FRIENDS OF THE DUNES

COASTAL DUNE VULNERABILITY AND ADAPTATION STUDY

EEL RIVER SHORELINE TRENDS

ACKNOWLEDGEMENTS

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As a partner to USFWS and FOD, GHD has enjoyed the interactions and benefits of working with Andrea Pickart and other USFWS staff and contractors, including Kelsey McDonald, and geomorphologists Patrick Hesp and Ian Walker.

In addition, GHD would like to acknowledge a valued client, the Wildlands Conservancy, for providing access to the Eel River Estuary Preserve, which, through other project work has served as a springboard for inquiry relating to dune systems and landscape and land use change. Our initial grant application posing the questions of the preface, at the scale of the littoral cell, began with the Wildlands Conservancy, and found expression in the partnership with USFWS and Friends of the Dunes, with GHD assuming the role of investigating the shoreline of the Eel River Delta. We are grateful for the partnerships that enable us to pursue these inquiries and contribute to the collective understanding of critical environmental issues.

Figure 1 (Cover): View of foredune on Eel River shoreline in study area. Photograph: GHD.

This report is intended to be viewed printed double-sided or in portable document format two-page w/cover view.

Contents

i. Figure Index

ii. Table Index

1. INTRODUCTION

1.1 CONTEXT

1.1.1 Coastal Systems

Coastal dunes develop at the interface between land and sea. Built by sediment, wind, waves, and vegetation, dunes “store” sediment, and are both a source for and recipient of sediment transported from offshore sources. They form a buffer that protects inland areas from inundation and dampen the effects of offshore wind and waves. They support unique habitats and wildlife adapted to their specific wind- and water-driven processes. Recreation, both along the beach and in the dunes themselves, characterizes most people’s use of coastal dune environments. In some regions, coastal development also dominates dunefields, with extremely high property values and treasured views.

The fluctuation of shorelines is a naturally-occurring phenomenon. Extreme weather events, such as flooding or high waves are episodic events that often mark extremes in shoreline change. Over many years, less extreme processes will rebuild or reshape the shoreline, averaging the amplitude of change. Studying the trend of shoreline movement, with attention to geomorphic characteristics and the effects of specific events on dune formation, can help to establish a baseline upon which the likely impacts of climate change can be projected.

Climate change threatens to unleash a cascade of effects on the natural processes that drive dune and shoreline formation. The degree to which those processes will be altered, and in turn, to which dunes will be altered, remains unknown. Sea level rise is the better understood of potential impacts. Cycles of wind and waves, rainfall-generated fluvial discharges, and behavior of offshore currents, are less studied, but have the potential to permanently change coastal landscapes

Any decision to implement options that modify the natural coastal forces of wind, storm surges, waves, tsunami, currents and water levels or that alter the morphological responses of the shoreline or sediment transport at the shoreline must be founded on a valid and comprehensive understanding of the behaviour of the coastal zone as well as the likely coastal impacts of climate change. These coastal processes and the trends for erosion and deposition occur within a coastal compartment or littoral cell. A littoral cell is the means to understand the “sources, sinks, transport and storage of sand in the nearshore zone… where …littoral transport begins at a rocky headland or section of the coast where the … upcoast section of sediment supply is restricted or minimal” and “sediments enter the littoral cell primarily from coastal streams and bluff erosion, and are transported alongshore under the influence of prevailing wave conditions” (Patsch and Griggs) (2007). Lack of understanding of littoral cells and sand budgets, and the interactions between littoral cells, has become apparent in California (Patsch and Griggs, 2007; and Moffatt and Nichol, 2013). The sediment budget for coastal Humboldt County is similarly challenged. A better understanding of sediment in the Eureka littoral cell would facilitate interpretation of the shoreline changes documented in this and other memos.

In Humboldt County, dunes are a prominent feature of the coastal landscape, varying significantly from the north end of the littoral cell, near Trinidad Head to its south end, near Centerville Beach. In places, these dunes appear to be eroding and causing risk to landscape and property. As such what is occurring and what could occur in the future in light of climate change needs to be understood so it can be appropriately managed. This report focuses on the shoreline and dunes adjacent to the Eel River Delta.

1.1.2 Eel River Delta Shoreline and Dunes

The dunes around the Eel River mouth are notable because, despite the considerable sediment supply from the Eel River, they remain remarkably narrow and less developed than dunefields to the north. On the north side of the Eel River mouth, these dunes separate the ocean from estuarine channels. On the south side of the Eel River mouth, diked former saltmarsh uses for ranching dominates. With the productive use of the ranchlands at stake, dune erosion,washovers, and a shrinking shoreline have been ongoing concerns and the impetus for homegrown dune recovery strategies. If climate change, as predicted, increases erosion of coastal environments, this locale will be among the most sensitive shorelines in Humboldt County. In this regard, it can also inform land managers of trends or trajectories to expect in shorelines.

The project study location is in coastal Humboldt County, California, within the Eureka Littoral Cell. It is focused on the shoreline segments encompassing the Eel River Delta, between Table Bluff to the north and the Wildcat Hills to the south. The shoreline of the Eel River Delta is part of a complex coastal ecosystem encompassing the Eel River and river mouth, coastal saltmarsh, brackish marsh, freshwater wetlands, and diked agricultural pasture.

These shorelines, while remote by the standards of the rest of California, are subject to a variety of human uses, including hunting, fishing, horseback riding, surfing, bonfires, camping and off road vehicle activities. The dunes primarily shield estuarine channel and ranch lands from high surf, although periodically overwashes do occur that result in dune flattening and sediment-filling of landward drainage channels. These periods of high surf typically result from a combination of high tides and storm events. In some cases, these deflated dunes have not recovered, and have fostered additional dune erosion.

In the shoreline around the Eel River delta, increased intensity of coastal processes could lead to erosion or decreased dune-building processes resulting in a partial or full disappearance of the dunes, and with them, the buffering capability that protects inland ranchlands and private property. In turn, changes in nearshore currents could result in increased dune-building processes. These possibilities must be considered in shoreline management and dune restoration, especially in light of climate change and sea level rise. These questions go beyond the scope of this study. They are, however, the main driver for this study i.e., this is a first step towards understanding shoreline trends, with the intent to build upon findings with climate change-specific studies that would include numerical modeling seeking to address these questions.

1.2 PROJECT BACKGROUND

This study has been prepared for Friends of the Dunes as part of the Coastal Dune Vulnerability and Adaptation project,("Dunes Climate Ready project") funded by the California Coastal Conservancy (CCC) and led by the United States Fish and Wildlife Service (USFWS). Friends of the Dunes is committed to conserving the natural diversity of coastal environments in Humboldt County, and has worked closely with USFWS on various efforts to restore and study coastal dunes. The USFWS Humboldt Bay National Wildlife Refuge has a long history of protecting and restoring dune environments, led by the vision, commitment, and drive of their Coastal Ecologist, Andrea Pickart.

Prior studies have addressed or characterized the shoreline or dunes within the project study area, or in nearby coastal dunes, or have otherwise attempted to understand the sediment transport processes that shape local dunes. These include but are not limited to:

- Development of Sand Budgets for California's Major Littoral Cells. Patsch, Kiki, and Griggs, Gary. Institute of Marine Sciences, University of Santa Cruz, California Department of Boating and Waterways, California Coastal Sediment Working Group. 2007.
- Dune Restoration and Shoreline Change, Humboldt Bay, California. Andrea Pickart. USFWS, 2014.
- Eel River Estuary Dune Reconfiguration Basis of Design Report. GHD, for the Wildlands Conservancy. 2017.
- Eel River Coastal Plain Dunes Assessment and Restoration Feasibility Analysis. Kamman Hydrology & Engineering, Inc. for The Wildlands Conservancy. 2016
- Eureka Littoral Cell, California, Coastal Regional Management Plan, Moffat and Nichol for the California Coastal Sediment Management Workgroup. 2017.
- National Shoreline Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast. USGS. 2006.

1.3 OBJECTIVE

The scope of this report forms part of a larger project with the goal, "(t)o understand and prepare for climate-change-related vulnerabilities of coastal dunes and beaches along the Eureka littoral cell," Accordingly, this memo contributes to Task 2A of this larger project, in which objective is to "(d)ocument historic changes in shoreline position and beach-dune morphology along the littoral cell, and tie to historic climatic variability."

Figure 2: Eel River shoreline dune barrier buffering sensitive coastal wetlands and pasture beyond, 2013. Source: California Coastal Records Project.

2. PROJECT METHODOLOGY

2.1 GENERAL

Overall approach to undertaking this study included literature review, aerial photography assessment of shoreline change, meeting with the broader project teams and site visits. Detailed outline of the aerial photography shoreline change assessment is provided below.

2.2 AERIAL PHOTOGRAPHY

In order to view historic changes of the shoreline over time, historical aerial images were acquired from a variety of sources including the USGS Earth Explorer, The Humboldt Bay Atlas, USDA NAIP, and the Humboldt County office of Public Works. Photos were acquired for the following years: 1939, 1948, 1954, 1958, 1965, 1970, 1981, 1988, 1993, 2005, and 2016. Photos from 2005 and 2016 were USDA NAIP imagery. Photos from 1948, 1954,1958, 1965,1970,1981,and 1988 were provided georeferenced from the Humboldt Bay/Eel River Delta Atlas Project. Photographs from 1939 and 1993 were georeferenced by GHD. Some sections of shoreline were not uniformly covered by the aerial photography. This is a limitation of the available imagery.

Photographs were referenced using criteria established by others. NAIP imagery from 2012 was projected in NAD 83 Zone 10. The northernmost unrectified aerial photo was overlaid with multiple control points representing stationary points with latitudes and longitudes that could be identified, and then transforming the photograph into the NAD 83 Zone 10 map projection. This procedure was repeated for additional photos in the series and turned into a geodatabase of aerial mosaics. After the photos were appropriately georeferenced in order for alignment between each photo, the shorelines were digitized for every year photos were available to GHD.

There are a several ways to delineate shorelines, and for this study it

2.2.1 Delineating shorelines

was chosen to digitize the toe of the foredune or incipient foredune, and when not fully developed the vegetation line that coincides with the foredune was used. This feature was the easiest to identify in historic photos. It is worth noting that as part of the shoreline digitizing exercise, there were areas that were unable to be digitized with certainty or clarity such as washovers, blowouts, and other highly dynamic areas such as sand spits because they are highly variable and ephemeral. Excluding them was agreed with the broader project team.

To verify the digitization of shoreline features, and to align with the broader project team methodology, GHD also participated in a multi-layered review that included comparing shoreline location estimates by two staff using historic aerials and reference aerial oblique photos of the shore. The final selected linework was then compared against a section of shoreline digitized independently by the USFWS team, which included both aerial photo and field GPS digitazation. Finally, this linework was reviewed in a team meeting by the local USFWS team and coastal geomorphologist Ian Walker.

2.3 DIGITAL SHORELINE ANALYSIS

In order to estimate change in shorelines, GHD then used the Digital Shoreline Analysis Software (DSAS) to create transects that ran perpendicular to the shorelines every 100 meters. Version 4.3, April 2012 was used. DSAS establishes a baseline against which shorelines are measured along each transect. The software performs analyses of the various transect data, including statistical outputs.

This study used the statistical outputs Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM), End Point Rate (EPR), and Linear Regression Rate (LRR) outputs. (Thieler et al, 2008-2017) To assist in analysis, the reaches of shoreline to the north and south of the Eel River were characterized as discrete (but related) segments. These are referred to as the north and south segments.

When using DSAS to obtain statistical outputs, one of the settings involves establishing a threshold of the minimum number of digitized shorelines that a transect needs to cross in order to be included in the analysis. This is important if one only wants to assess areas where one has shorelines for all 11 years, which would limit the number of output results. On the other side, if one wanted to see what the change is over more geographic area, one would need to lower the threshold. However, if it were too low then there might be areas where there are only two shorelines digitized and the result would be interpreted as “change between the entire time difference” when it really only reflects change between two years.

Accordingly, it was decided that it was best to run the DSAS using two different thresholds and then compare the results. The first threshold was 100% of the shorelines (11 in the north segment, 10 in the south segment), which means only those shorelines digitized in all 11/10 years were used. Some sections of shoreline, particularly near Centerville Beach, were therefore excluded by this run. The second threshold was set at 8, which is about 75%. This enabled us to capture sections of shoreline, such as Centerville Beach, that would have otherwise been excluded from the analysis.

There are different methods that DSAS uses to calculate shoreline change, each is “based on measured differences between shoreline positions through time.” The statistical analyses used in this study include:

Shoreline Change Envelope (SCE). The SCE measures the extremes in shoreline variability by documenting the farthest and nearest locations of the shoreline from the baseline position. The year or interval of years between these extremes is not reflected in the output. In this case, the baseline was drawn parallel to the shorelines and 500m seaward. (Thieler et al, 2017)

This statistic documents the most extreme difference in shoreline positions through the 77-year time period studied.

Net Shoreline Movement (NSM). NSM measures the change in shoreline from the oldest to most recent shorelines. It excludes intermediary shoreline positions, which may have demonstrated significant disturbance and recovery. Due to this exclusion, it provides context for understanding if the system is generally gaining, losing, or stable over time.

NSM was performed for each interval of years (i.e. from 1939 to 1949, 1948 to 1954, etc) on both north and south segments to determine shoreline change in that interval. This was to identify years where there might have been large events that caused shoreline change. With sufficient data over time, this also may also assist with establishing an interval and magnitude of those large events.

End Point Rate (EPR). The EPR calculates the average rate of shoreline change over the period of time of the oldest and most recent selected shorelines. It divides the distance of shoreline movement by the difference in years between the shorelines, in exclusion of data from other years. This averaging may be of use in estimating trends over time.

Linear Regression Rate (LRR). The LRR more comprehensively assess all data, creating a “best-fit” regression line for data from each transect. The slope of the line provides the linear regression rate. It conforms with accepted statistical modeling approaches. A consideration of using LRR is that the regression line can be skewed by outlier data, and the rate of change can appear muted compared to other statistical outputs.

LRR analysis was performed on transects with thresholds of 10 years in the south and 11 years in the north. As noted elsewhere, this results in the exclusion of some reaches of shoreline. LRR analysis was then performed on both segments with a threshold of 8. The results were similar, allowing for similar conclusions of the overall shoreline.

2.3.1 Estimating Error

Shoreline digitization inherently includes some margins of error, which can be attributed to quality of imagery, accuracy of imagery

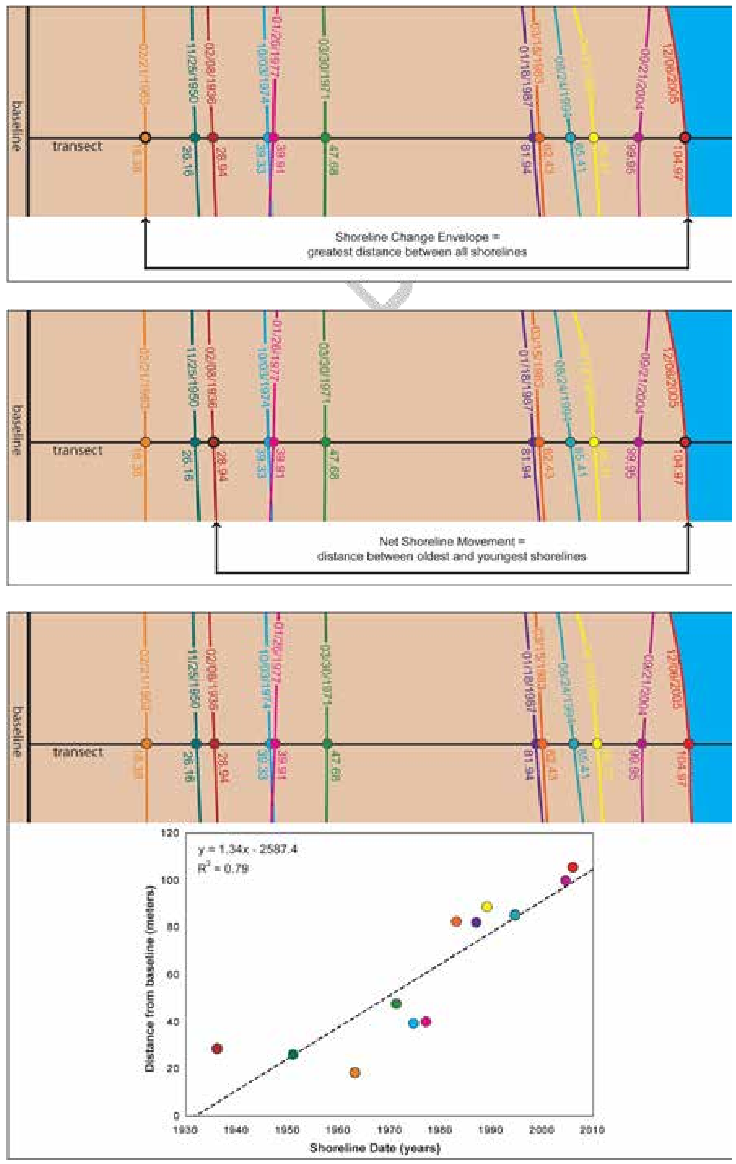

Figure 3: Illustrations of DSAS analytical outputs. Source: DSAS, 2012.

georectification, and measurement error when digitizing the lines. To account for the last error source, the amount of error was estimated by digitizing 1km segments of the shoreline three separate times for each year. These were then averaged and the distance from this average to the final shoreline used was calculated. This provided the average error for each year. This error estimation is considered the uncertainty value, and was included as an attribute for each shoreline. The DSAS software takes the uncertainty into account when computing statistical outputs.

3. GEOMORPHOLOGY OF THE EEL RIVER SHORELINE AND DUNES

3.1 COASTAL GEOMORPHIC PROCESS

While this study focuses on documentation of shoreline change, it is helpful to contextualize the project in terms of the coastal geomorphic processes propelling the change. Coastal processes are the hydraulic and sedimentary processes driven by tides, currents, waves, coastal winds and tsunamis. Forces exerted by wind and water act on the ocean floor and shoreface to drive currents, move sediments, erode exposed bedrock and shape the coastline, estuaries and the nearshore seabed.

Coastal processes relevant to a particular location include, but are not limited to, winds,waves, water levels (tides, storms, waves etc.), currents (rip currents, alongshore currents, density currents, surface wind currents, Continental shelf waves, large ocean circulations etc.), rainfall and runoff, and tsunamis (Cox et al, 2012).Waterborne sediment transport (alongshore sand movement, onshore/offshore transport, entrance scour, storm erosion etc), storm surge, wave overtopping, slope stability, sediment type, and vegetative cover (Cox et al, 2012) and human interactions with the environment play a role in shoreline stability. Figure 4 provides a conceptual map of those interactions. Future climate change will influence these interactions.

3.2 LARGE SCALE PROCESS OF THE EEL RIVER LITTORAL CELL

According to Cox et al (2012), to develop an understanding of large scale coastal processes it is necessary to undertake the following:

- Define a coastal compartment (or beach cell) with identifiable boundaries across which the rate of sediment transport can be readily estimated (through field measurement, historical analysis

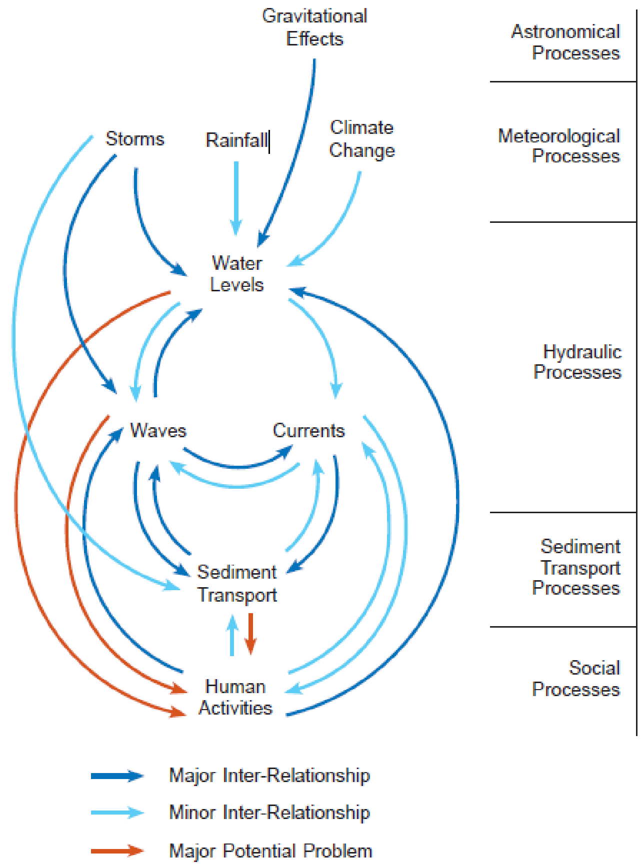

Figure 4: Interaction of coastal processes and human activities. (Cox et al 2012).

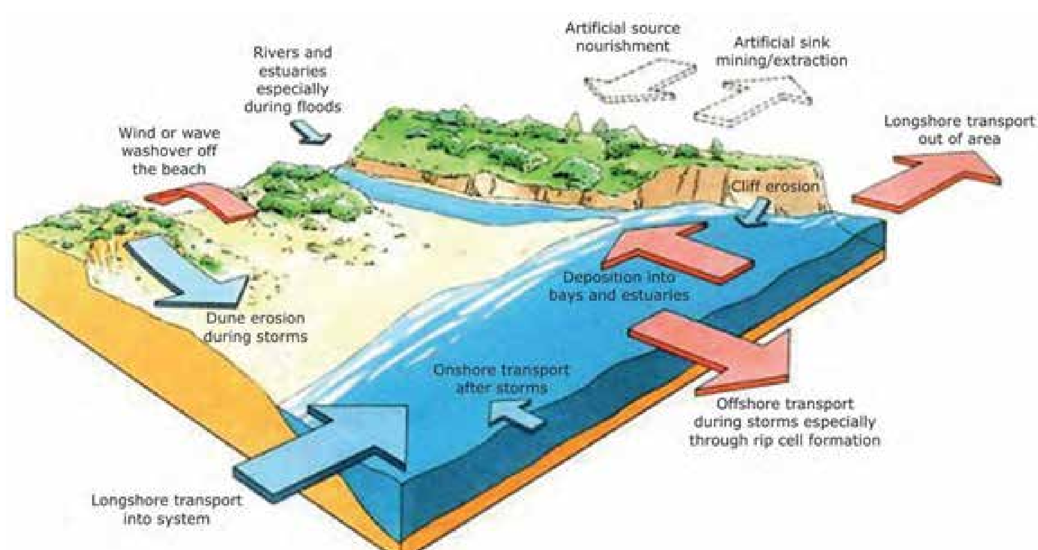

Figure5: Example of a coastal conceptual model of sediment sources and sinks (Cox et al 2012)

Figure 6: Northward moving sediment plume from Eel River Mouth. January 18, 2016. Photo: Brad Finney

or numerical computation).

