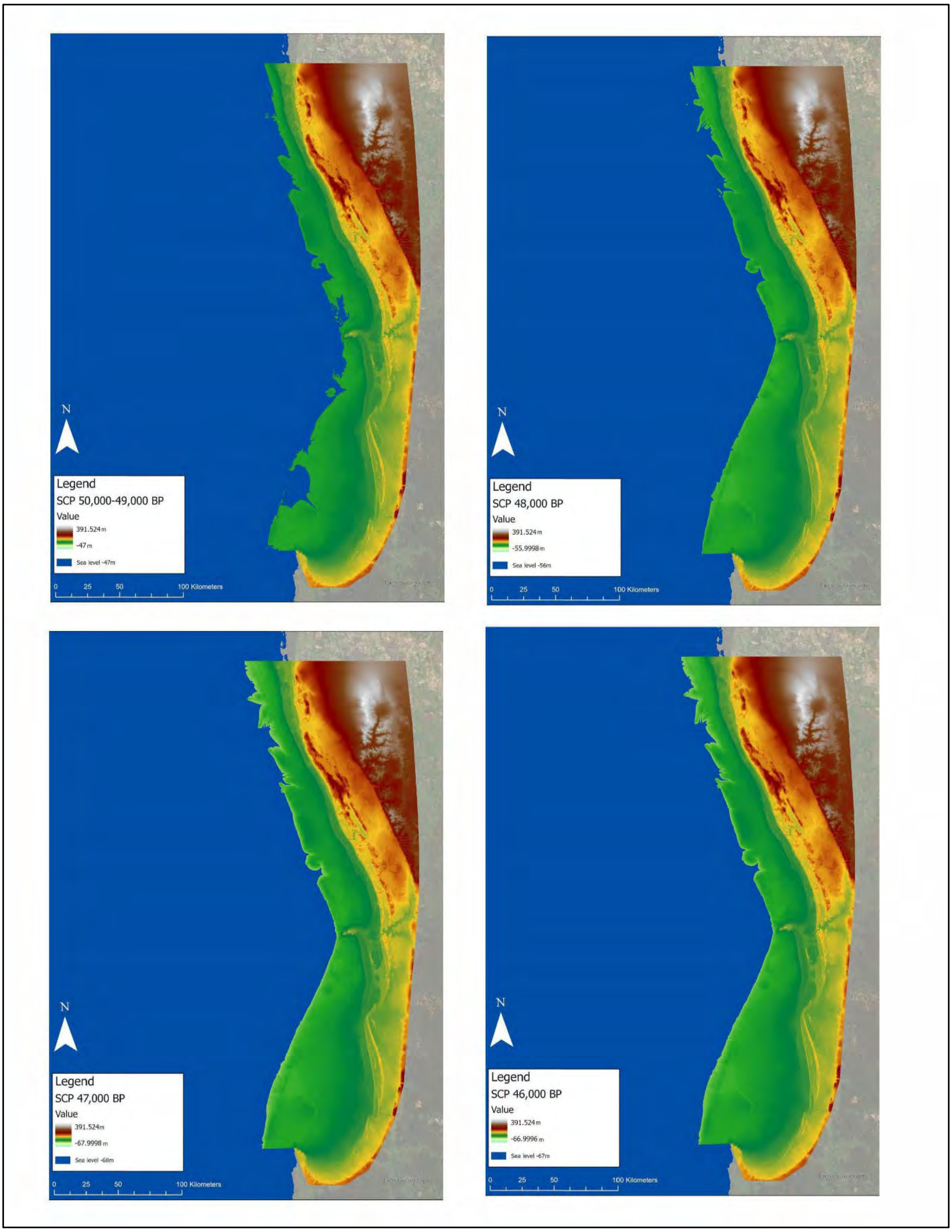

Figure A: Topography between 50,000 to 46,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