- Identify and quantify (based on the coastal process understanding) the internal sediment movement pathways within that compartment and corresponding changes to the shoreline and the seabed.
- Quantify any sediment movement across the boundaries of the identified beach compartment (sediment budget).

The moderate climate of coastal northern California is derived from southerly offshore currents. Rainfall is typically between 30 and 40 inches per year, with most of it between the months of November and March. Fog has historically characterized summers. (Patsch et al, 2016). Costa and Glatzel (2002, cited in Patsch et al, 2016) note that the prevailing winds have velocities averaging 4 to 15 miles per hour, and come from the north and northwest. (Patsch et al 2016)

The north and south cells of the study area are subareas of the Eureka littoral cell. As noted elsewhere, these cells represent the reaches of shoreline north and south of the Eel River mouth, between Table Bluff and the bluffs of the Wildcat Hills (the southerly end of Centerville Beach).

3.2.1 Sediment Sources and Sinks

"A sediment budget equates the sum of all sediment inflows, less all outflows across the boundaries to the change in sediment in the compartment. If the total outflows exceed the inflows, the seabed and/or coastline in the compartment is eroding. Conversely, if the inflows exceed the outflows, then the seabed/coastline is accreting. A balance indicates no net change within the compartment (although there may still be redistribution within the compartment)" (Cox et al 2012). Figure 5 provides an overview of these processes.

Patsch et al note that the Eel River is a high sediment load bearing river, with the "highest recorded average annual suspended sediment yield of any river its size in the United States" (Brown and Ritter, 1971, in Patsch et al, 2016). Despite the well documented sediment discharges, the movement of this sediment in the coastal environment is not a settled question. One estimate that the Eel River contributes an average of 2,300,000 cubic yards of beach sand annually (Patsch, 2016) has been recently disputed. However this estimate has been used in planning discussions for the sediment budget in the littoral cell and remains illustrative of the magnitude of sediment observed.

Patsch et al (2016) discussed the potential role of submarine canyons or the continental shelf as sediment sinks, and reported on studies conducted over 30 years to determine the effect of submarine canyons near the Eel River mouth. Research by Ritter (1972) and Nittrouer (1999) concluded that sediment is distributed along or near the edge of the continental shelf, while Morehead and Syvitski (1999) modelled a distribution of sediment 12 miles to the north of the Eel River mouth and within 6 miles of the shore. Studies conflicted on the role of submarine canyons specifically as sinks with Silver (1971) observing that the submarine alluvial fan at Eel Canyon is too small for the amount of sediment that would be expected to be deposited, and Greene and Conrey (1966) identifying a filled canyon closer to shore, suggesting that the canyon is indeed being filled.

Similarly, studies conflict on the direction of longshore currents and movement of sediment to the north. Moffat & Nichol (2017) report that:

> (D)ue to differences in wave intensity and direction throughout the year, littoral-zone material moves both directions (north and south) in the Eureka Littoral Cell. For example, a 27-year monthly average of the wave climate at the closest national Data Buoy Center (NDBC) buoy, located 17 nautical miles west of the Humboldt Bay entrance (Buoy 46022), shows a strong seasonal signal. In the late fall and winter, when long-period, storm driven swell dominates the record, maximum wave heights can reach 32 to 40 ft. In the late spring and summer, when wind waves tend to predominate, maximum wave heights can reach 16 to 32 ft. (Moffatt & Nichol, 2017).

Figure 7: Bluff Erosion near Fleener Creek, south of Centerville Beach. Top: Vegetated Bluffs, 1979. Bottom: Erosion, 2013, Copyright (C) 2002-2017 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org

However, it is also acknowledged that some sand may actually be transported southward around Cape Mendocino to be deposited in more distant submarine canyons. (Moffat & Nichol, 2017).

A further natural process that influences the balance of sediment in the littoral cell is bluff erosion (Figure 7). The contribution of bluff erosion to the Eureka littoral cell is estimated at 0%. While minute, bluff erosion is observed along the southern extent of the littoral cell, and may be contributing to the south beach and dunes of the Eel River delta. In an area with relatively low development pressure with stabilized runoff rates, it is more likely that the bluff erosion is tied to a combination of wave attach and tectonic activity: the highly active Mendocino Triple Junction is a relatively close distance offshore.

3.2.2 Climatic Processes

Climate drives precipitation and wind processes that affect sediment mobility. Extreme weather events that could be influencing coastal shoreline changes along the Eel River shoreline include floods and El Niño Oscillation (ENSO) events. Appendix B provides a table of ranked La Niña and El Niño events from 1948 to the present.

Significant flood events for the region include:

- 1937 Historical high flood elevation at Fernbridge of 7.74 meters on December 11, 1937 (NOAA website).
- 1955 – December large flood event (Town of Scotia website)
- 1964 – December (NOAA) Large and renowned flood event. Historical high flood elevation at Fernbridge of 8.99 meters at Fernbridge on Dec 23, 1964 (NOAA website).
- 1966 – January 5, 1966 (Eureka Humboldt Standard)
- 1974- Historical high flood elevation at Fernbridge of 8.03 meters on January 16, 1974 (NOAA website).
- 1986 – Historical high flood elevation at Fernbridge of 7.92 meters on February 18, 1986 (NOAA website).
- 1997 – "Humboldt County's fifth-largest flood" (Humboldt County)
- 2005-2006 – December-January. Historical high flood elevation of 7.74 meters on December 31, 2005 (NOAA website).

The El Niño Southern Oscillation contributes episodes of intense storms with potential for increased erosion hazards along the California coast. (Barnard et al, 2017) Wave direction, the onset of peak annual high tides, sediment supply from watershed sources, and other factors may attenuate the potential for extreme coastal erosion. Climate change or other anthropogenic changes affecting these factors could expose shorelines to increased erosion. Climate change scientists have not determined with confidence if ENSO cycles will yield an increase in El Niño or La Niña events. (Di Liberto, 2014). Figure 8 describes ENSO fluctuations over 68 years, which includes the time period of this study.

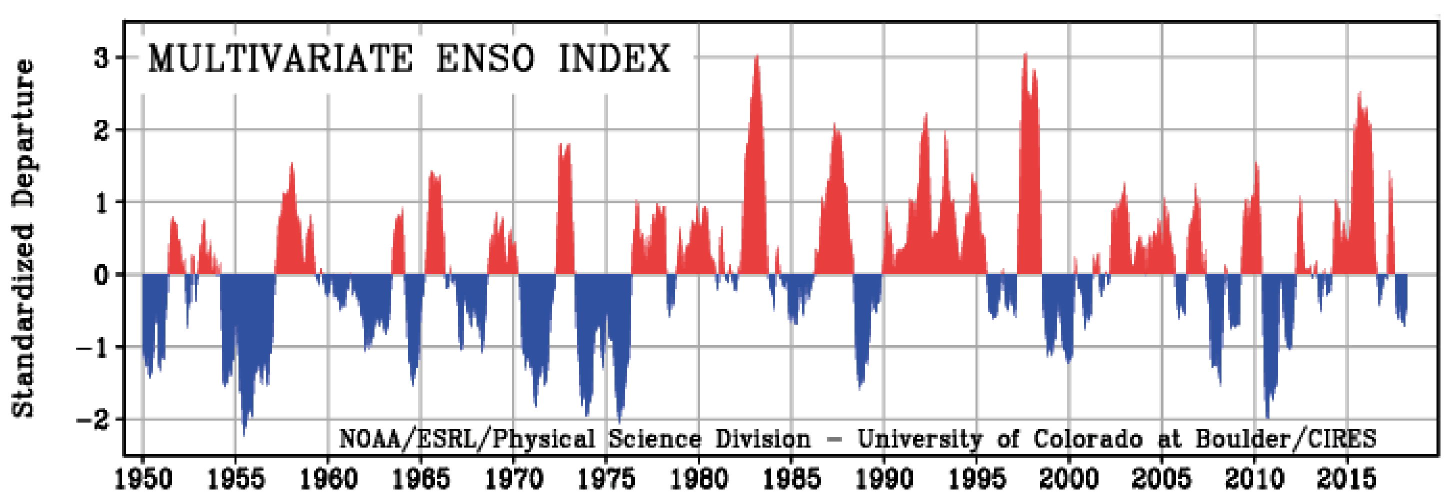

Figure 8: Multivariate ENSO Index, 1950-Present. Source, NOAA.

4. SHORELINE CHANGE

The results of the digital shoreline analysis provided trends on erosion and deposition along the study area coast, with the site split into two distinct areas i.e. the south segment of the Eel River mouth and the north segment of the Eel River mouth.

4.1 SHORELINE ANALYSIS SUMMARY

A linear regression rate of +1.53 m/year was measured for the north and a linear regression rate of -0.45 m/year was measured for the south). Accordingly, this equates to the north portion of the site accreting approximately three times more than the south is eroding. Furthermore the net shoreline movement in the north segment accreted by 106.92 m between 1939 and 2016, and the net shoreline movement in the south eroded by 16.39 m between 1948 and 2016. The EPR in the north was 1.39 m/year and the EPR in the south was -0.24 m/year (Figure 9, Table 1).

	North (11 threshold)	South (10 threshold)
End Point Rate, EPR (m/yr)	1.39	-0.24
Net Shoreline Movement, NSM (m)	106.92	-16.39
Shoreline Change Envelope, SCE (m)	130.87	52.92
Linear Regression Rate, LRR (m/yr)	1.53	-0.45

Table 1: Shoreline Change Summary

Figure 9 (Facing page): Shoreline Change Summary Map

Shoreline Change (1948-2016)

Linear Regression Rate (m/yr)

-2.5 - -2.0
-2.0 - -1.5
-1.5 - -1.0
-1.0 - -0.5
-0.5 - 0
0 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
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Friends of the Dunes
Coastal Dune Vulnerability & Adaptation Study

Job Number 11125126
Revision A
Date 29 Jun 2017

Shoreline Accretion and Erosion Trends
Eel River Segments

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Data source: Esri basemaps, 2017. USDA NAIP Orthoimagery 2016. Created by:jclark2

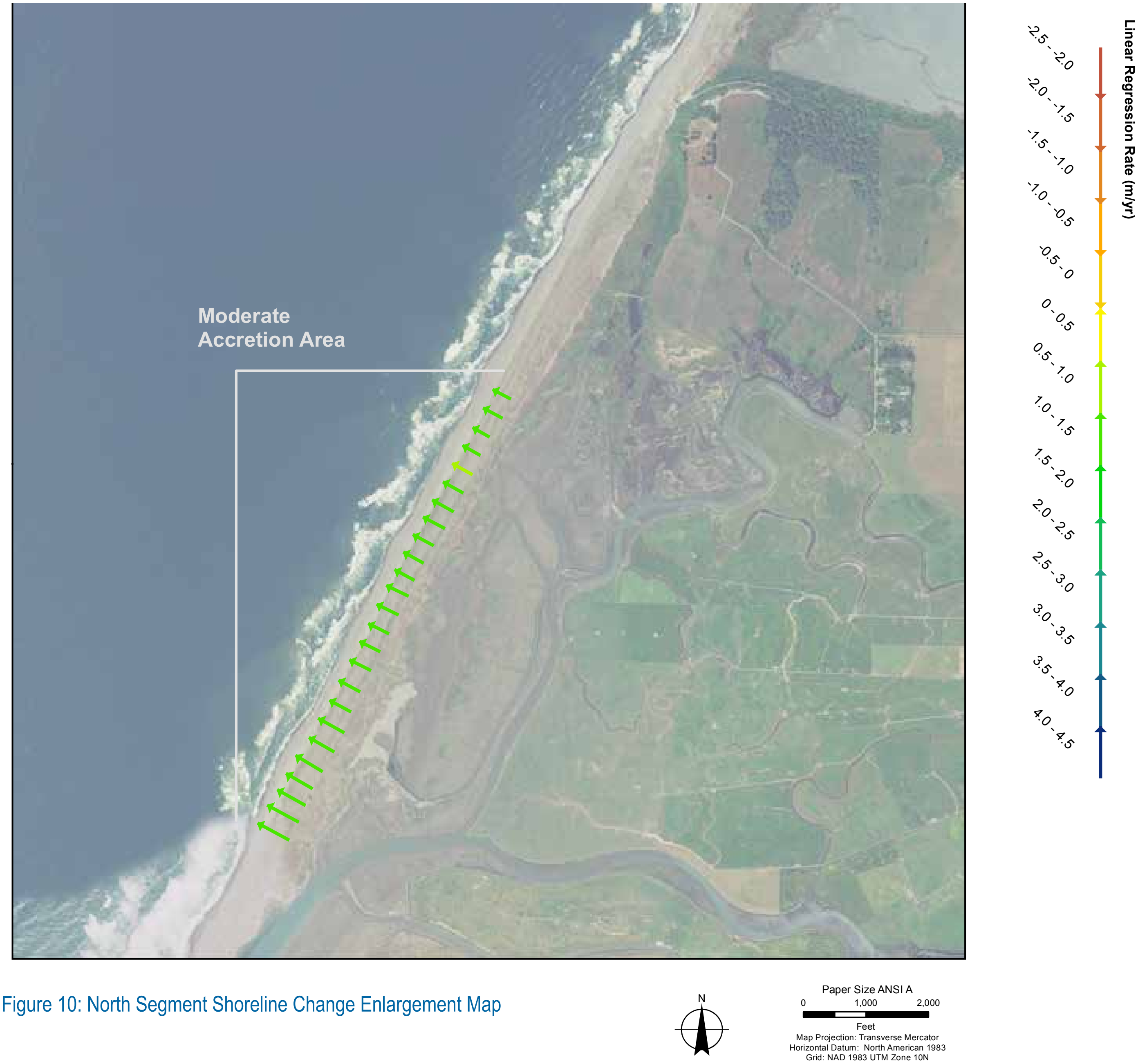


Figure 10: North Segment Shoreline Change Enlargement Map

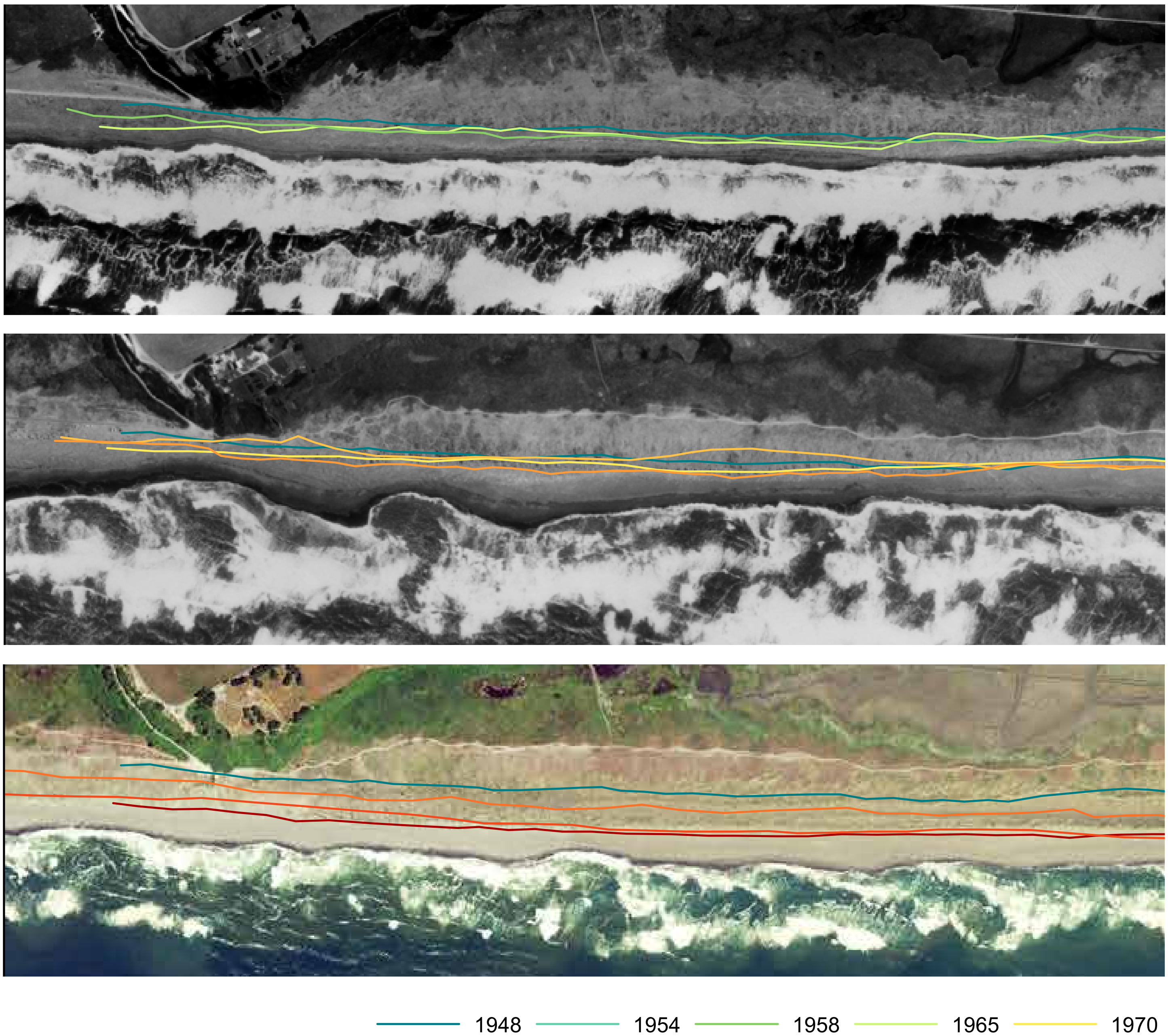
4.2 NORTH AND SOUTH SHORELINE SEGMENTS

The extent of shoreline accretion and erosion is presented in Figures 10 and 11 illustrating the trends for the North Eel River segment and south Eel River Segment.

In these two figures it is apparent that the northern portion of the study site has had an average of 0.5 to 2.0m /year accretion rate between 1948 and 2016; whereas in the southern portion of the study site the trend is erosion of -0.5 to -1.5m/year between 1948 and 2016. This trend of erosion in the south and accretion in the north is in agreement with the works of Kamman, Patsch and Griggs and Moffatt and Nichol.

Between 1948 and 1988, both North and South shorelines followed the same trends of erosion and accretion, albeit at different rates. From 1988 on, however, the two shorelines eroded and accreted during different intervals.

Figure 11: South Segment Shoreline Change Enlargement Map



4.2.1 North Segment Shorelines

The North Segment has shown a continuous trend of dune barrier widening from 1948 to 2016. Widening occurred in different reaches of this segment at different intervals. Excluding the highly dynamic and unstable areas around the Eel River mouth, slight seaward widening is first observed between 1948 and 1965, with more widening at the southern end of the segment, becoming almost negligible at the northern end. This seaward movement of the shoreline increased from 1970-1981. In 1988 there is a period of erosion as the 1988 alignment aligns with the 1948 alignment. From 1993 there has been continuous shoreline accretion as the shoreline moves seaward.

Reaches that did not maintain shorelines between 1948 and 2016 are omitted. The Eel River mouth migrated in and out of these reaches.

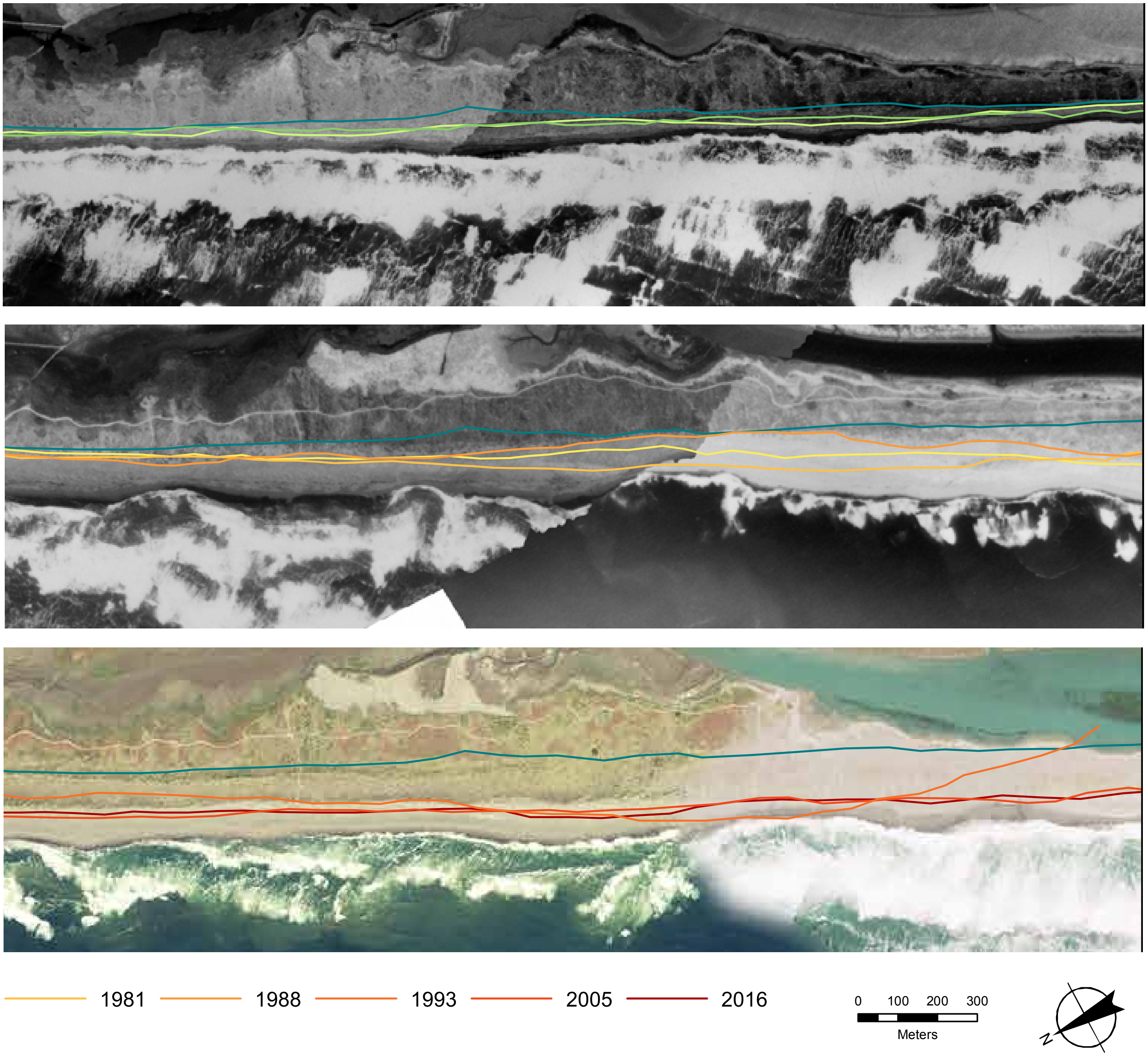


Figure 12: Compilation of the north segment shorelines. Top: background photograph, 1965, with shorelines from 1948, 1958, 1965. Middle: background photograph, 1988, with shorelines from 1948, 1970, 1981, 1988. Bottom: background photograph, 2016, with shorelines from 1948, 1993, 2005, 2012.

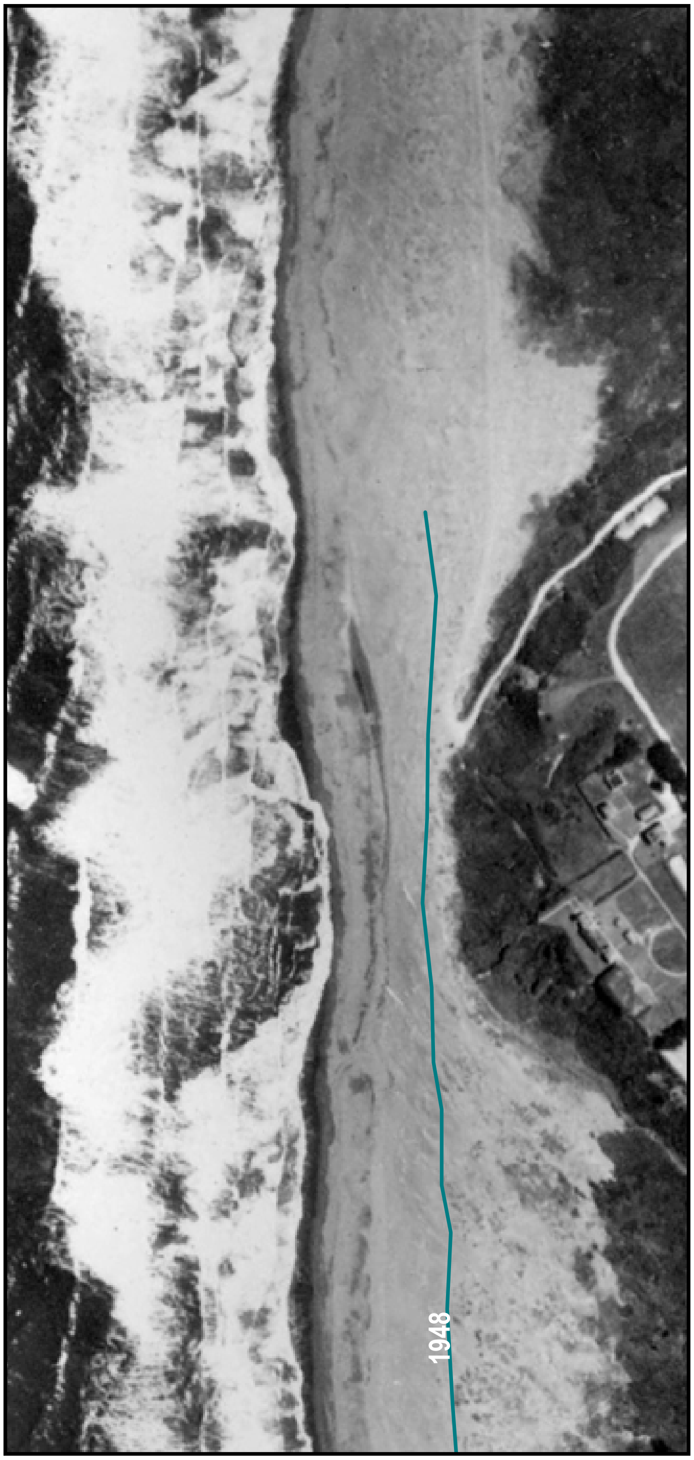
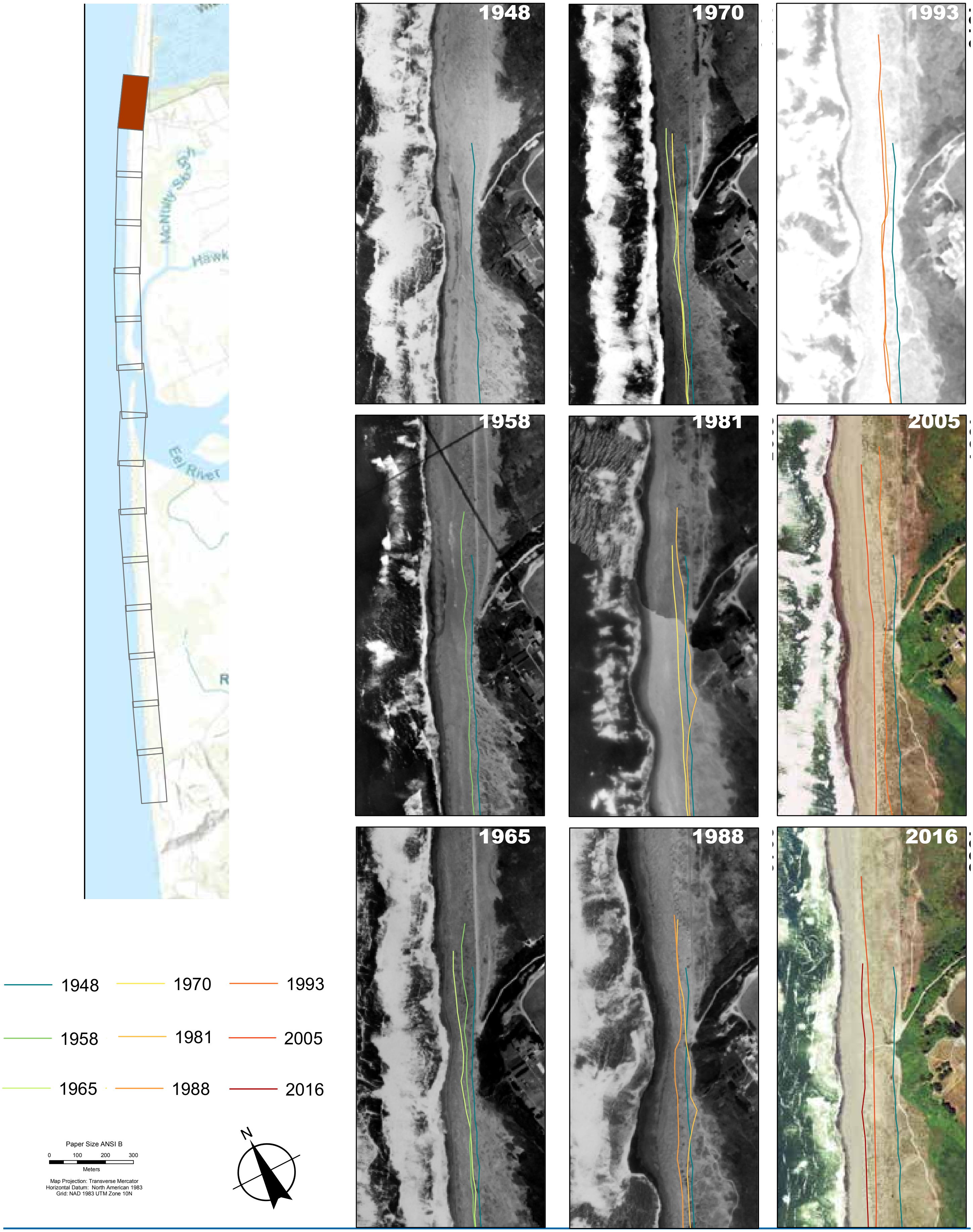


Figure 13: Enlargements of shoreline segments from 1948 (left), and 2016 (right).

From 1948 to 2016 there has been a continuous trend of the barrier widening as the shoreline / dunes prograded seaward. This trend appears to have accelerated from 1993 to the present.

Figure 14 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.


Hawk
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Paper Size ANSI B
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Meters
Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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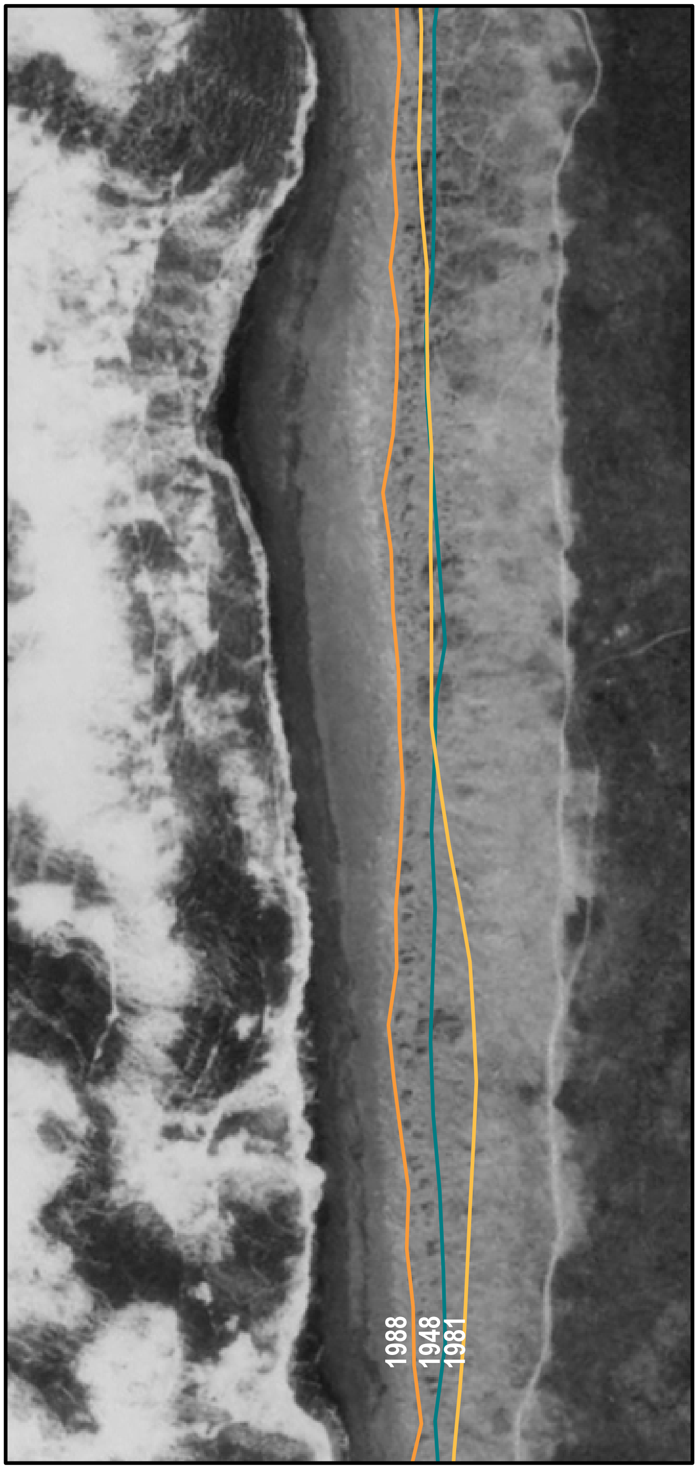


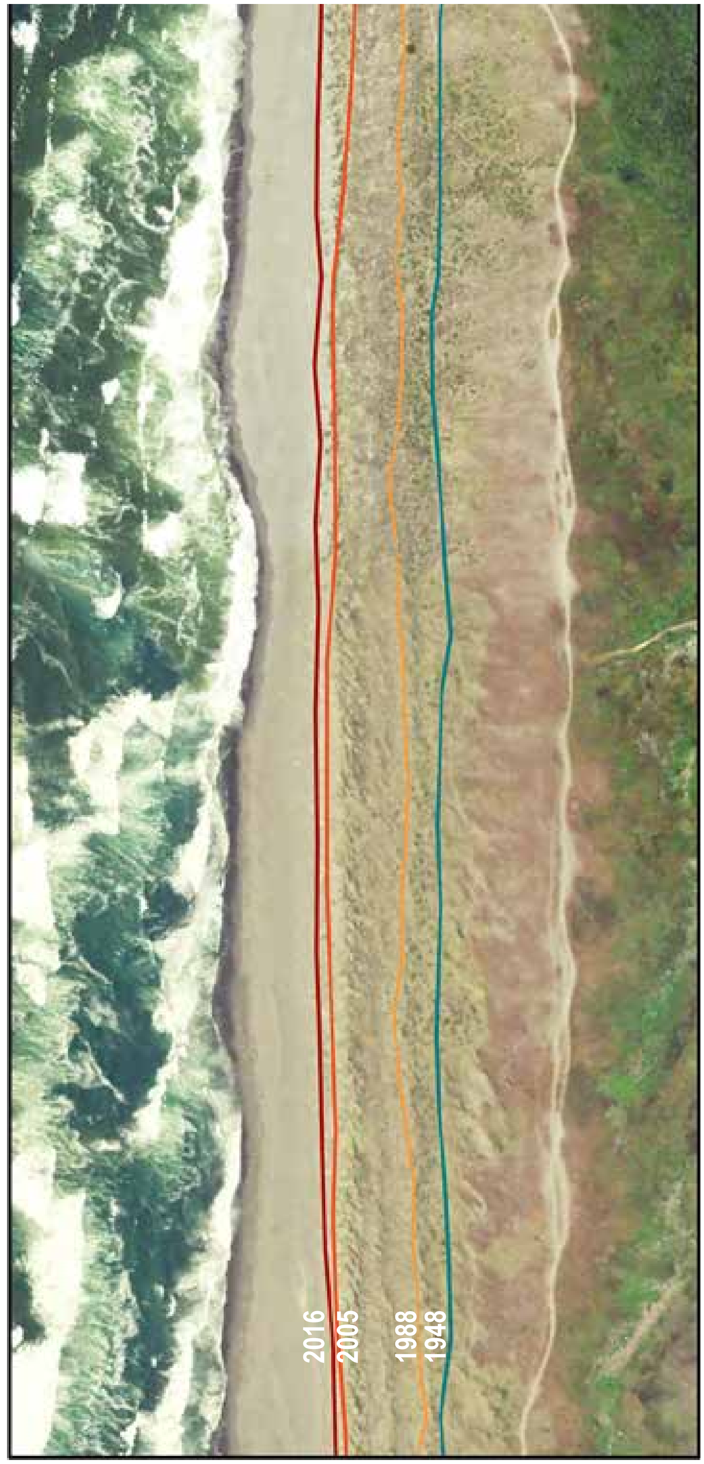
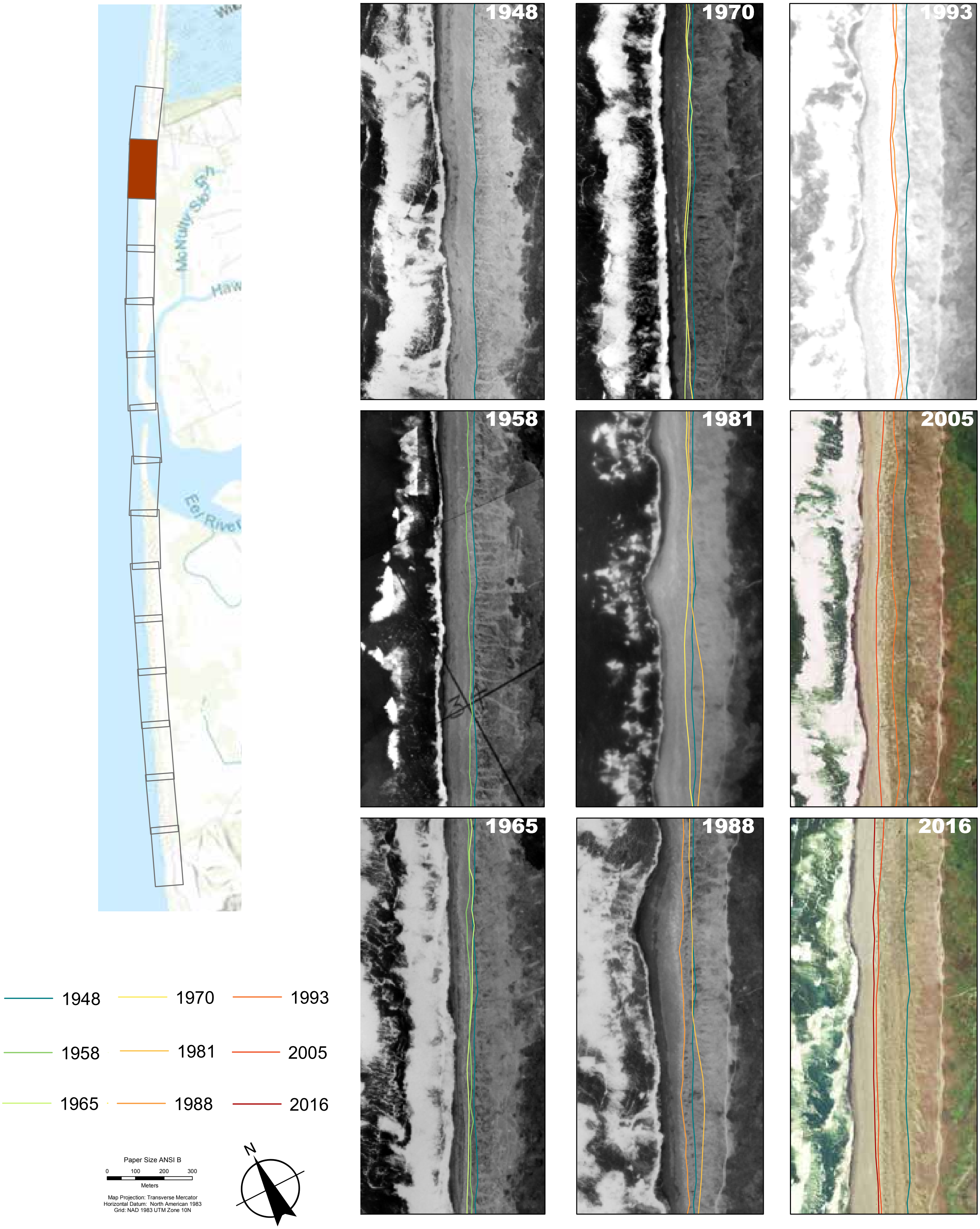


Figure 15: Enlargements of shoreline segments from 1988 (left), and 2016 (right).

From 1948 to 1988 the shoreline has been relatively stable. Since 1988 there has been a continuous trend of the barrier widening as the shoreline / dunes prograded seaward.

Figure 16 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.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Paper Size ANSI B
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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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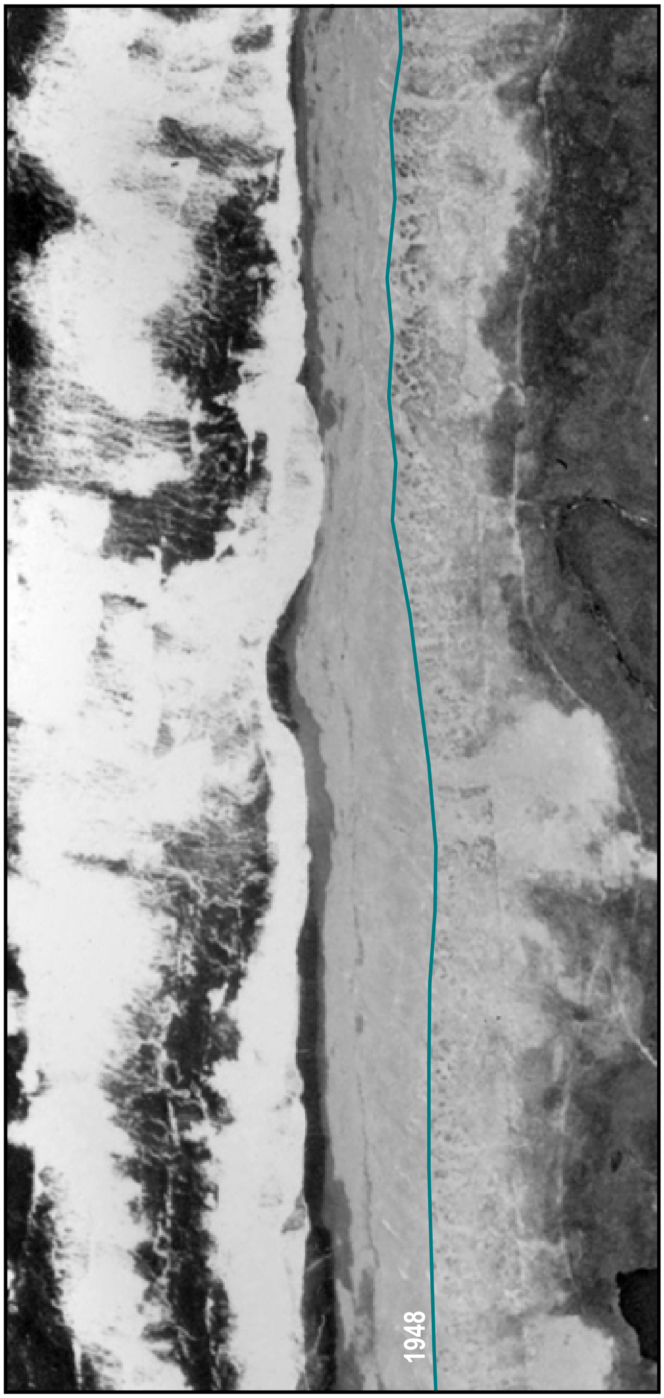