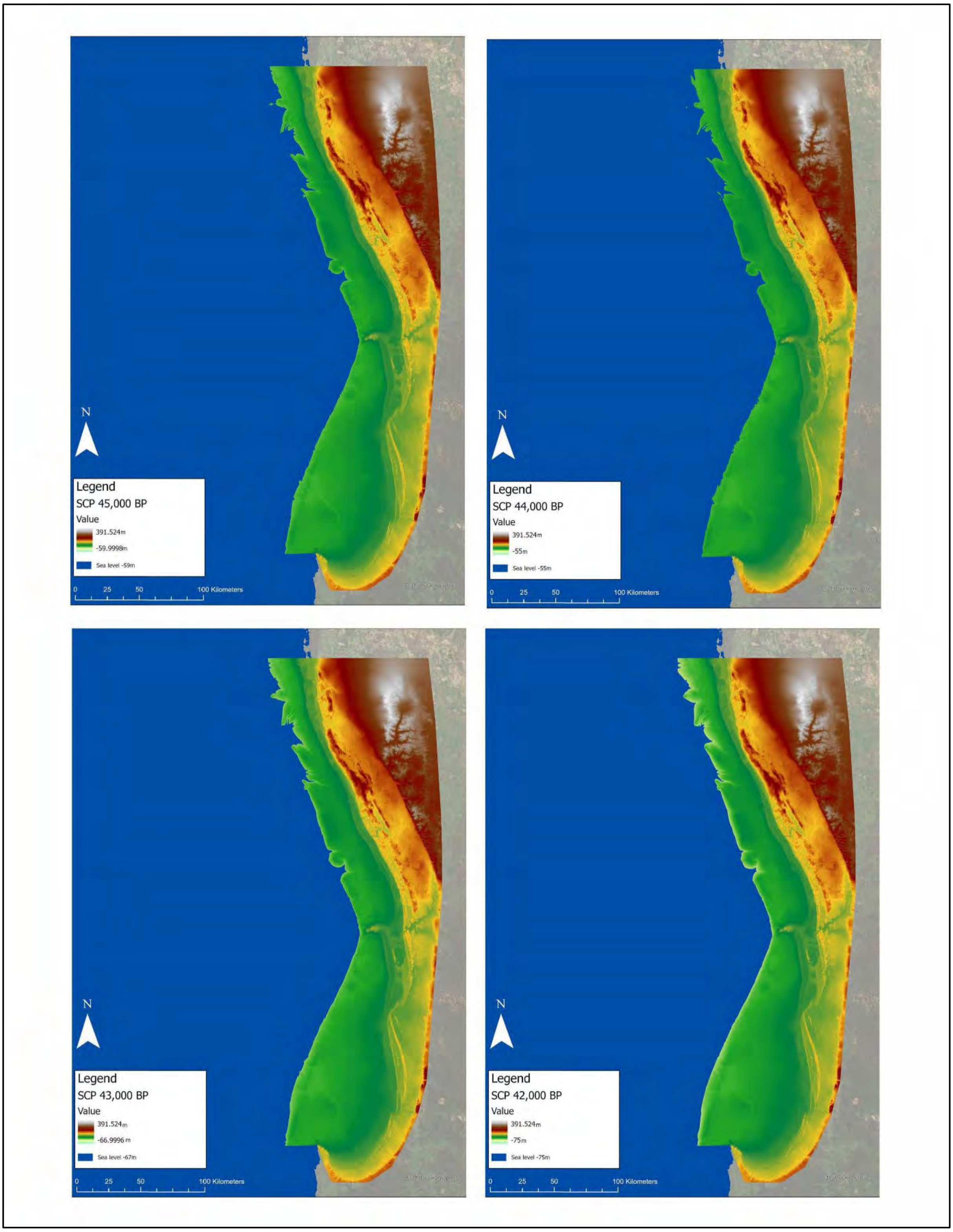

Figure B: Topography between 45,000 to 42,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

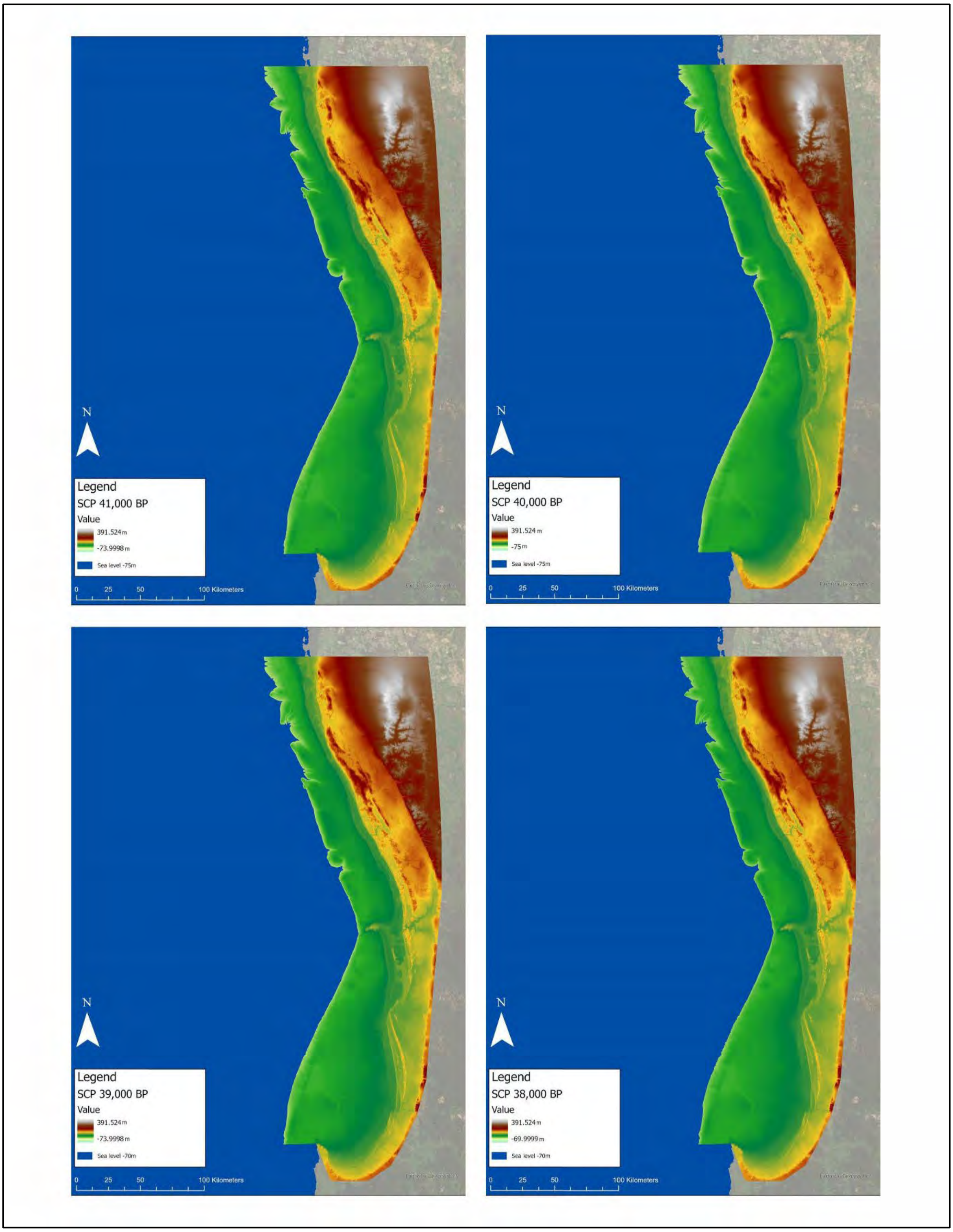

Figure C: Topography between 41,000 to 38,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