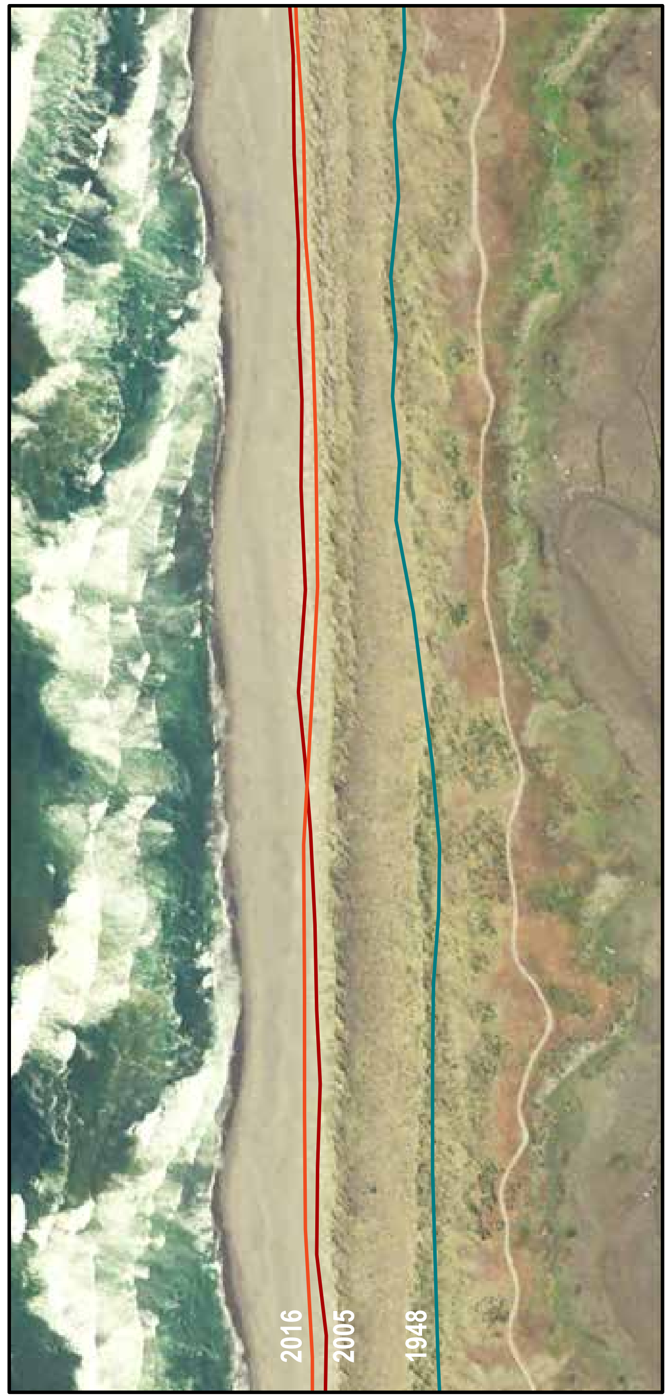
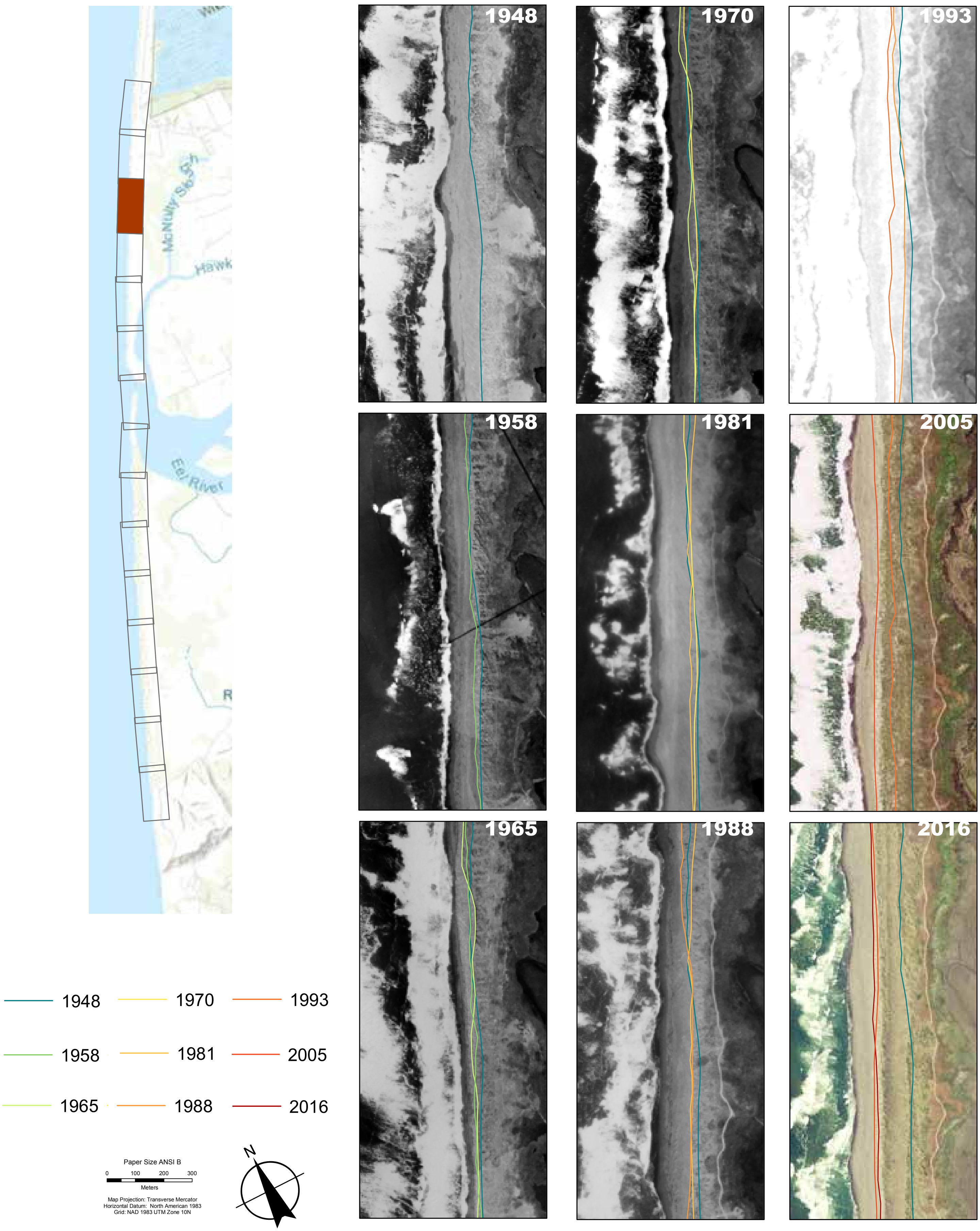


Figure 17: Enlargements of shoreline segments from 1965 (left), 1988 (center), and and 2016 (right).

From 1948 to 2016 there has been a continuous trend of the barrier widening as the shoreline / dunes prograded seaward, with accelerated movement from 1993 onward.

Figure 18 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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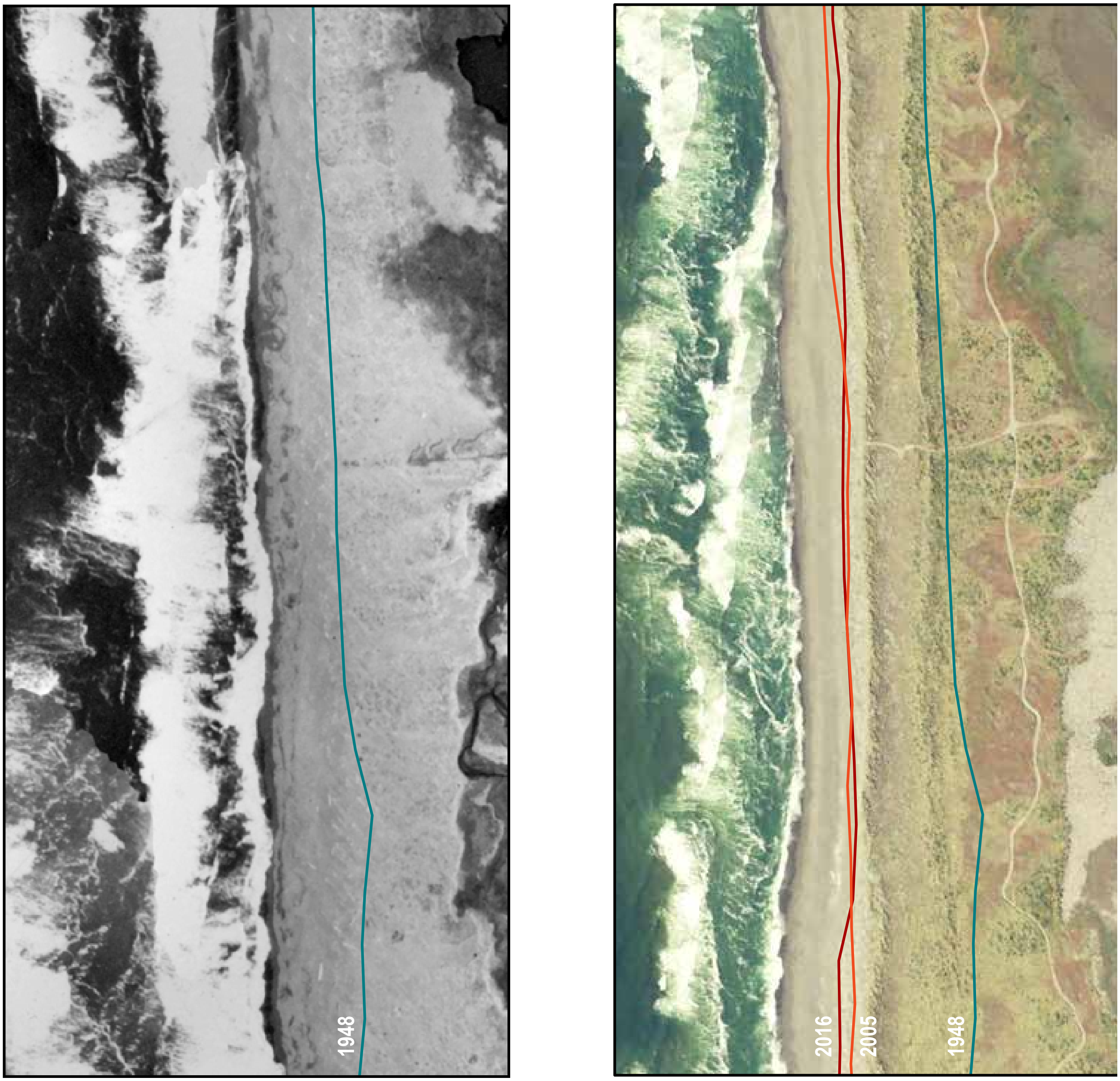
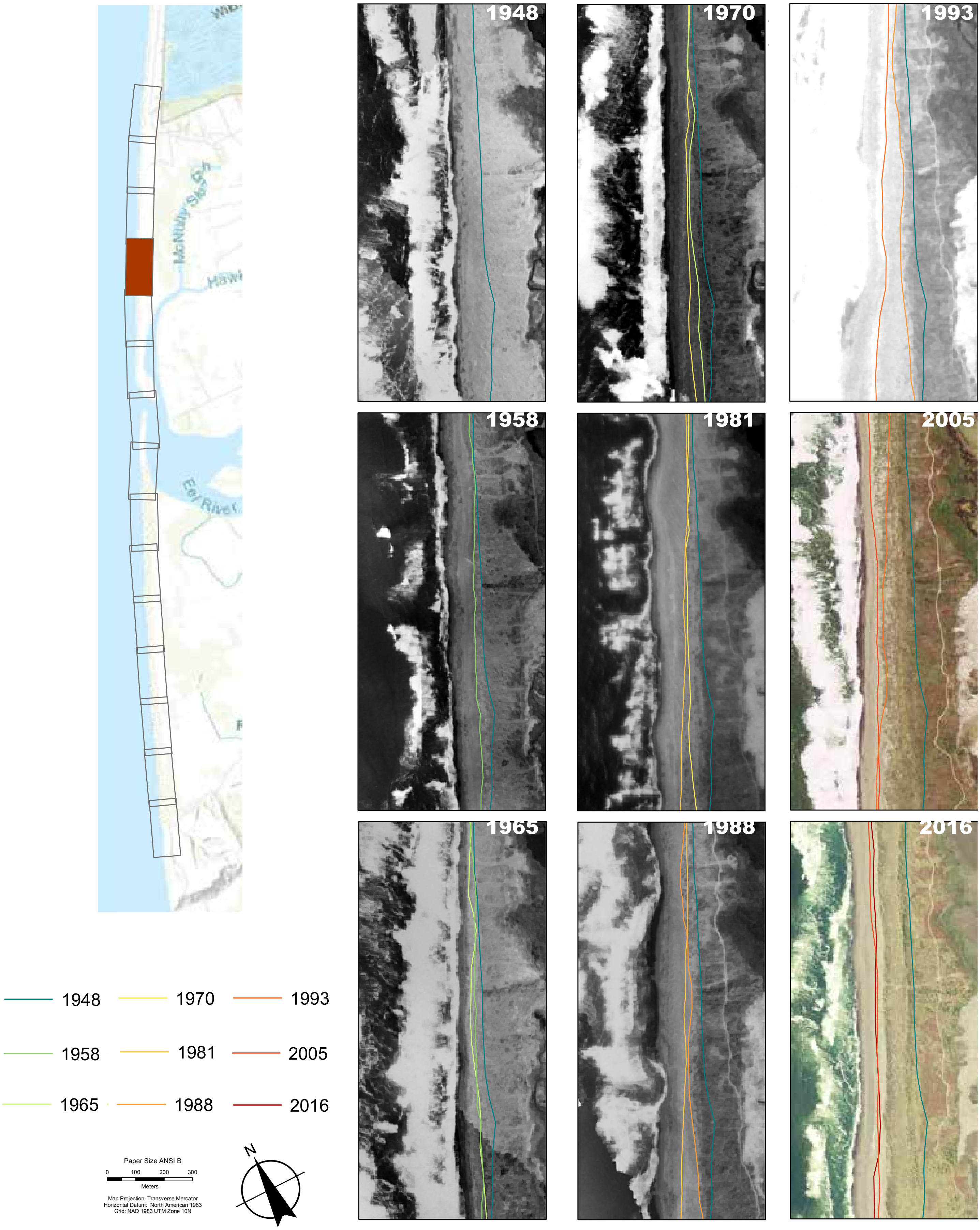


Figure 19: Enlargements of shoreline segments from 1948 (left), and 2016 (right).

From 1948 to 2016 there has been a continuous trend of the barrier widening as the shoreline / dunes prograded seaward. Shoreline movment increased from 1993 onward.

Figure 20 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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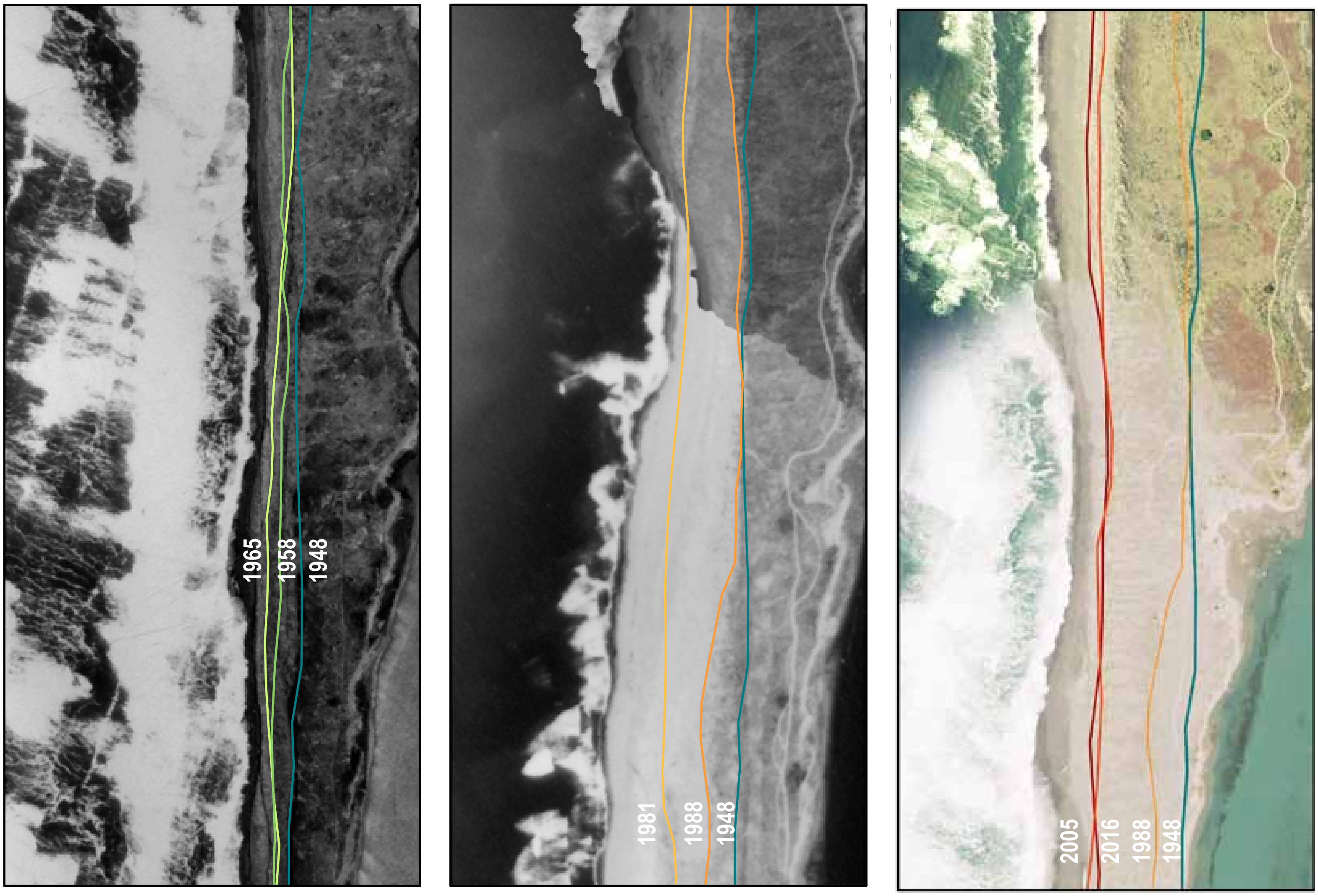
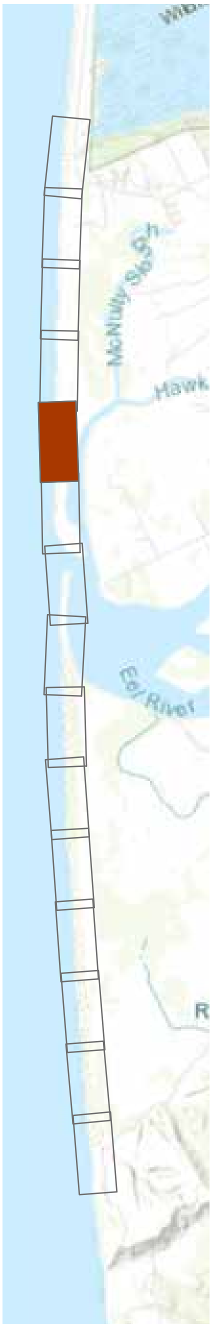
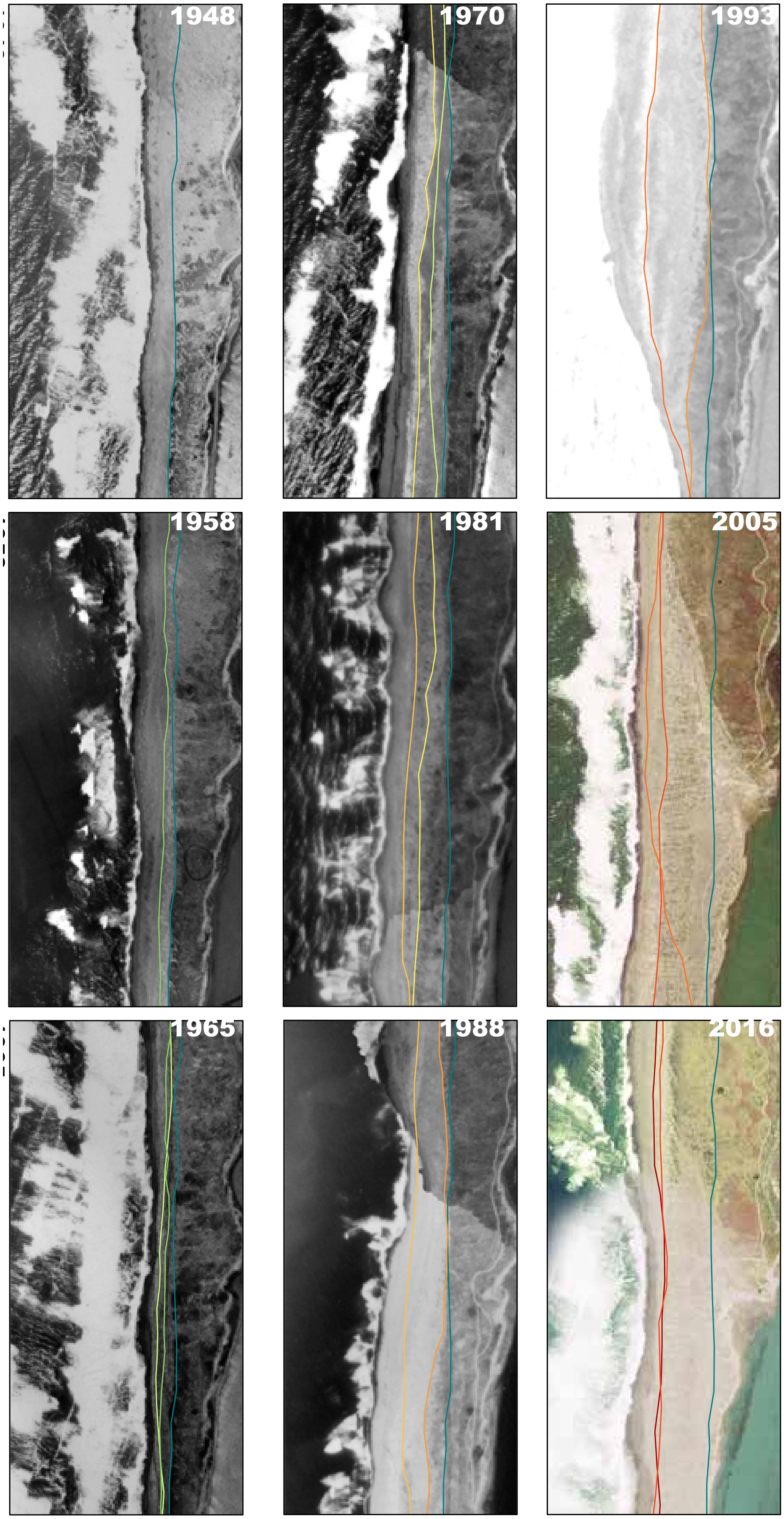


Figure 21: Enlargements of shoreline segments from 1965 (left), 1988 (center), and 2016 (right).

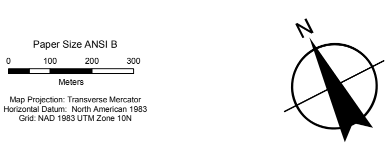
From 1948 to 1965 the shoreline was relatively stable with minor progradation. This seaward movement of the shoreline increased from 1970-1981. In 1988 there is a period of erosion as the 1988 alignment aligns with the 1948 alignment. From 1993 there has been extensive shoreline accretion as the shoreline moves seaward. These more extensive fluctuations could be attributed to this portion of the site being part of the Eel River sand spit at the river mouth.

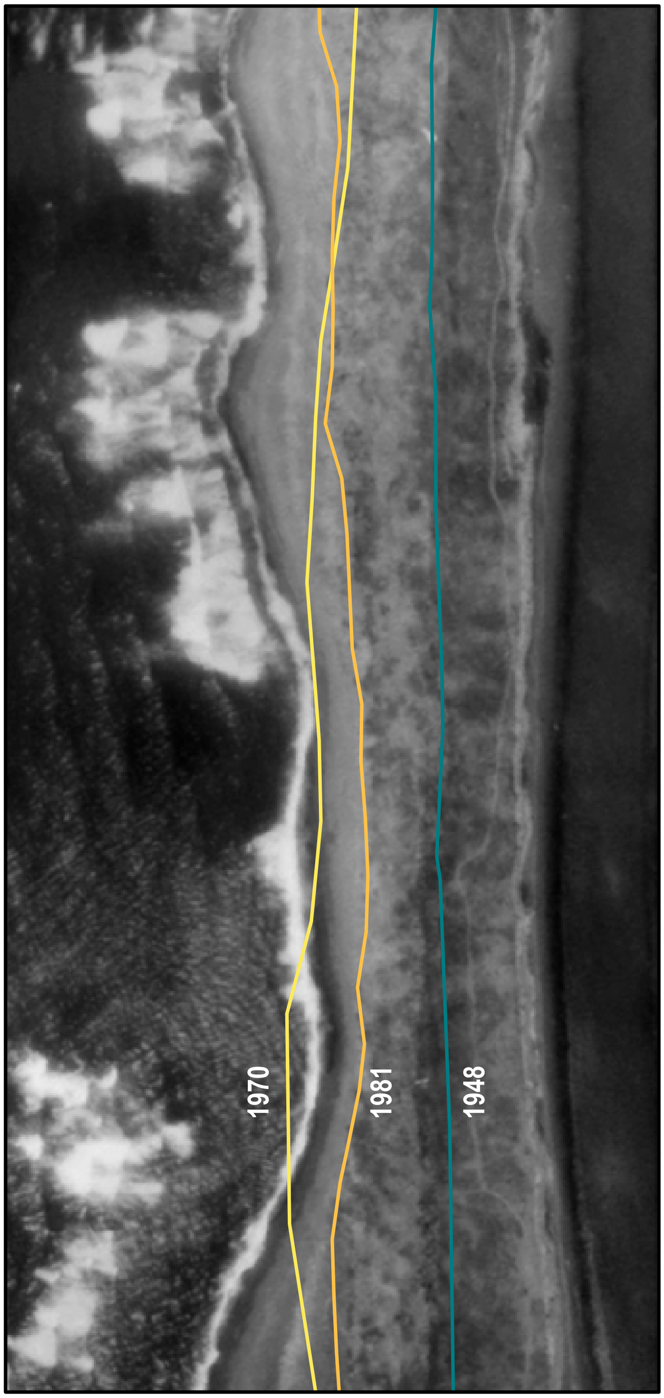
Figure 22(Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.





1948	1970	1993
1958	1981	2005
1965	1988	2016





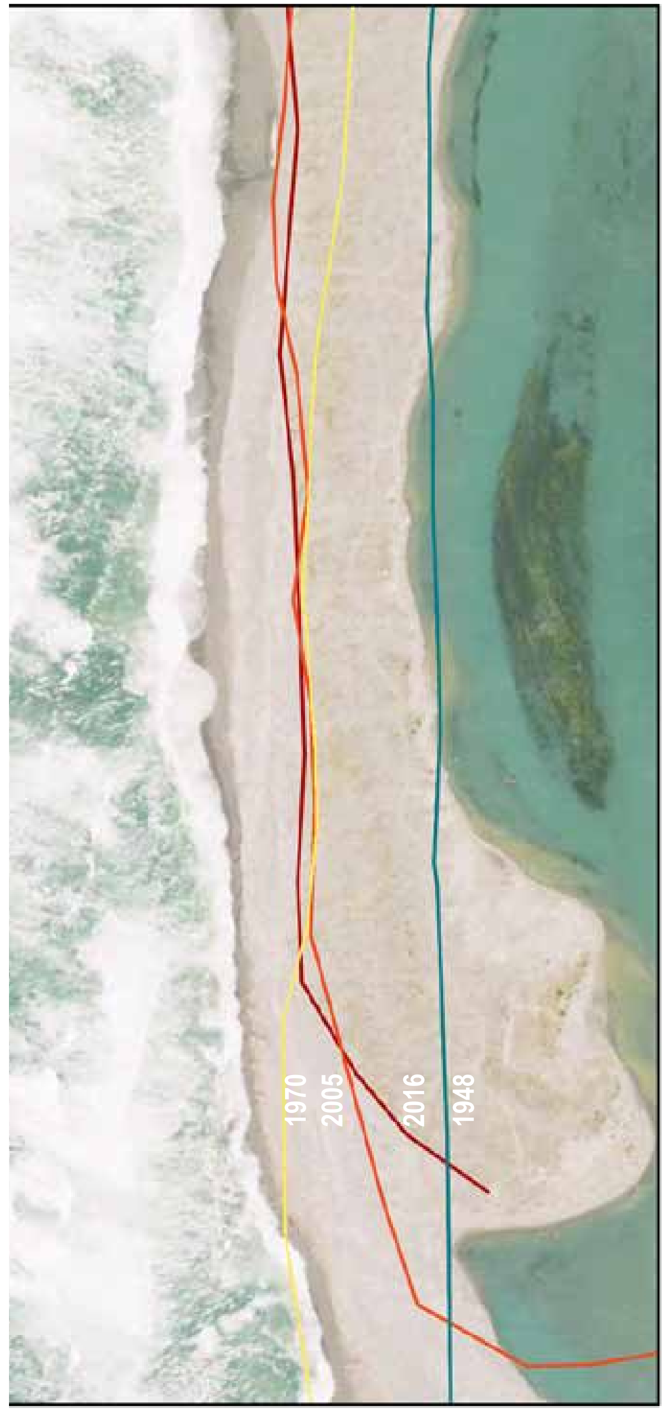
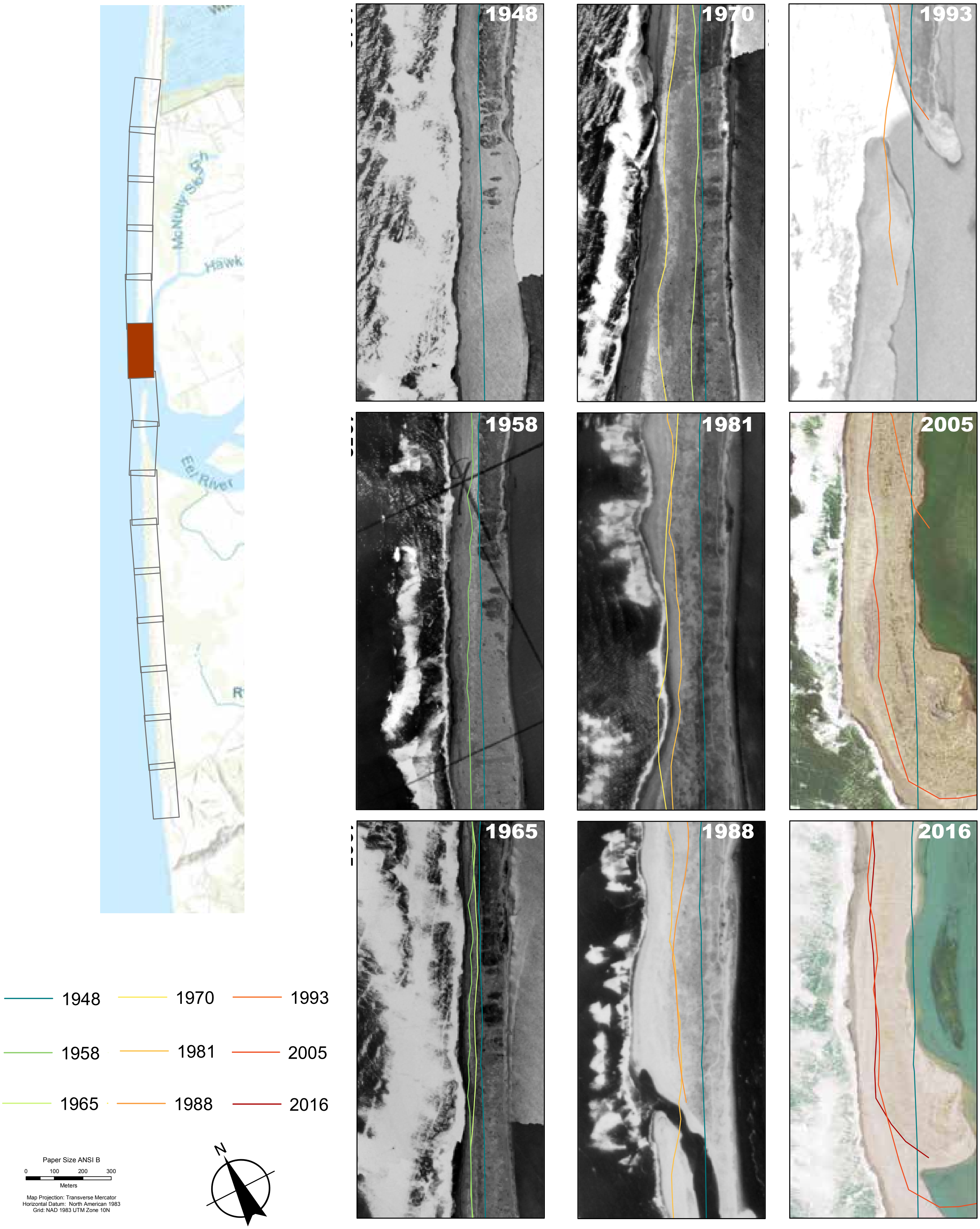


Figure 23: Enlargements of shoreline segments from 1981 (left) and 2016 (right).

From 1948 to 1970, the dune prograded seaward, while eroding from the east. These fluctuations could be attributed to this portion of the site being part of the Eel River sand spit at the river mouth.

Figure 24(Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.



Hawk
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Paper Size ANSI B
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Meters
Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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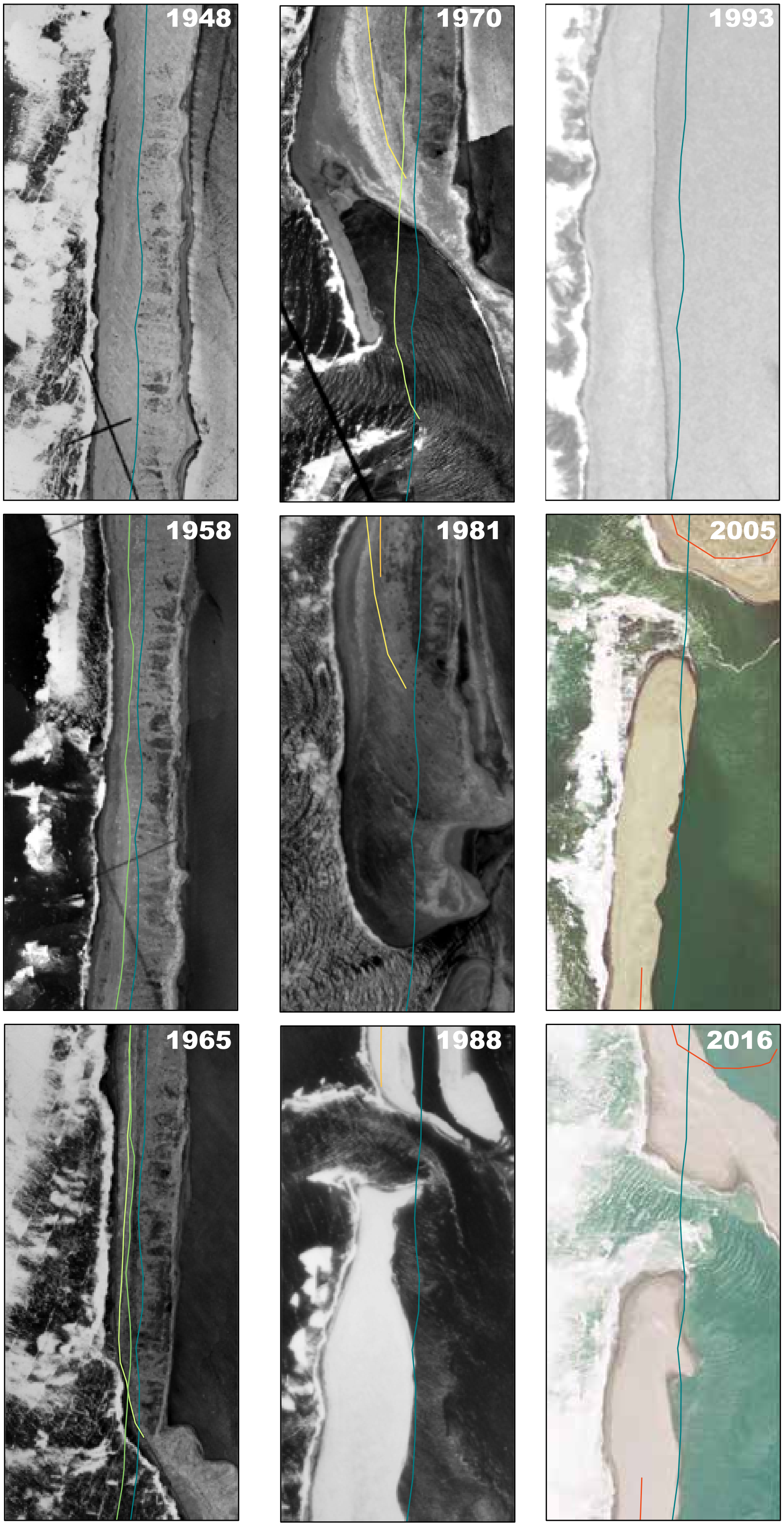
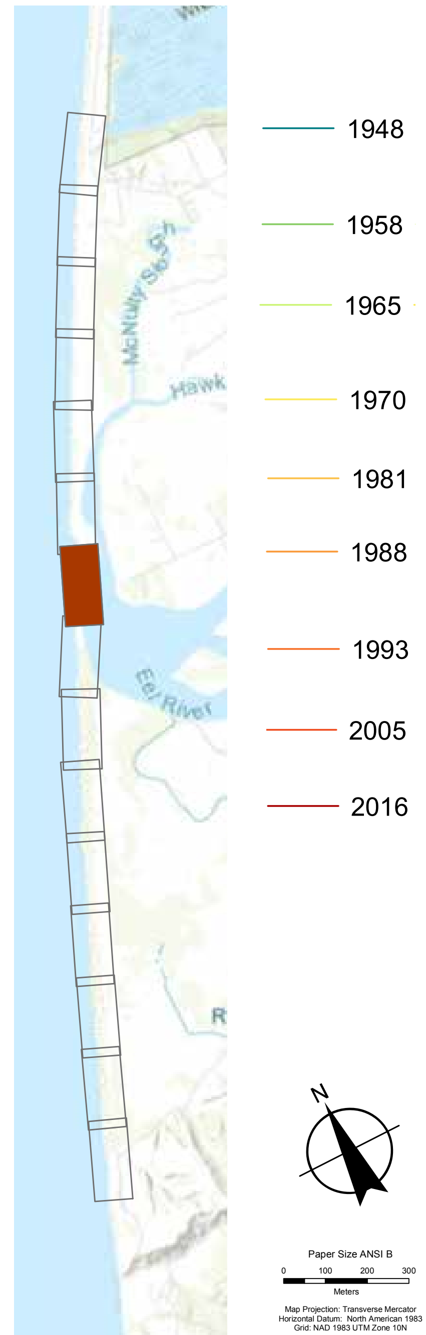
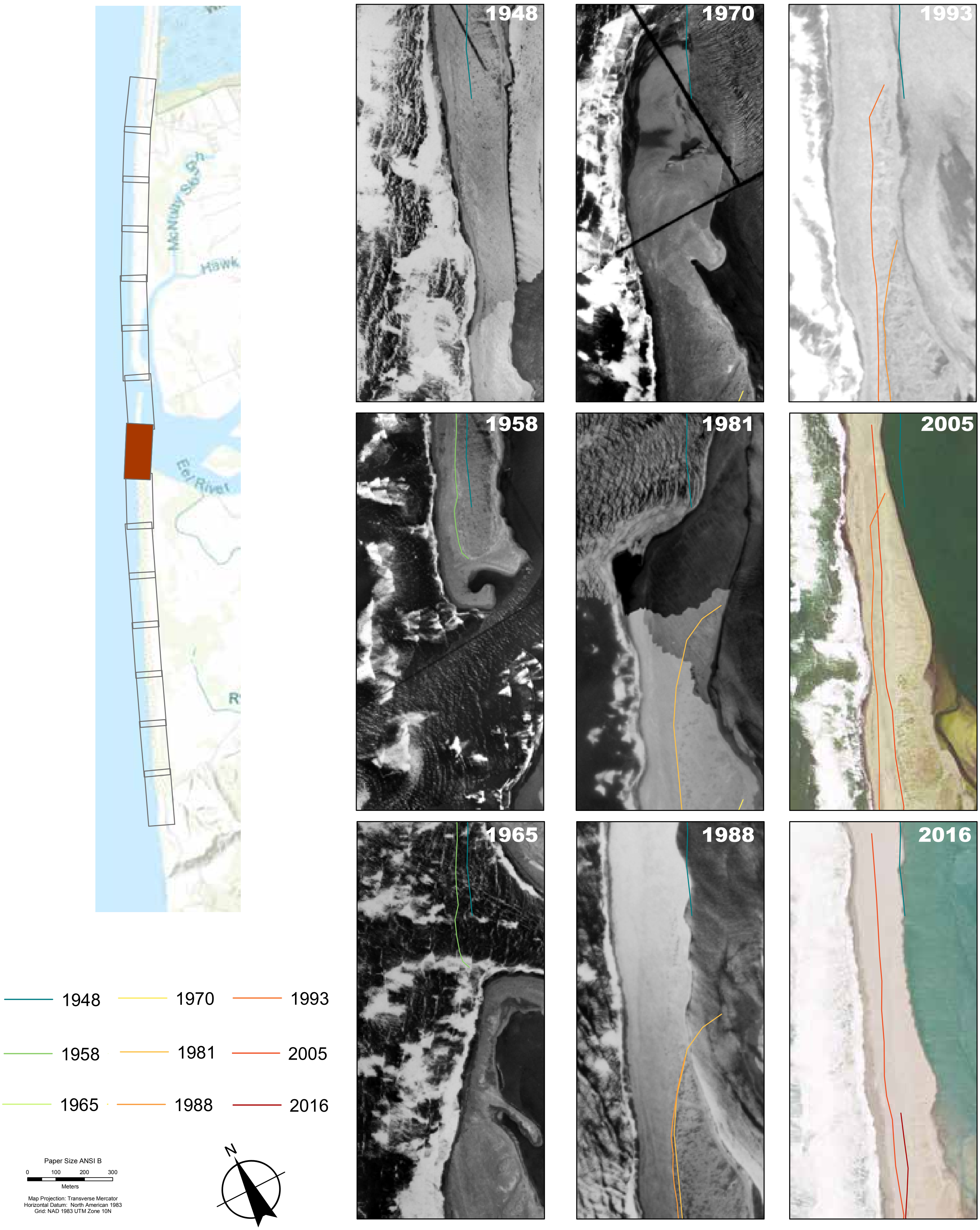




Figures 25 (left) and 26 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.

These shoreline segments were excluded from analysis due to the highly dynamic influences of the Eel River limiting foredune development.


McNulty Slough
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Eel River
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Paper Size ANSI B
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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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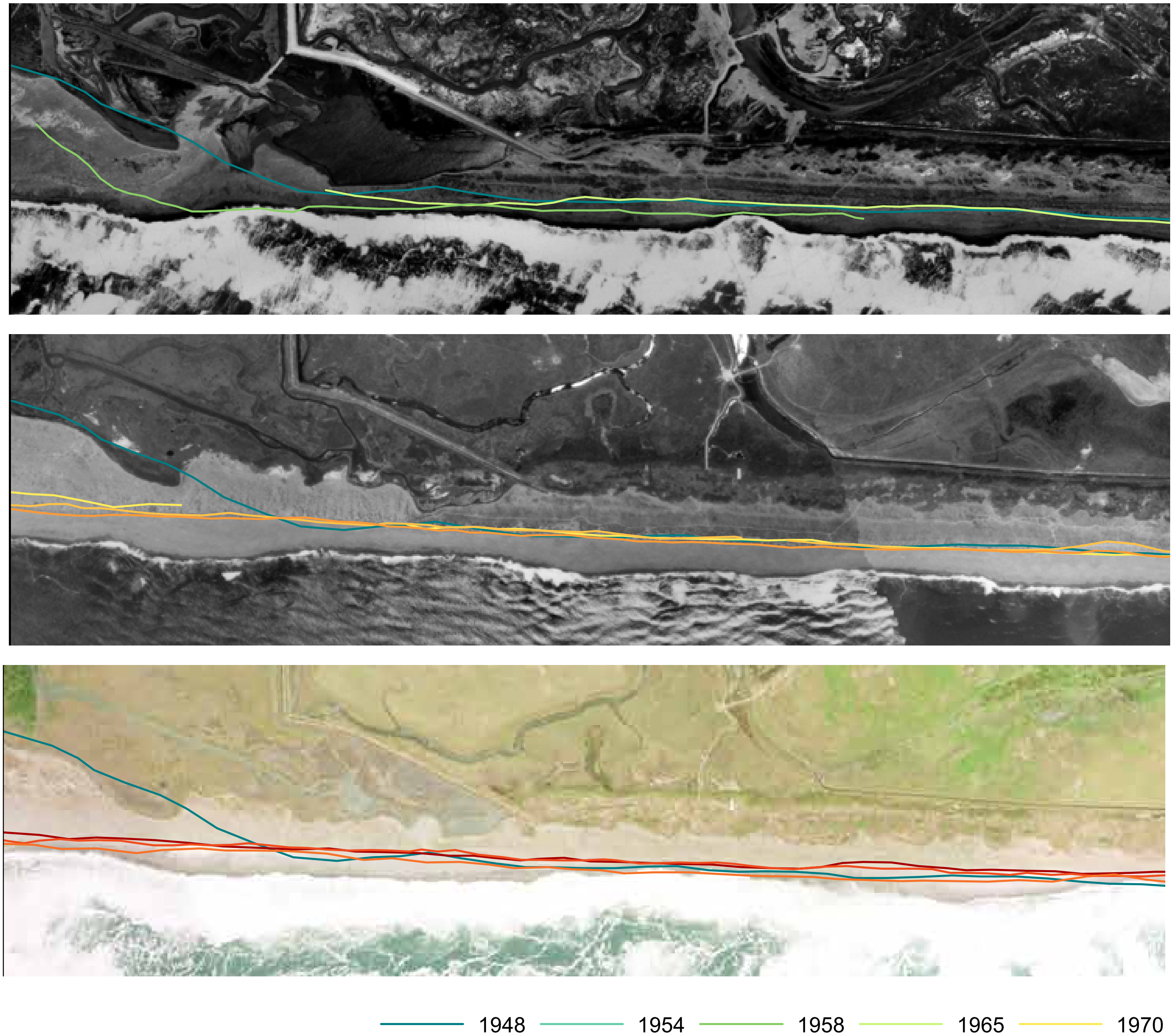


4.2.2 South Segment Shorelines

South of the Eel River mouth, this segment has mostly eroded landward along its length. The exception is in the northernmost reach, near the Eel River sand spit river mouth, where a relatively flat area with minor dune formation in 1948 developed a dune from 1958 onward.