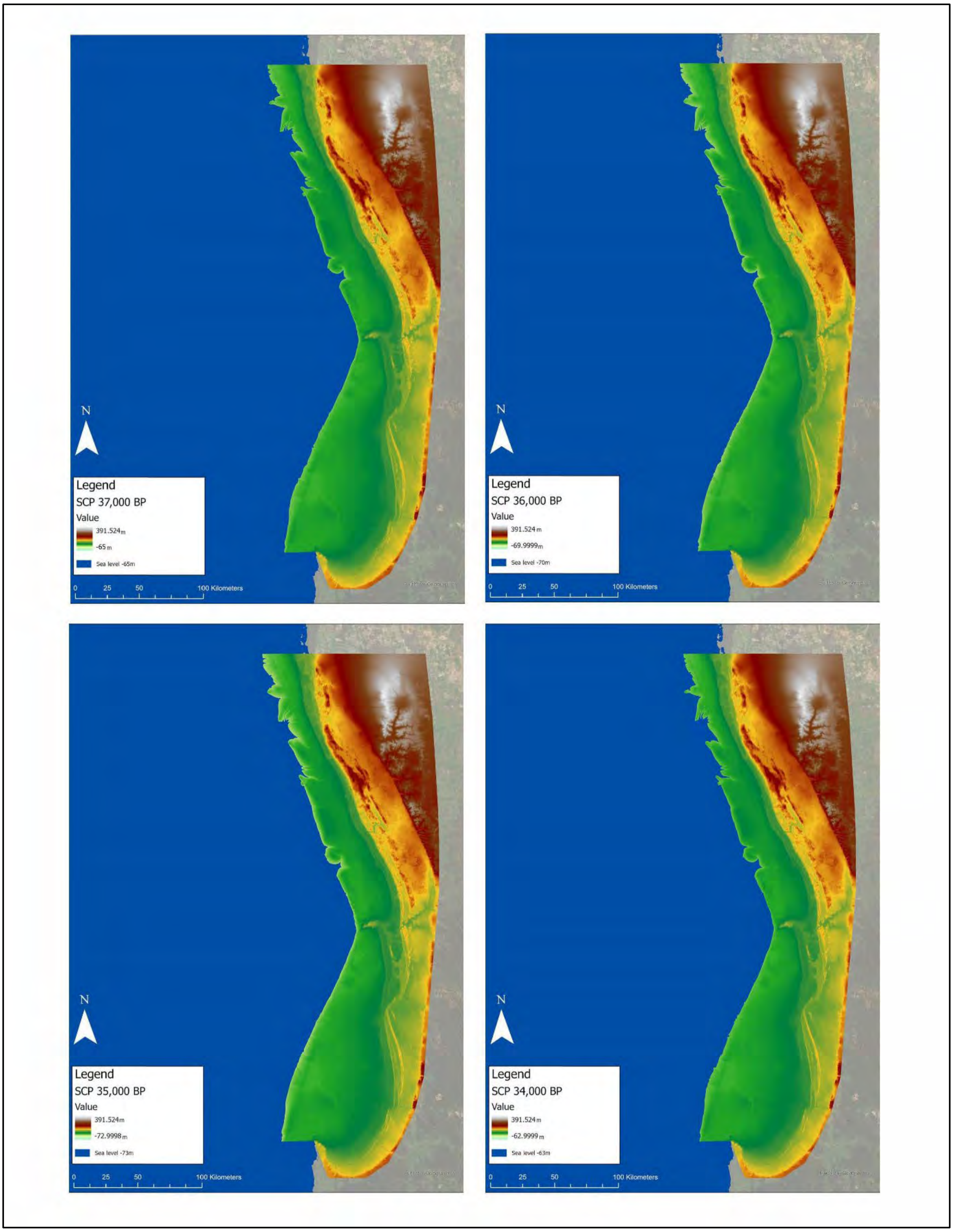

Figure D: Topography between 37,000 to 34,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

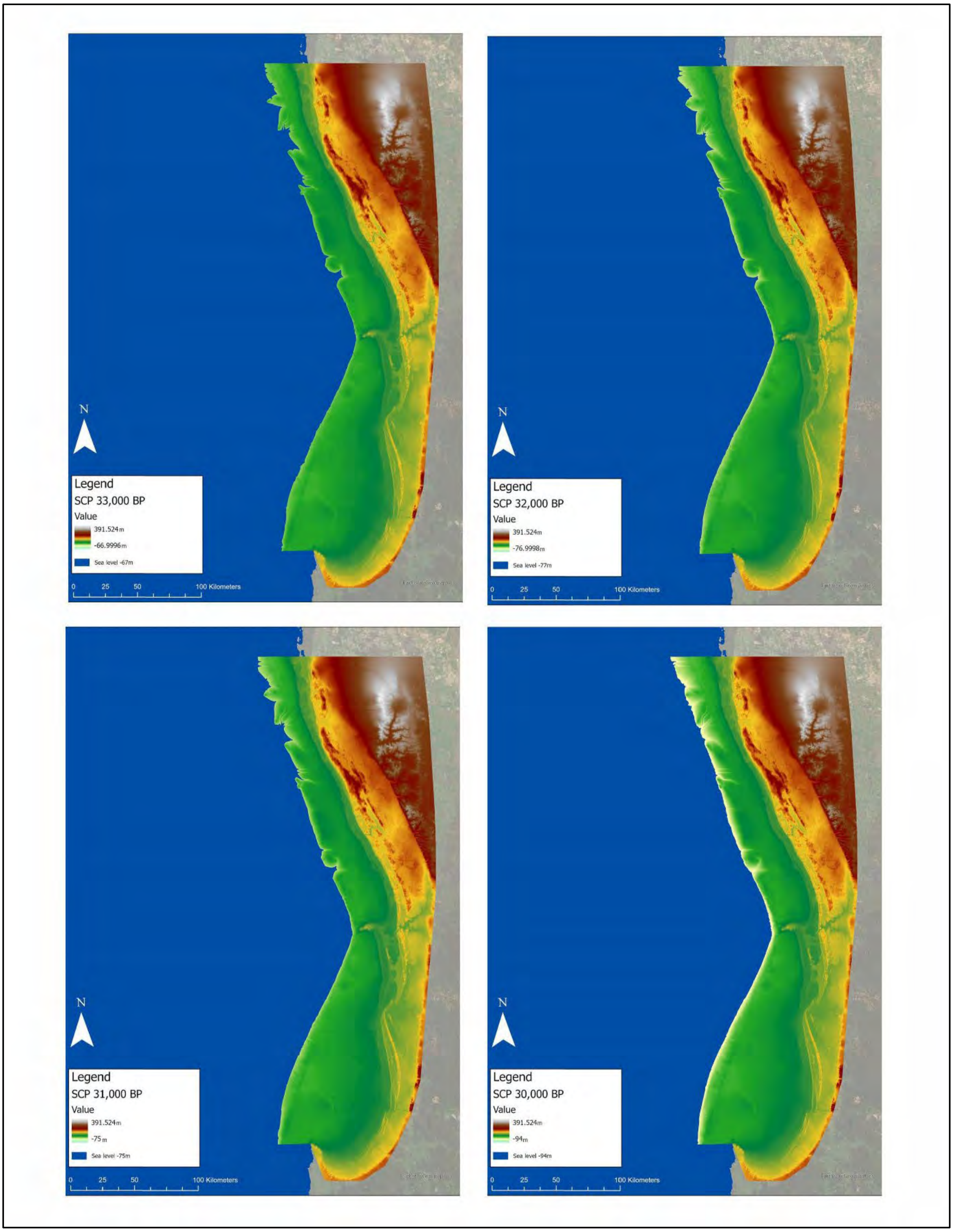

Figure E: Topography between 33,000 to 30,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