The middle reach of this segment has shown a continuous trend of the dune eroding. In the southern half of the segment, dune blowouts and washovers are visible in the aerial photographs, with a large area in 2016 that prevented foredune mapping thorugh there.

The following pages provide detailed views of shoreline segments by each year, including aerial photographs and enlargements selected to illustrate specific indicated shoreline changes.

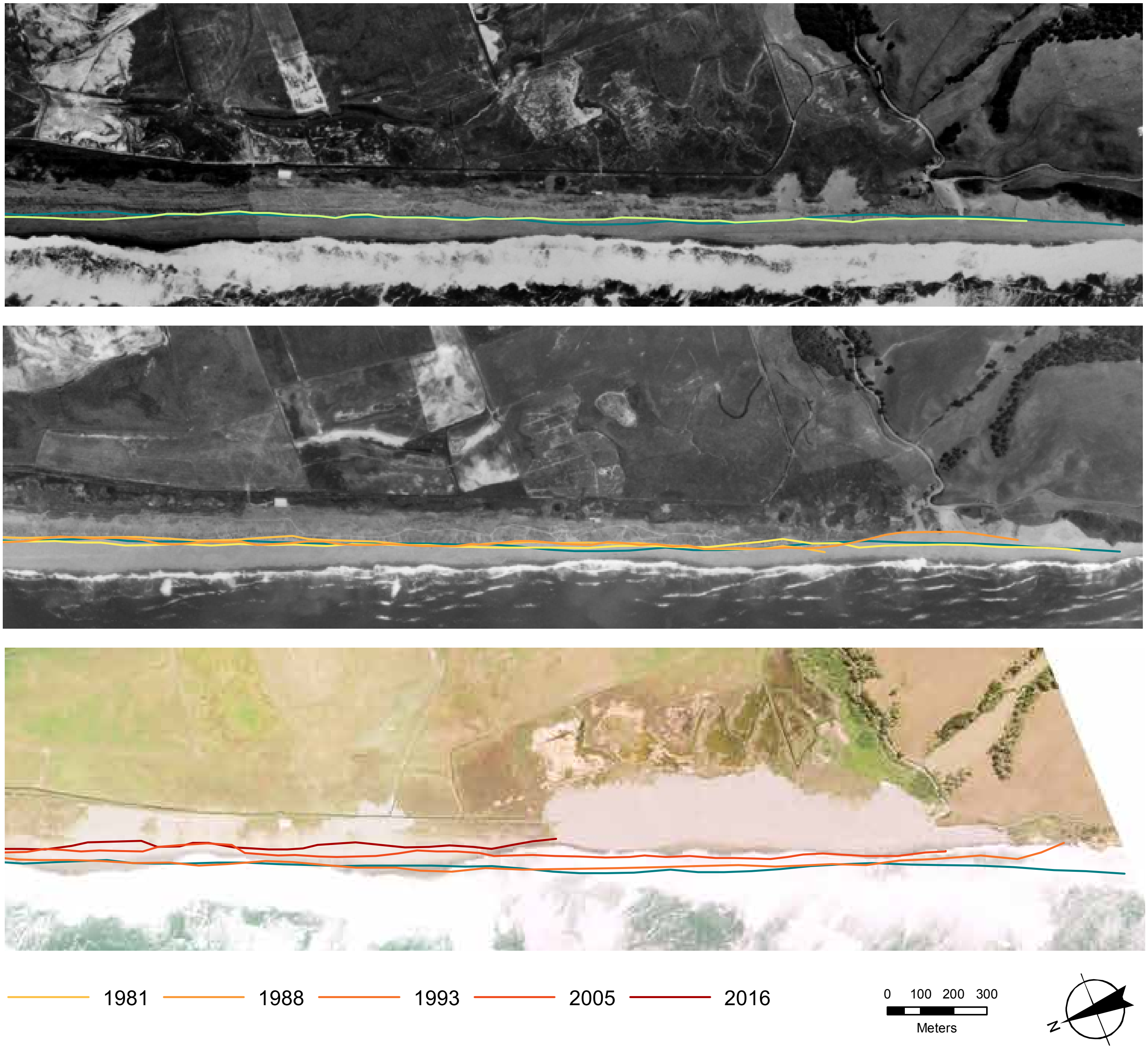


Figure 27: Compilation of the south segment shorelines. Top: background photograph, 1965, with shorelines from 1948, 1958, 1965. Middle: background photograph, 1988, with shorelines from 1948, 1970, 1981, 1988. Bottom: background photograph, 2016, with shorelines from 1948, 1993, 2005, 2012.

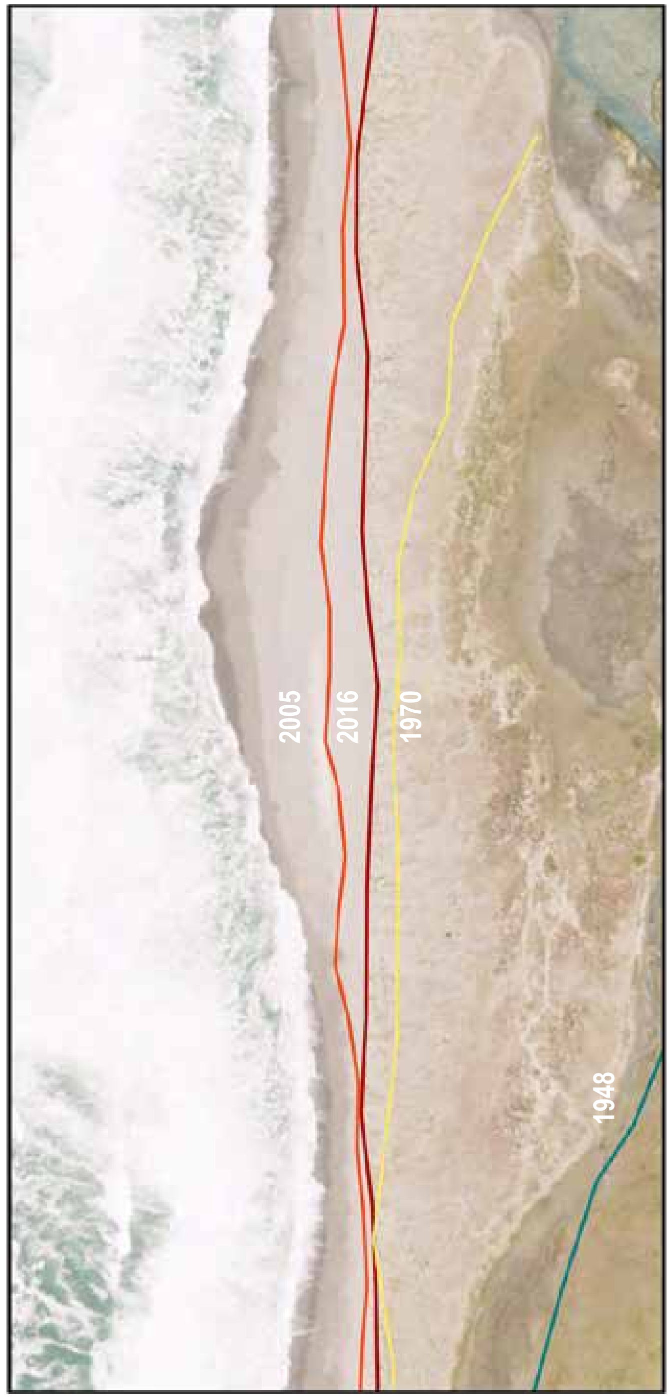
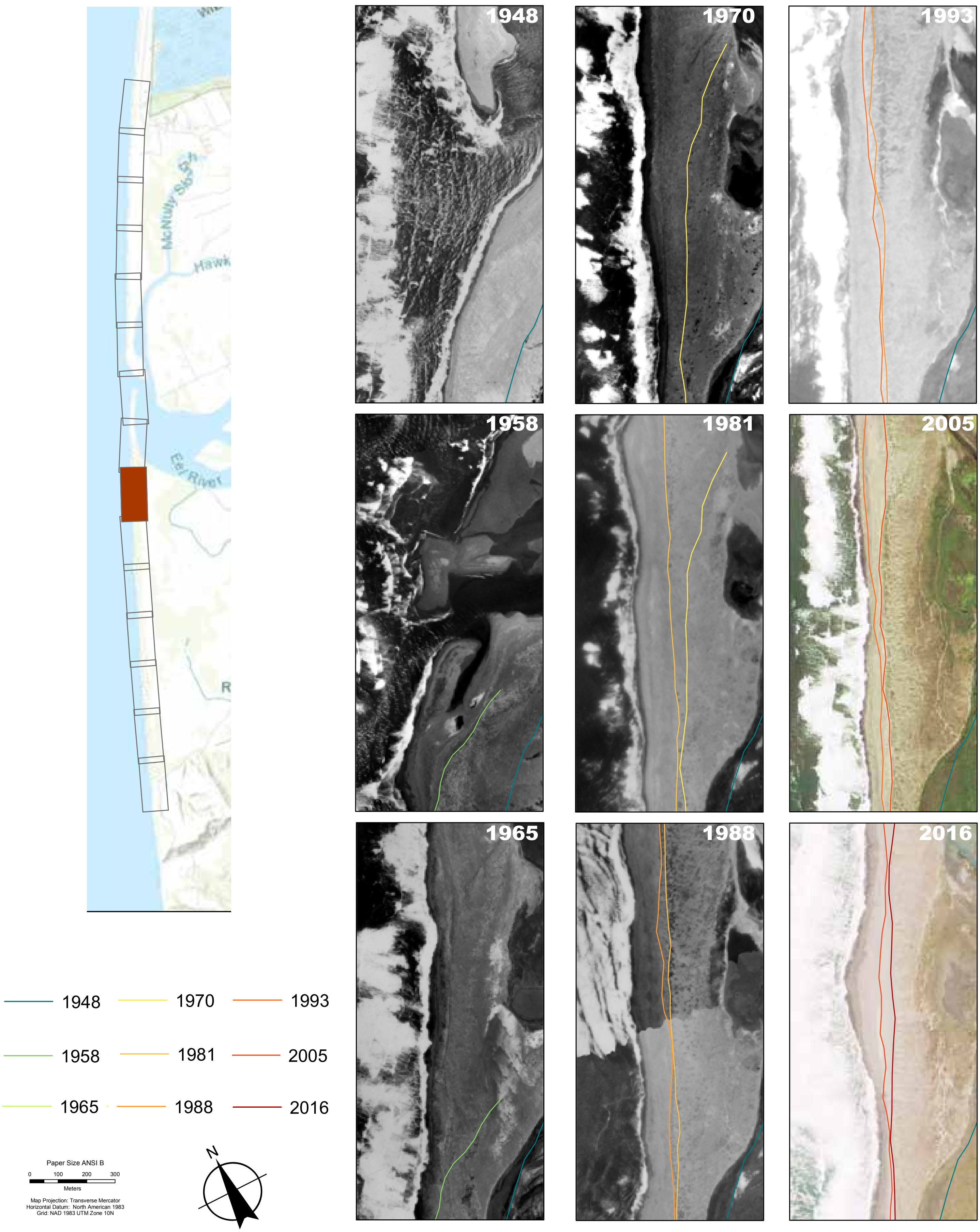


Figure 28: Enlargements of shoreline segments from 1948 (left) and 2016 (right).

In 1948 the sand spit and shoreline of the south portion of the site was relatively flat with minor dune formation at the western extent (blue line). From 1958 a dune started to form seaward of the 1948 line and stabilize as can be seen more clearly in 1970, 1981, 1988, 1993, 2005 and 2016, with clear vegetation cover in 2005.

Figure 29 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.


McNulty Slough
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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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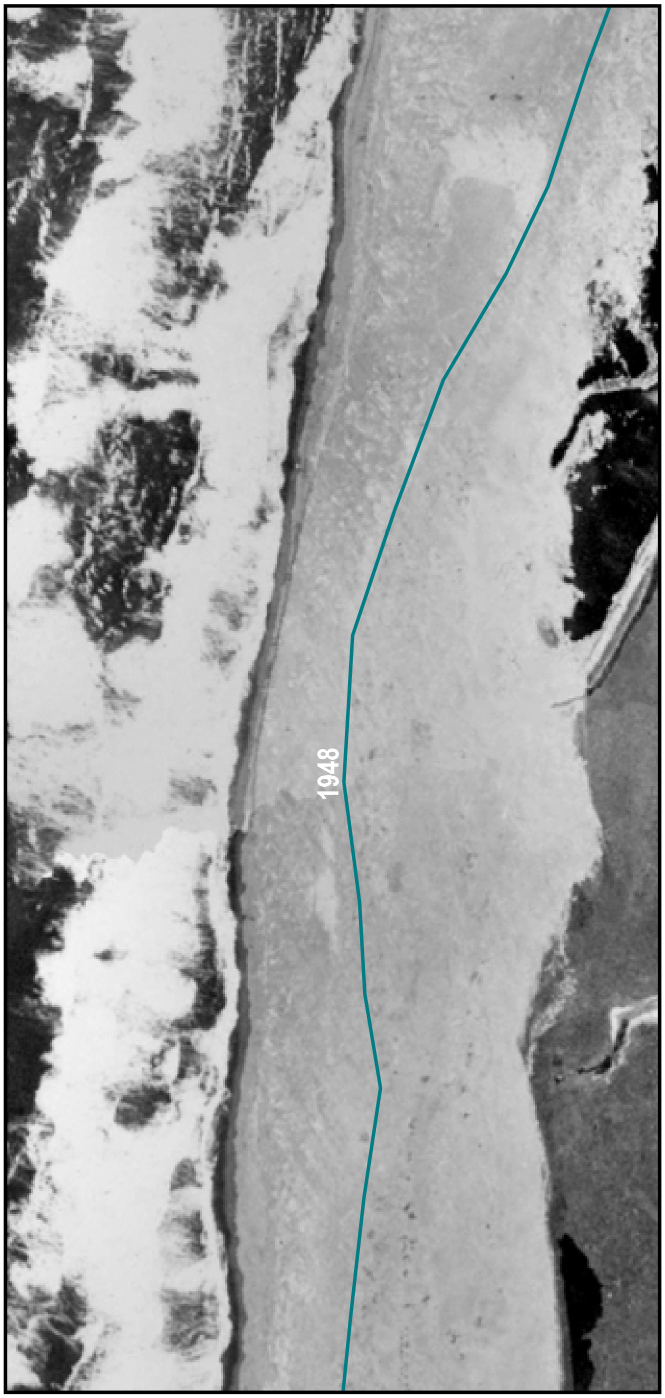


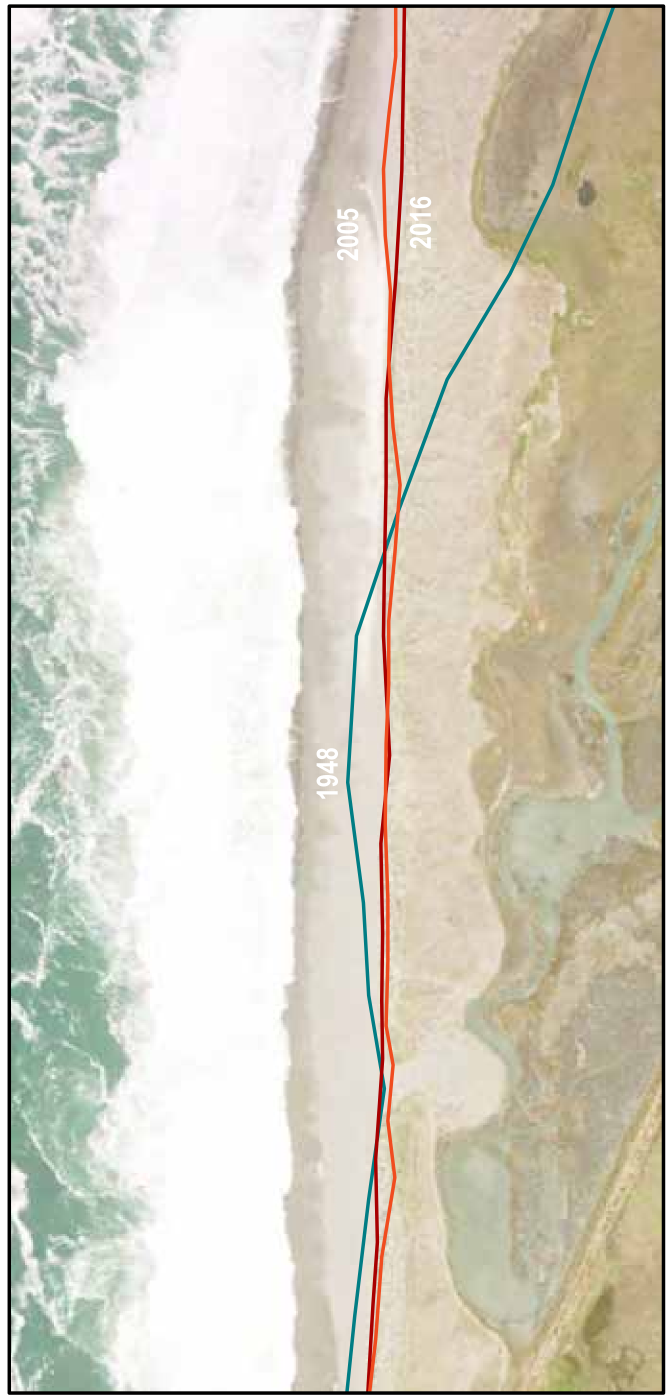
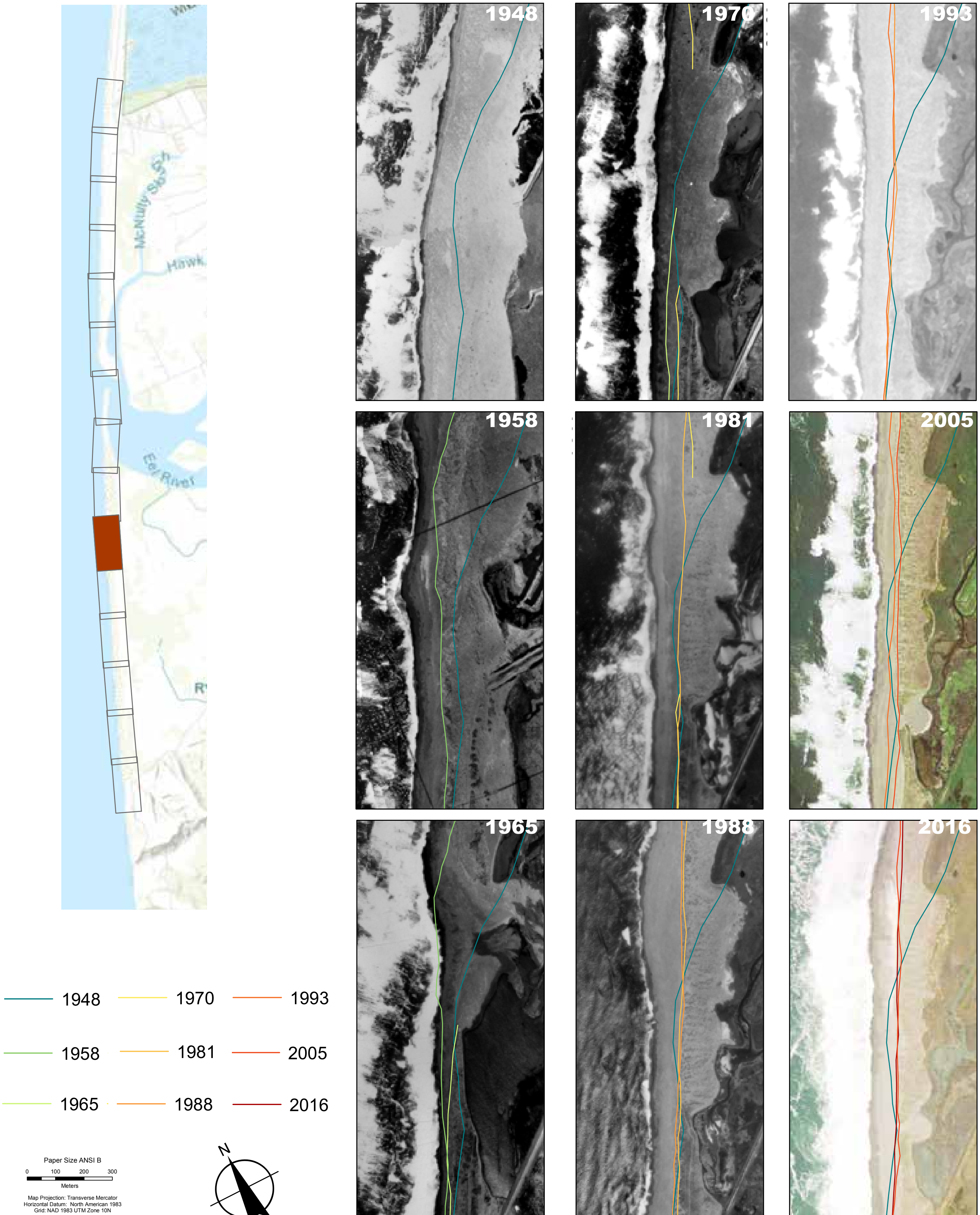


Figure 30: Enlargements of shoreline segments from 1948 (left) and 2016 (right).

From 1948 to 2016 there has been a continuous trend of the dune eroding and accreting slightly in the south of Figure 30 with the exception of the northern portion of the site which has remained stable. In the southern portion, dune blowouts and washovers had begun to form.

Figure 31 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.



Eel River
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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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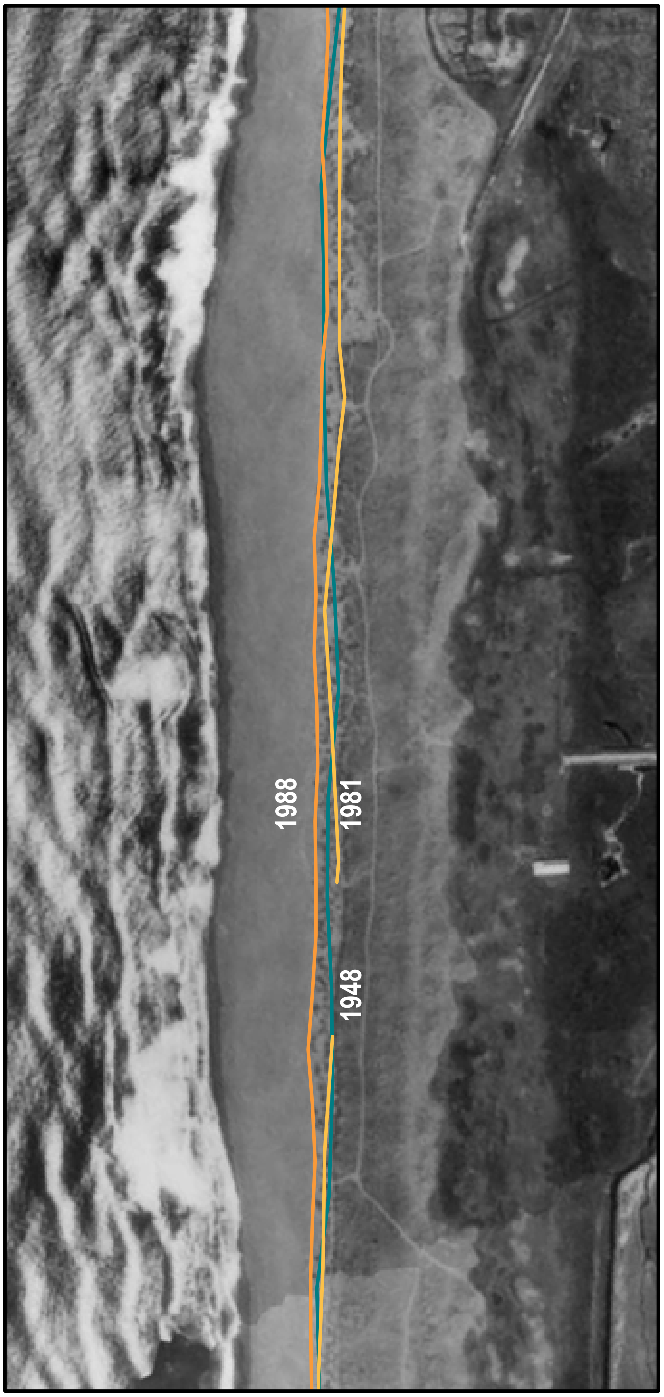


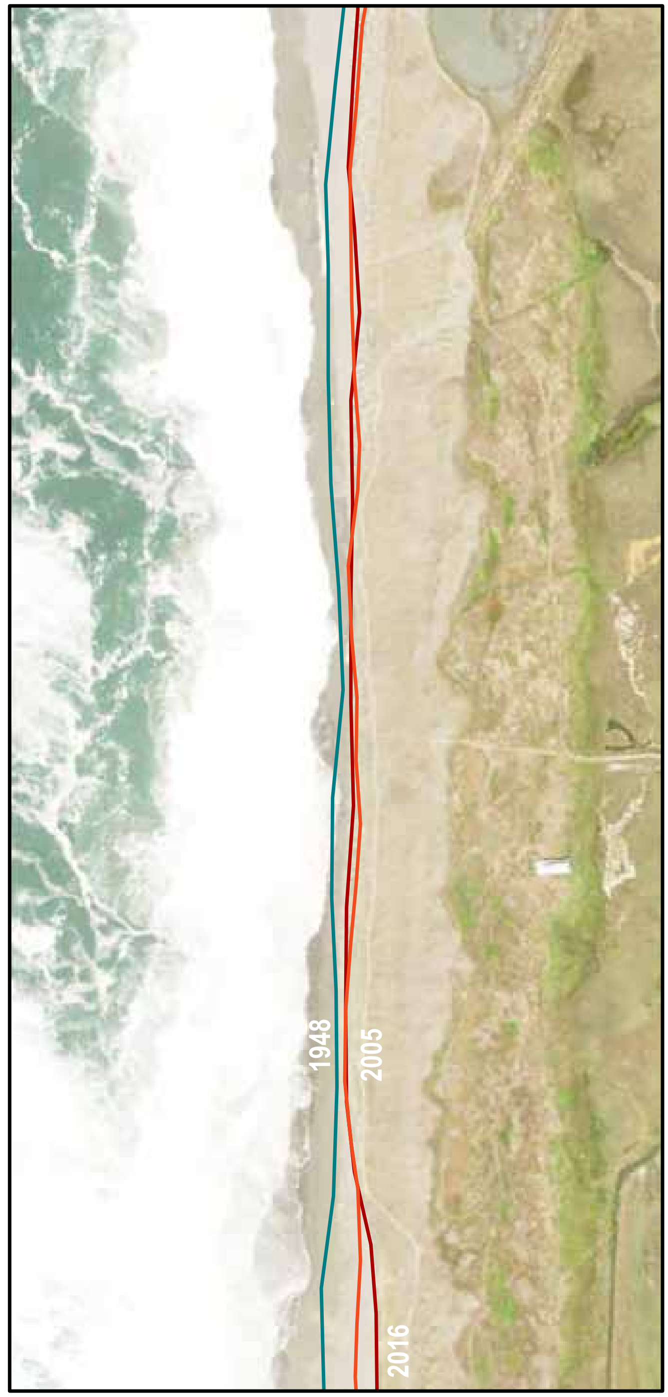
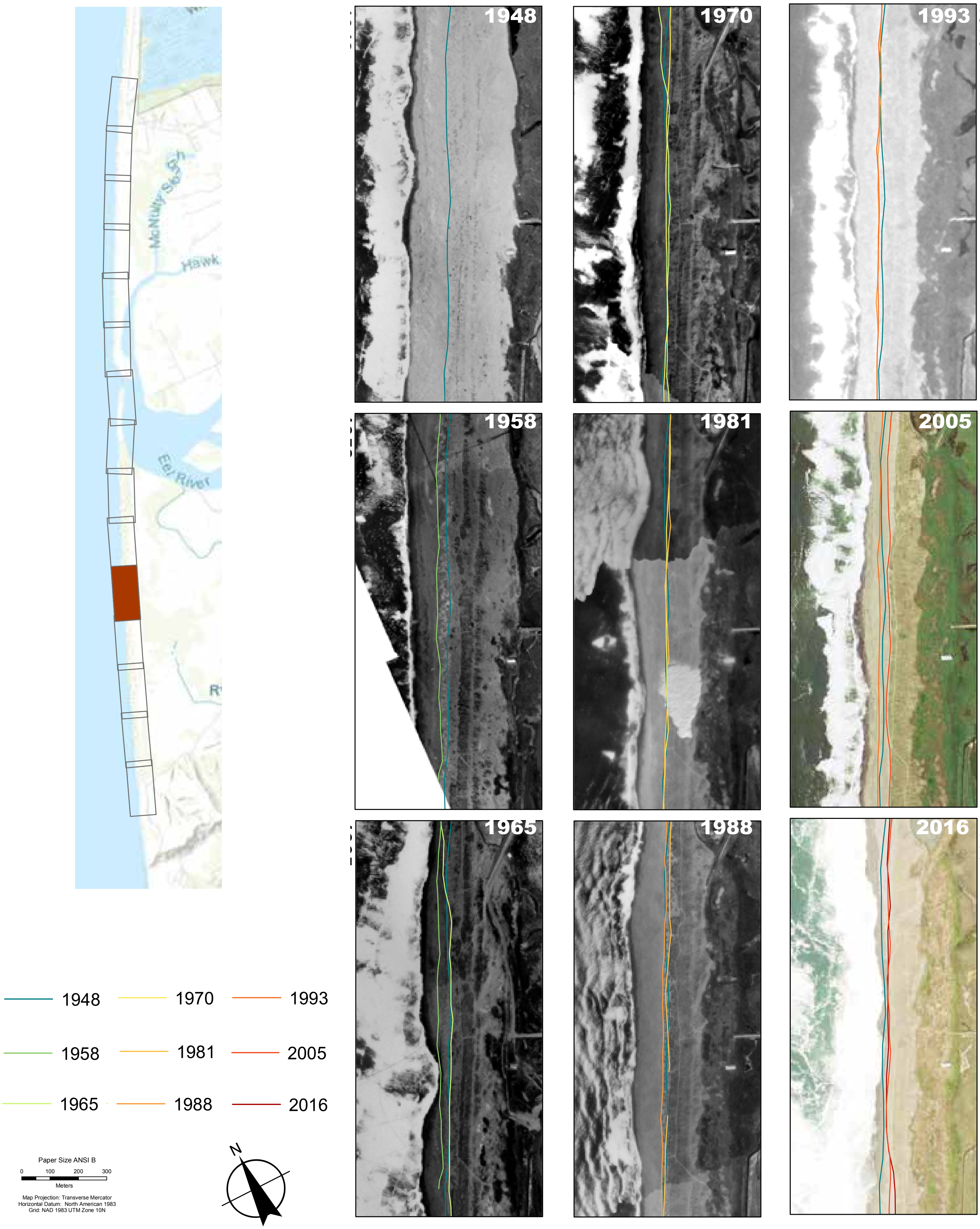


Figure 32: Enlargements of shoreline segments from 1988 (left) and 2016 (right).

From 1948 to 1988 this site has been relatively stable. From 1993-2016 there has been a pattern of erosion as the shoreline moved slightly landward. Again in this site washovers can be seen as clear coastal features in 2016.

Figure 33 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.


McNulty Slough
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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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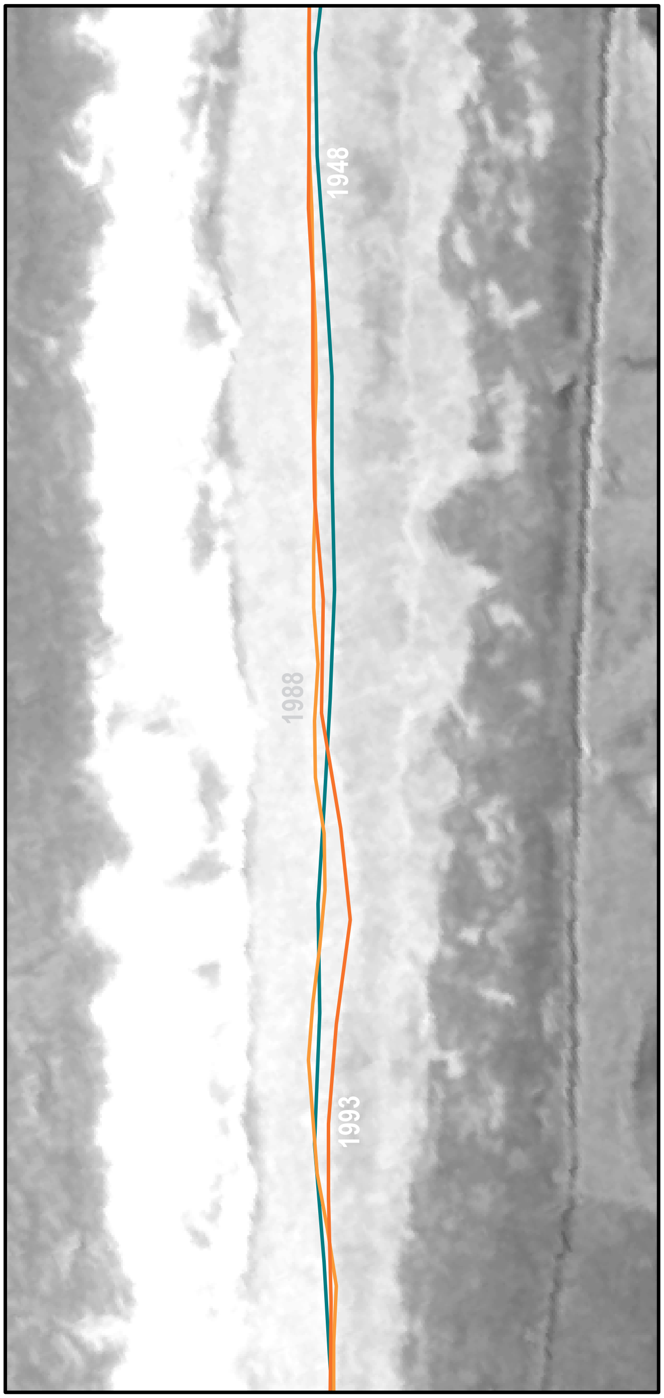


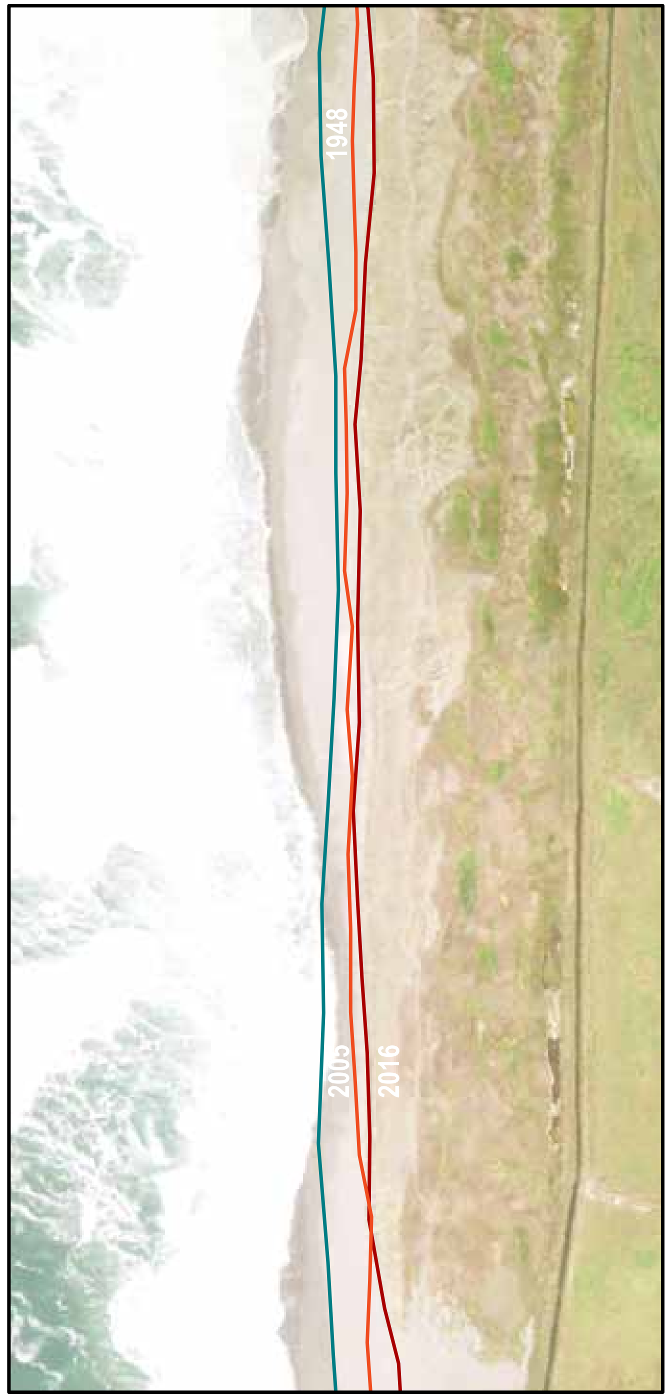
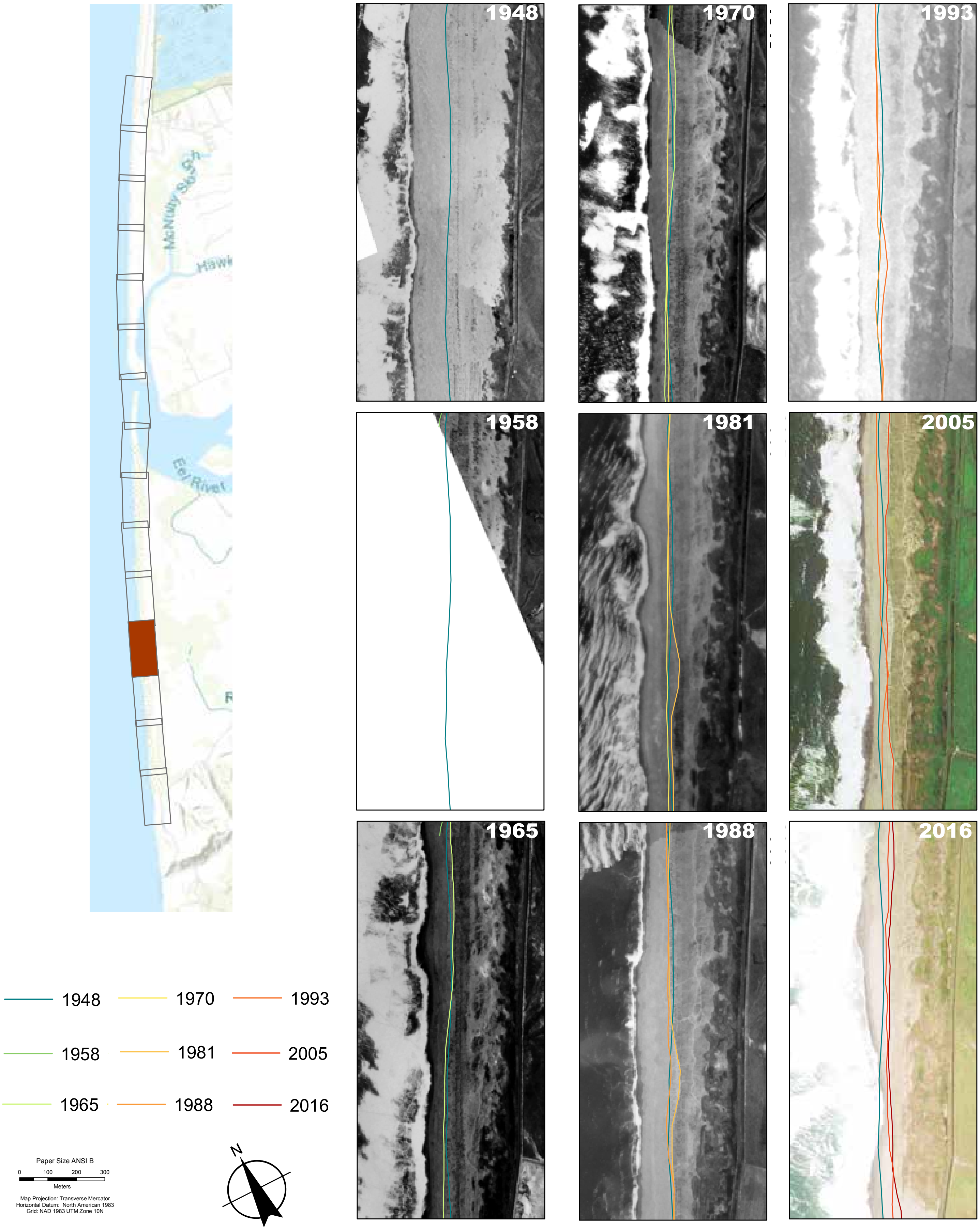


Figure 34: Enlargements of shoreline segments from 1993 (left) and 2016 (right).

From 1948 to 1988 this site has been relatively stable. From 1993-2016 there has been a pattern of erosion as the shoreline moved slightly landward. Again in this site washovers can be seen as clear coastal features in 2016.

Figure 35 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.