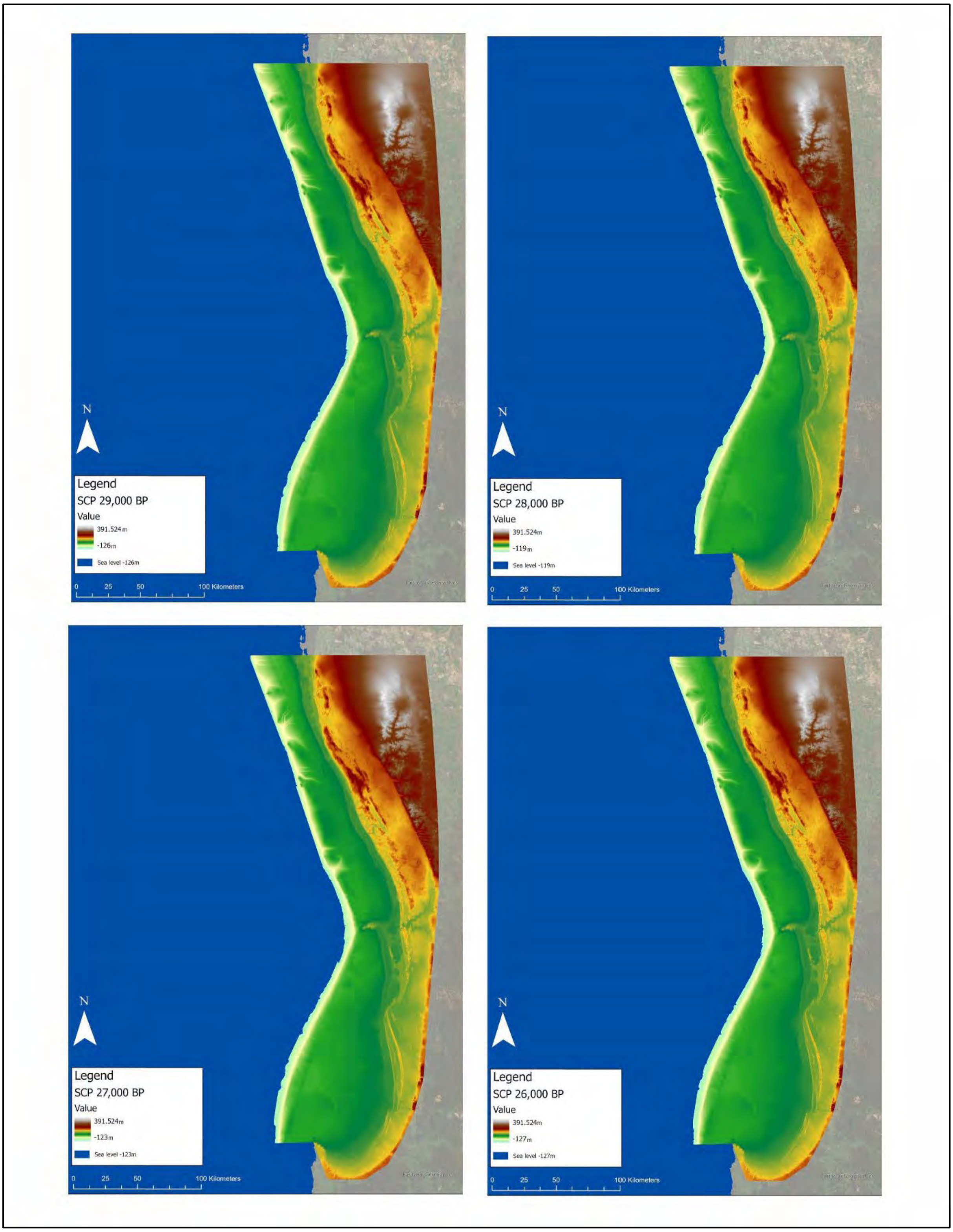

Figure F: Topography between 29,000 to 26,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

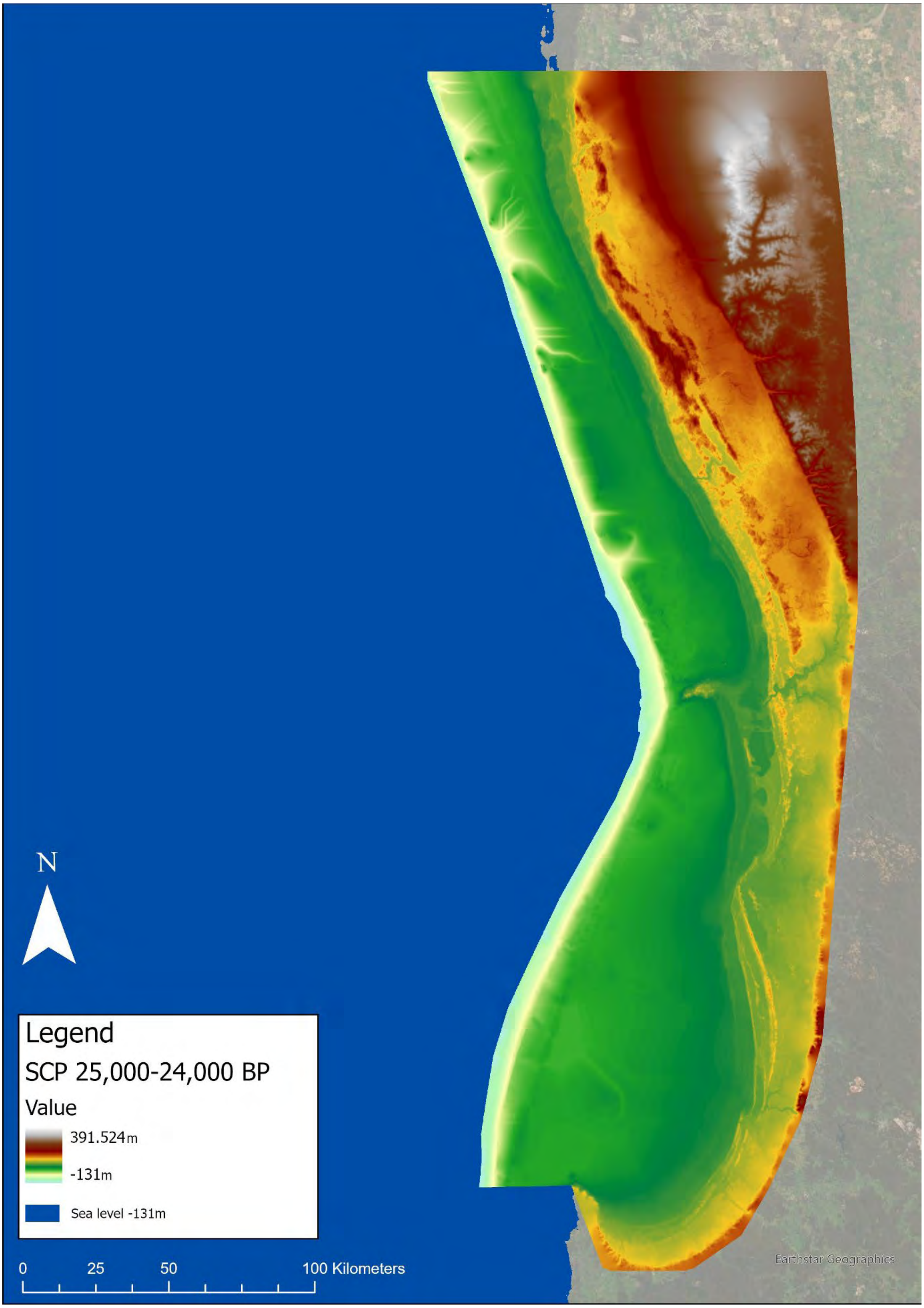

Figure G: Topography between 25,000 to 24,000 years BP. This time period represents the lowest sea level, and greatest area of emergent landscape, during the known period of human occupation on the SCP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

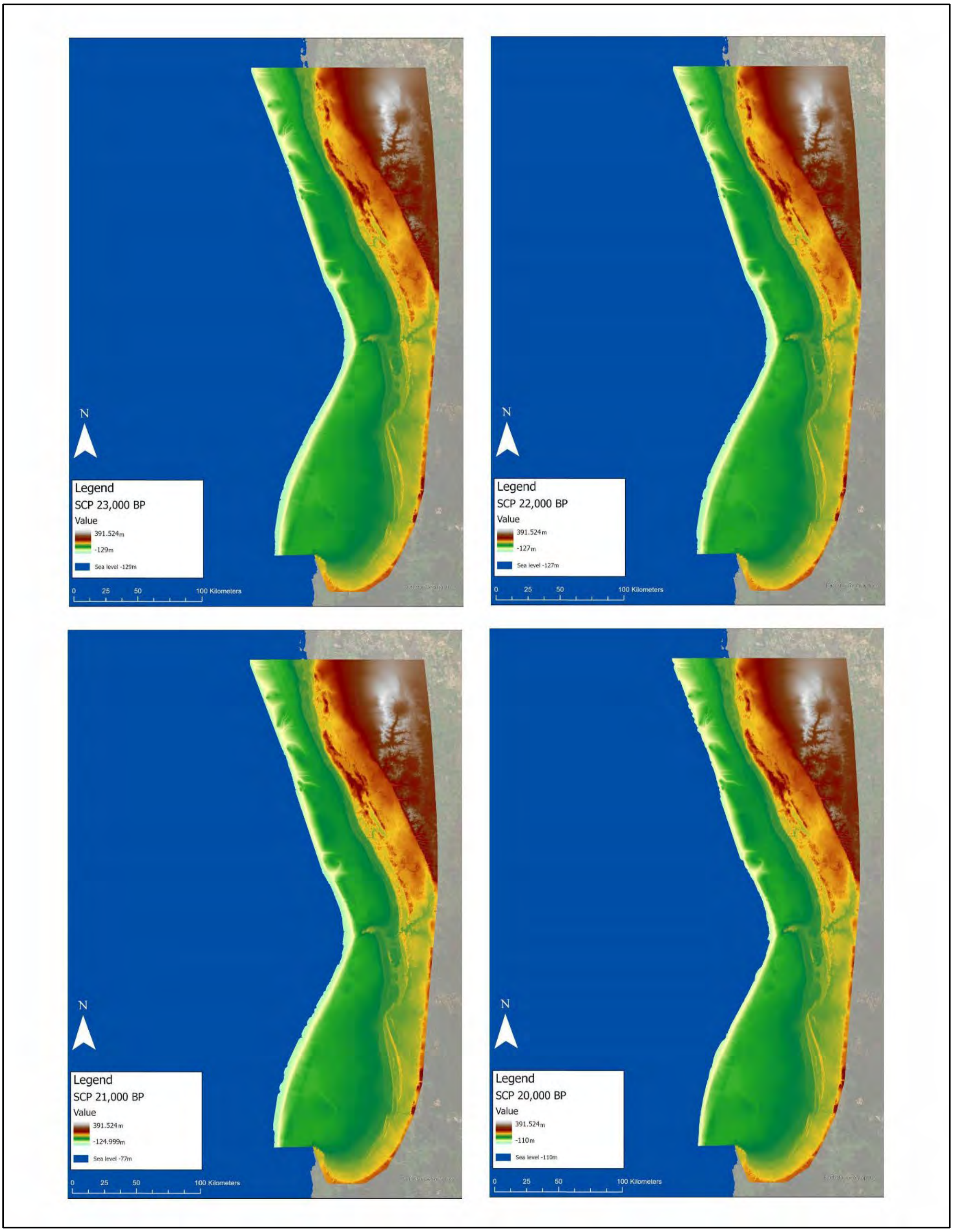

Figure H: Topography between 23,000 to 20,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

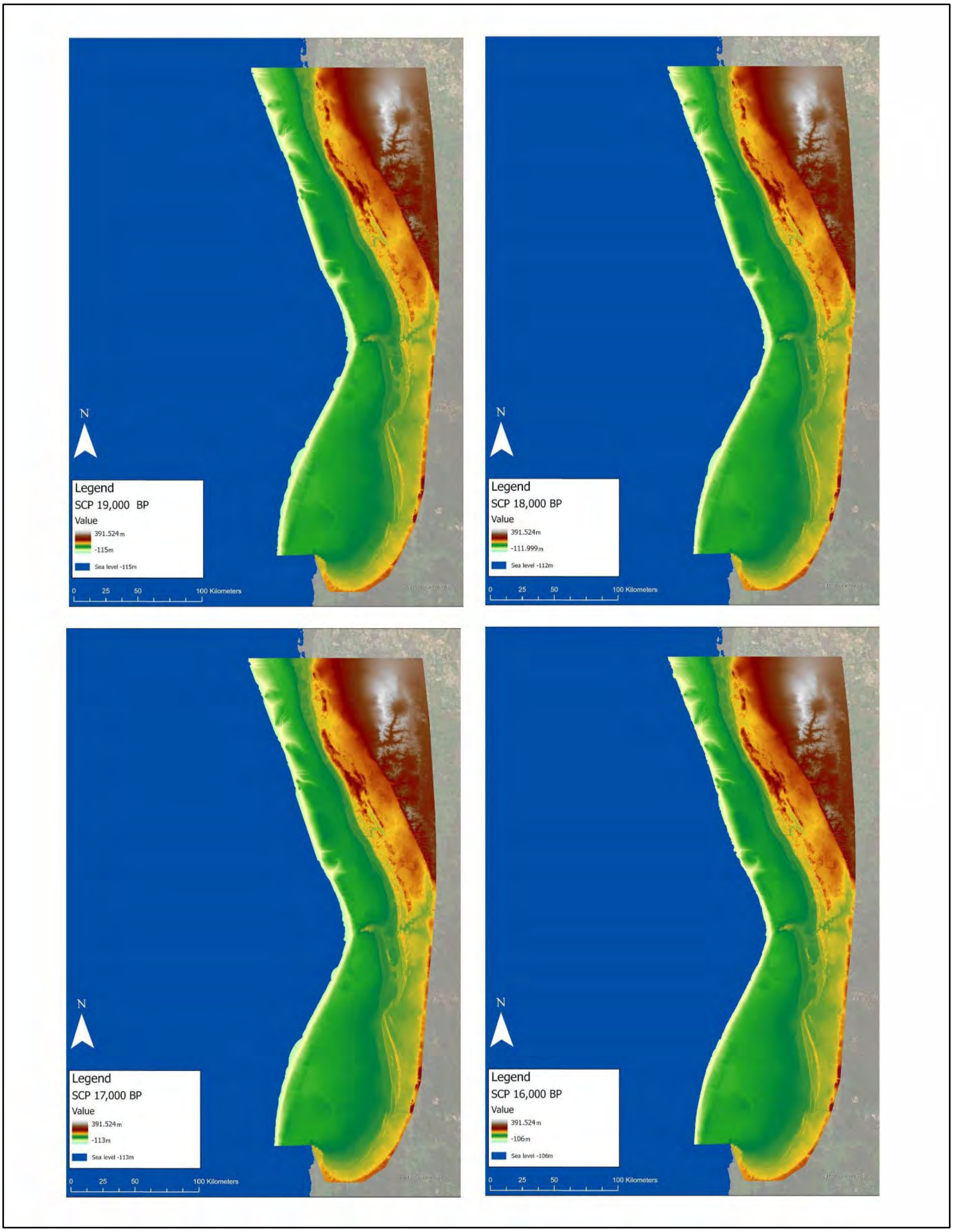

Figure I: Topography between 19,000 to 16,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

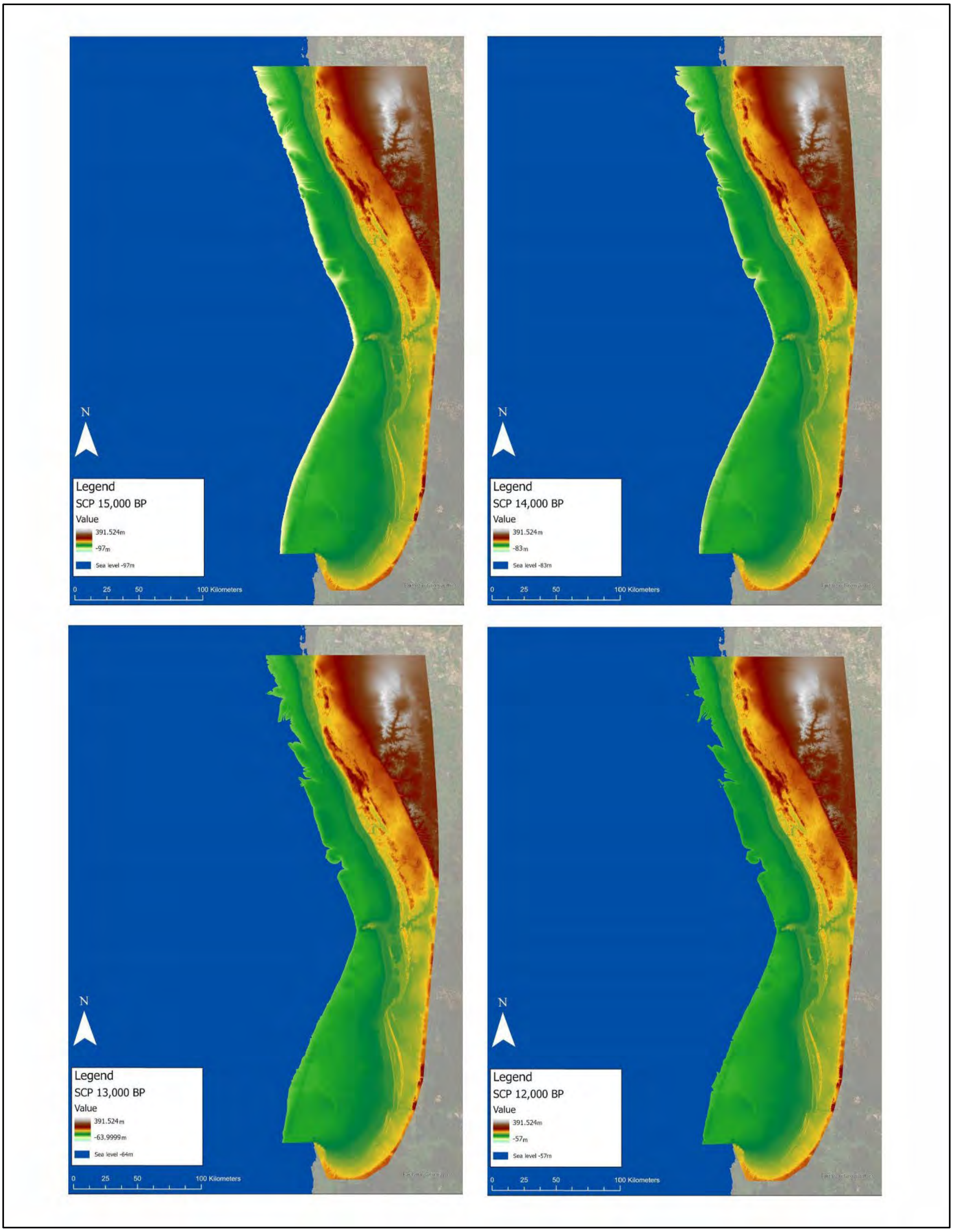

Figure J: Topography between 15,000 to 12,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

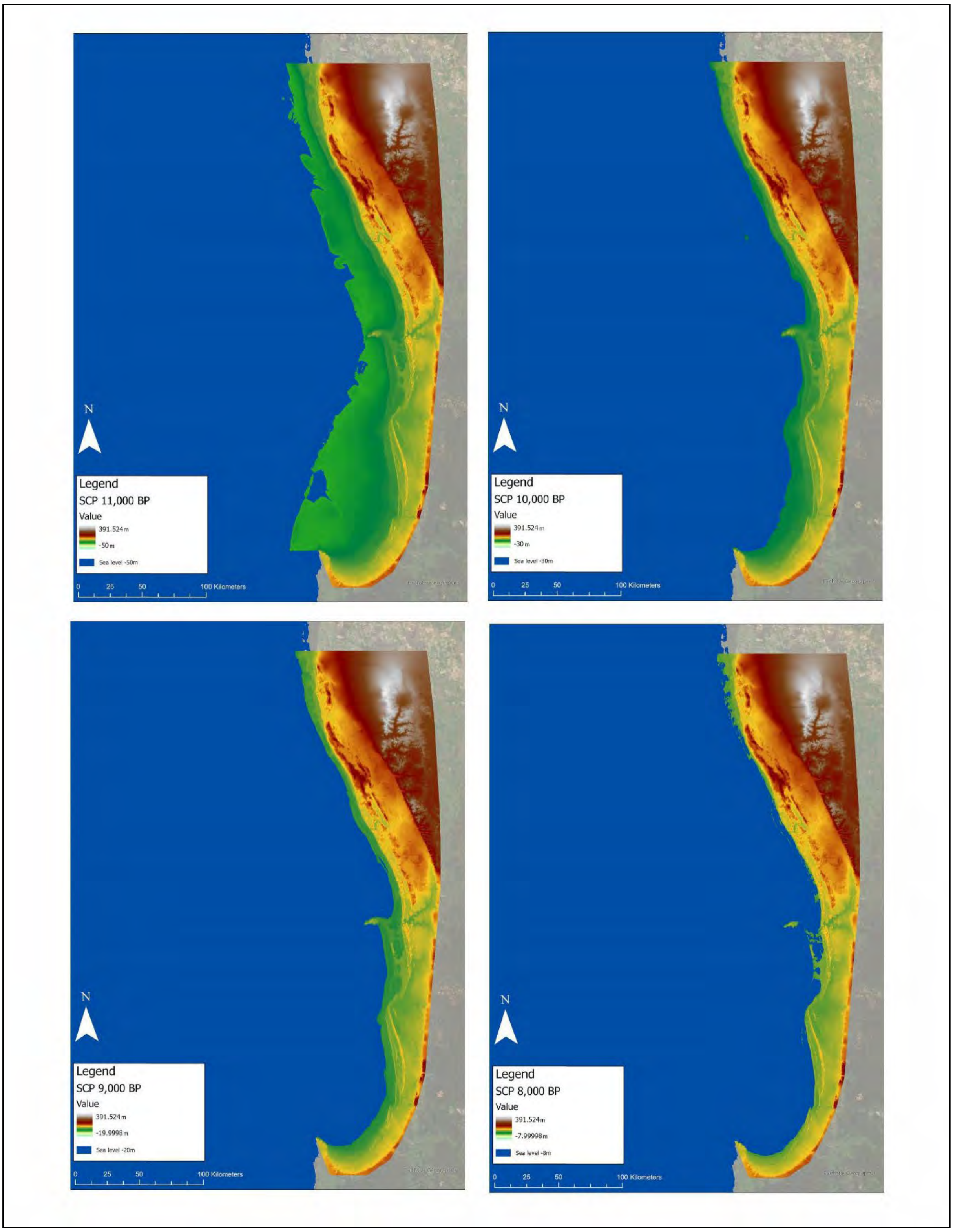

Figure K: Topography between 11,000 to 9,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

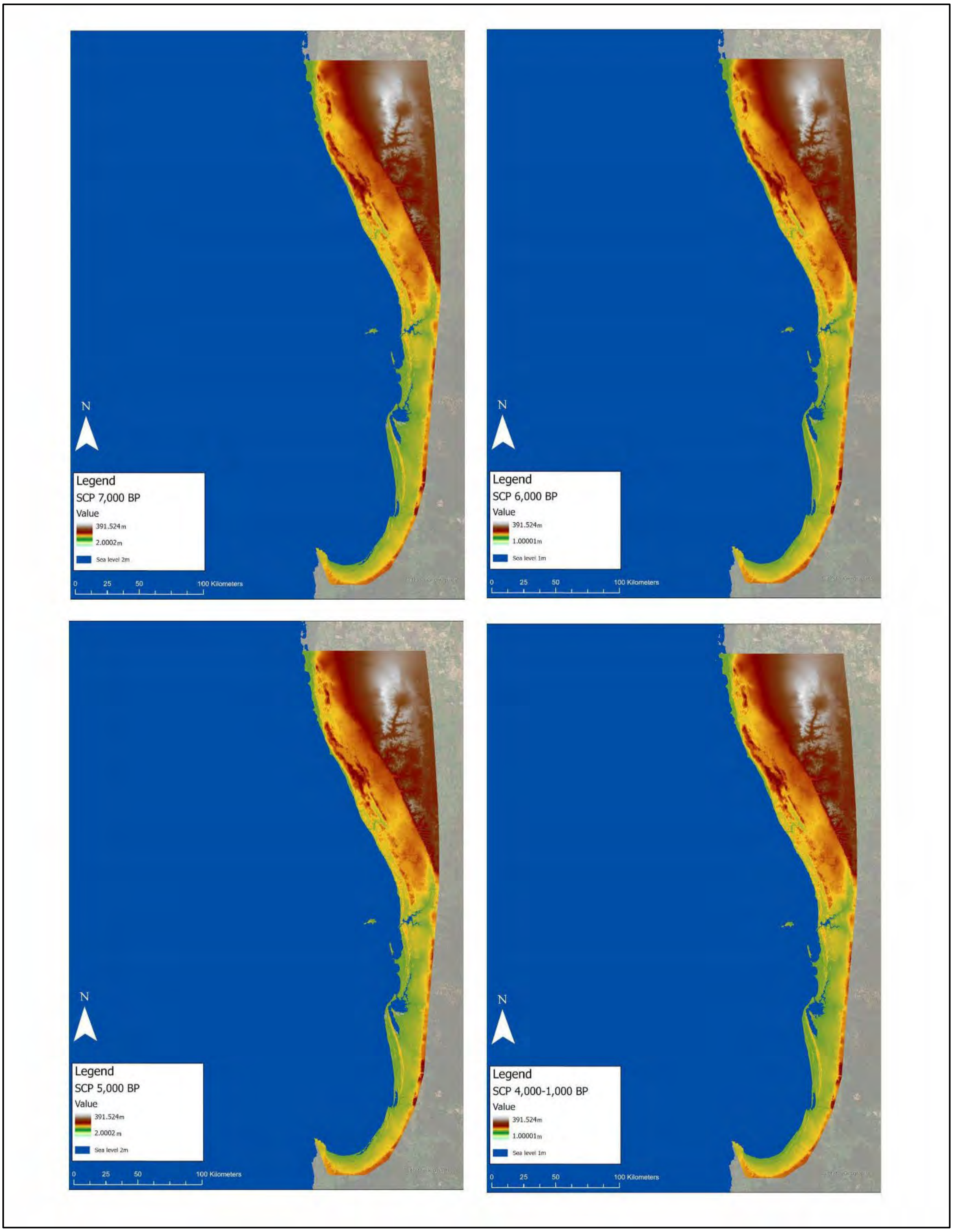

Figure L: Topography between 7,000 to 1,000 years BP. Elevation/depth values refer to present sea level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.

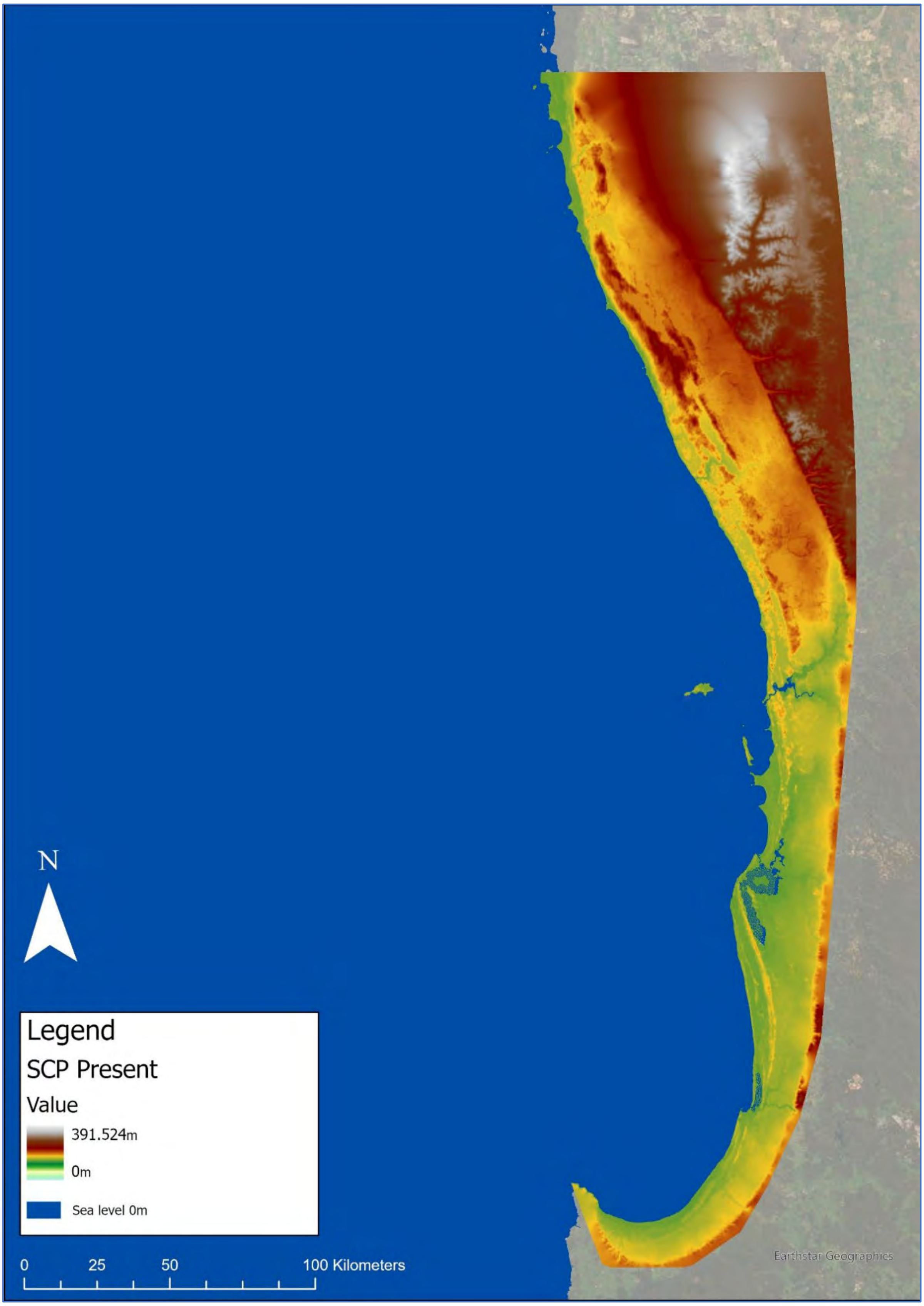

Figure M: Present-day topography. All heights are relative to Mean Sea Level. Satellite imagery: ©2022 Esri / Maxar / Earthstar Geographics.