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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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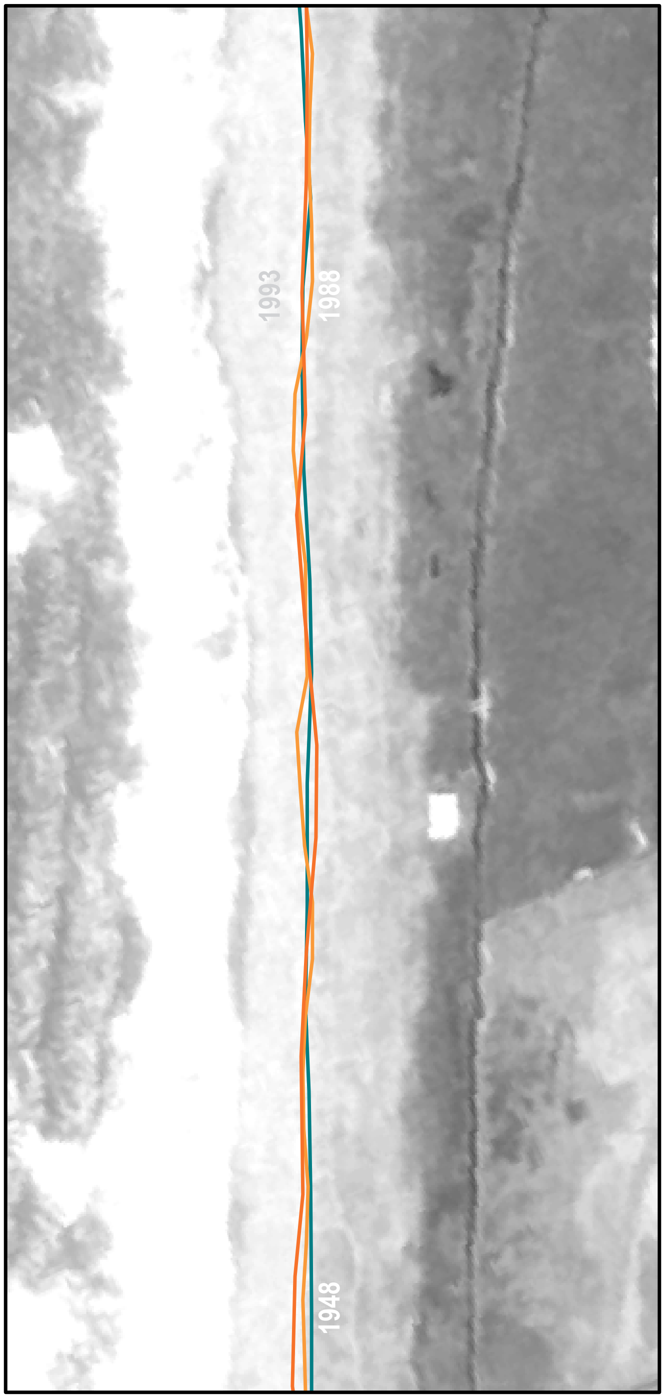


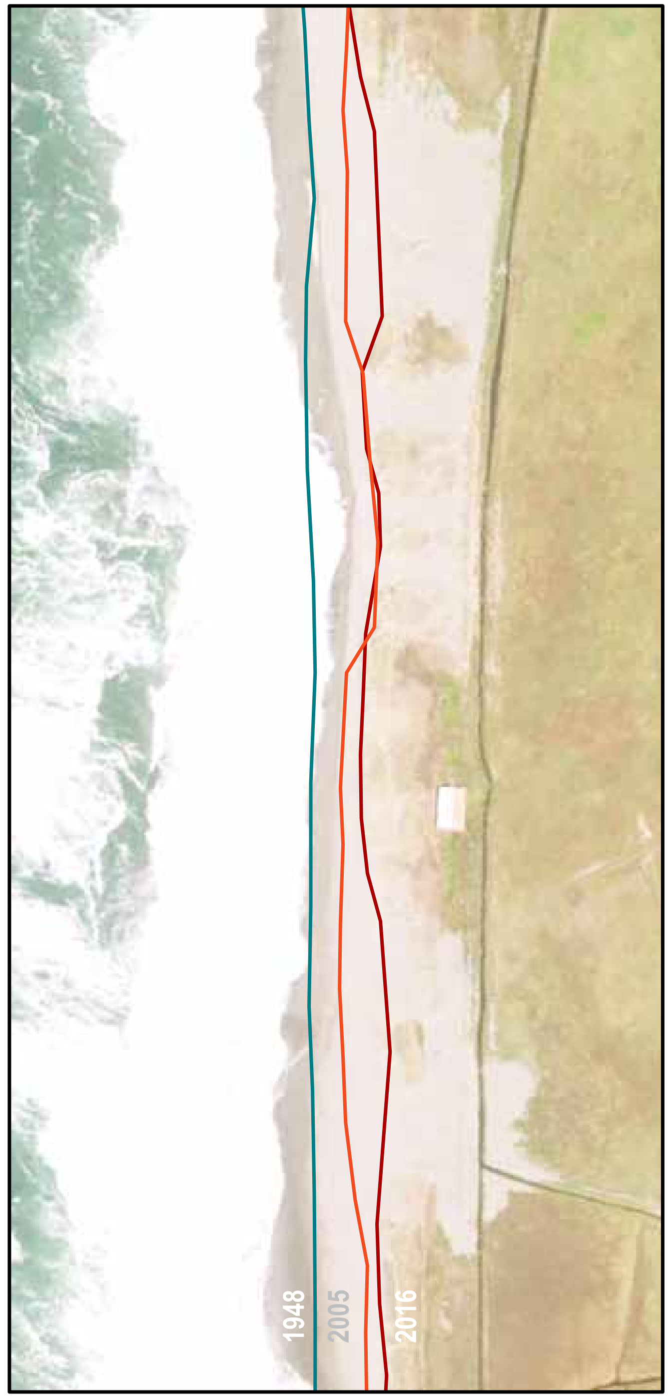
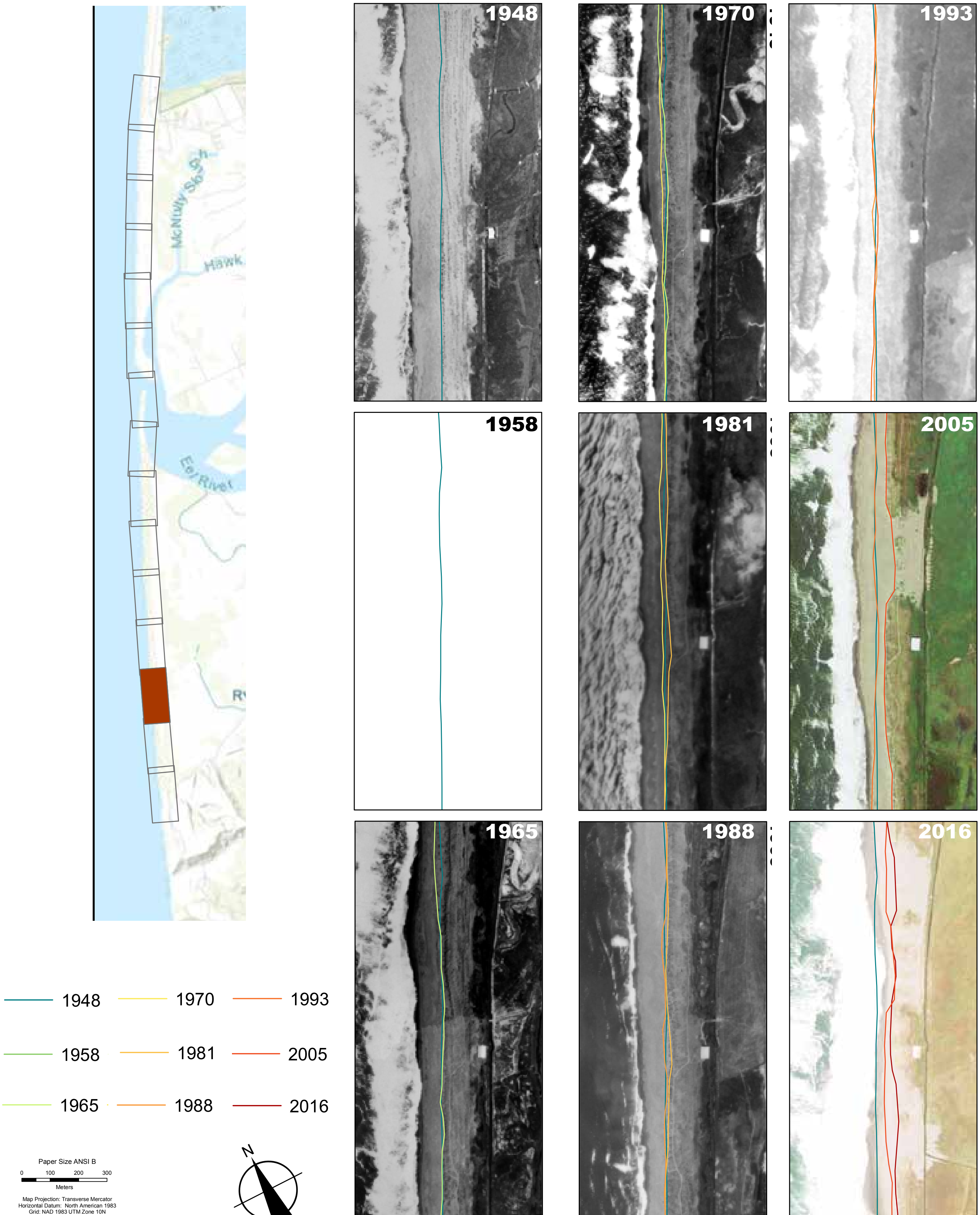


Figure 36: Enlargements of shoreline segments from 1993 (left) and 2016 (right).

From 1948 to 1993 this site has been relatively stable. From 1993-2016 there has been a pattern of erosion as the shoreline moved slightly landward. Again in this site washovers can be seen as clear coastal features in 2005 and 2016.

Figure 37 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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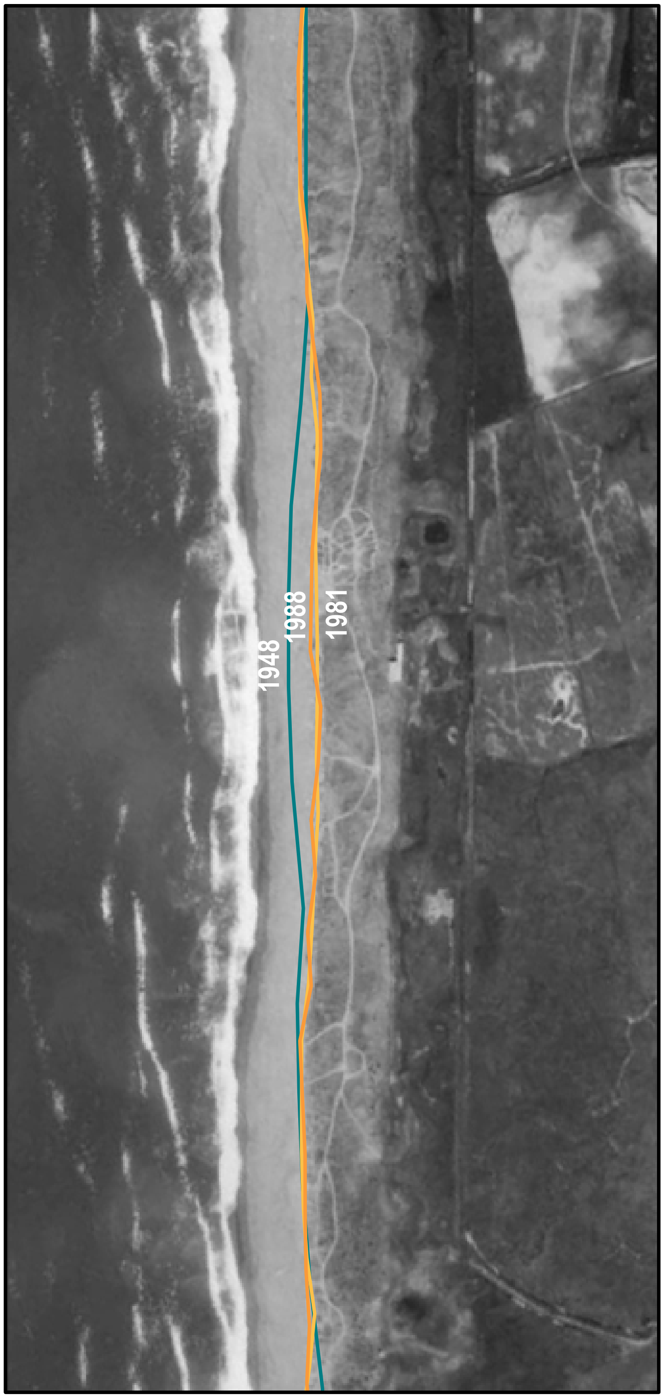


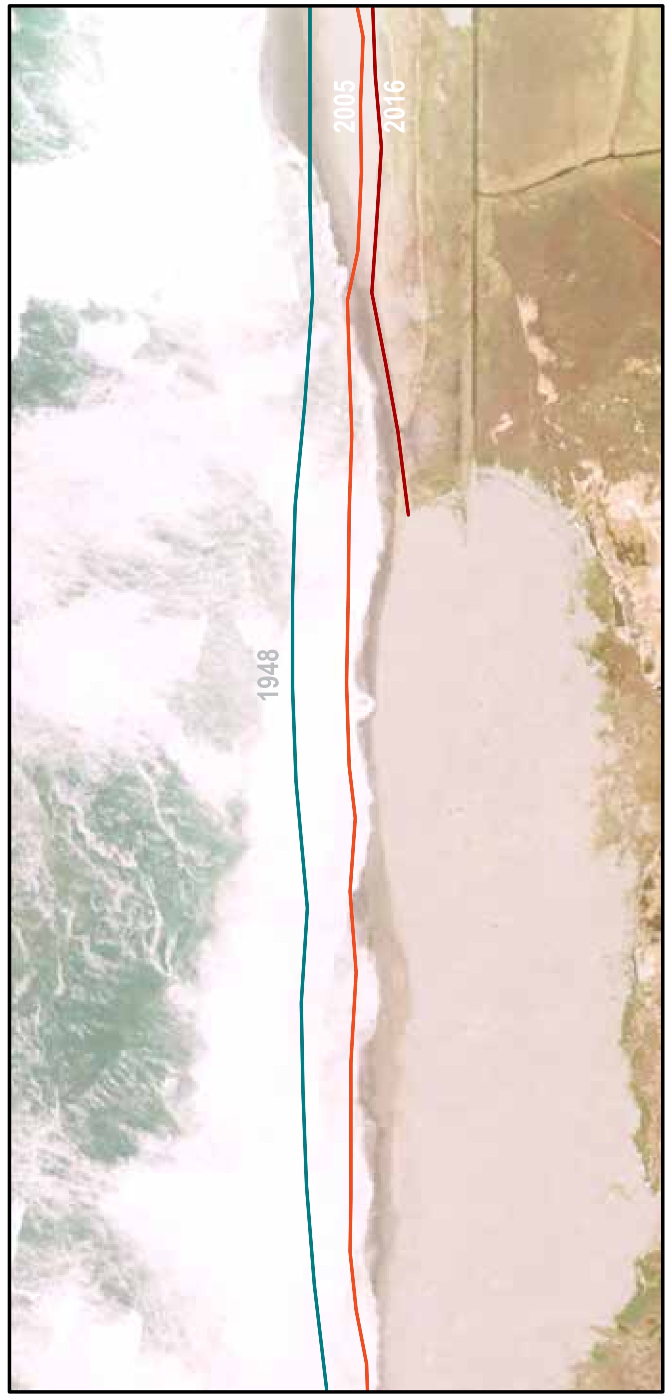
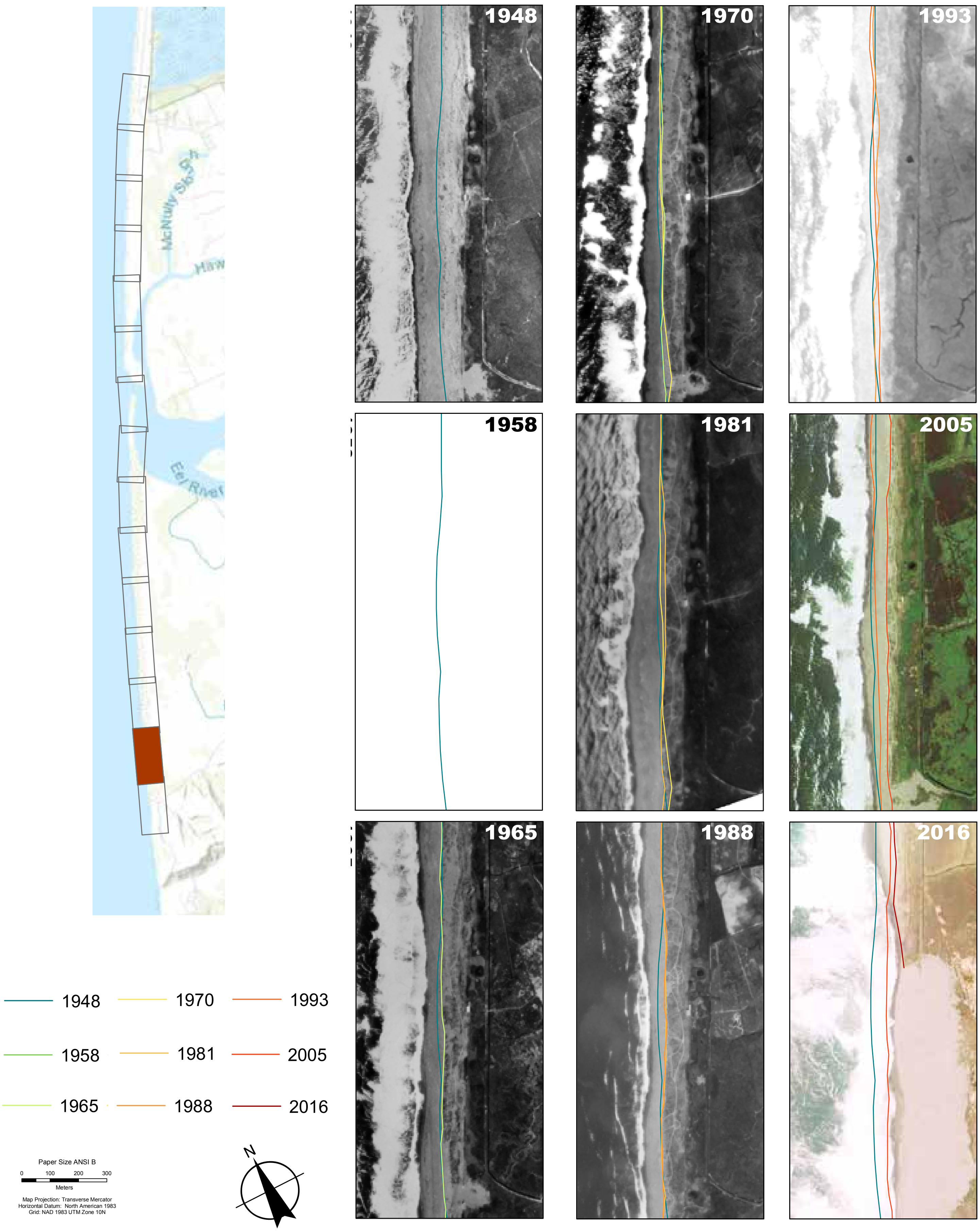


Figure 38: Enlargements of shoreline segments from 1998 (left) and 2016 (right).

From 1948 to 1988 this site has been relatively stable with the exception of minor erosion in the center of the site. From 1993-2016 there has been a pattern of erosion as the shoreline moved landward. In 2016 very extensive washovers can be seen dominating the majority of the site.

Figure 39 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.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Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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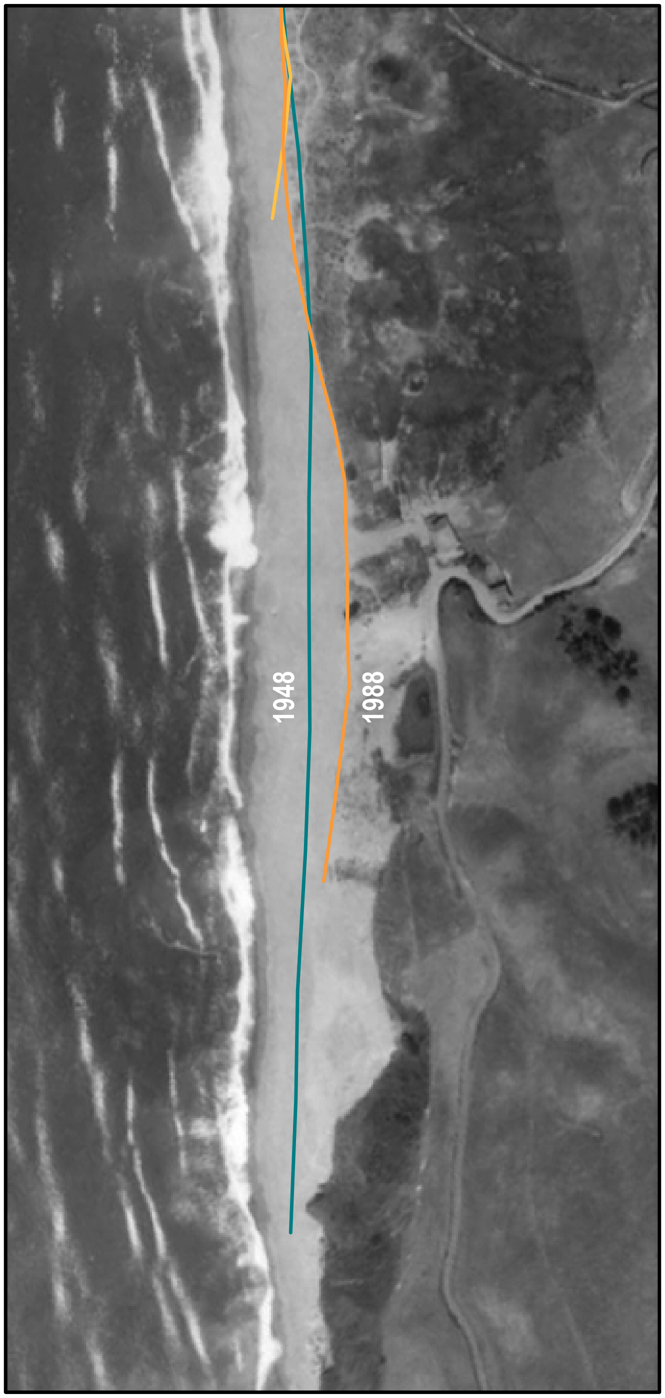


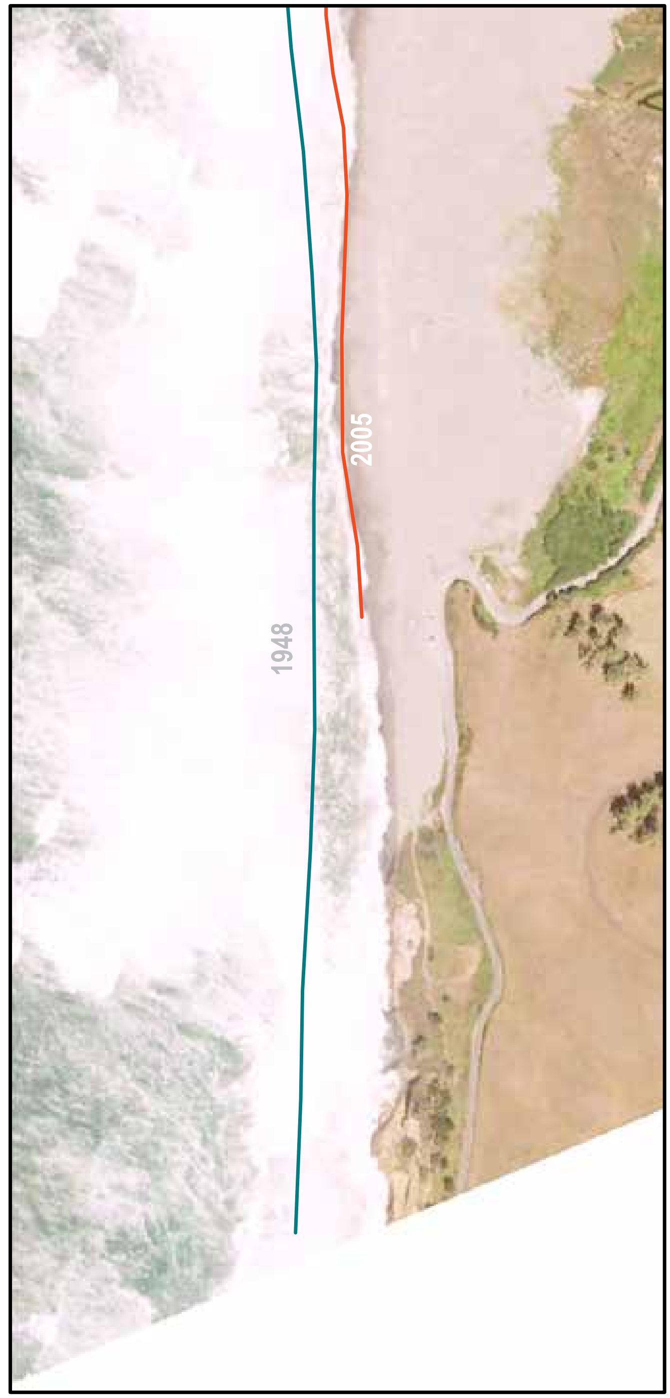
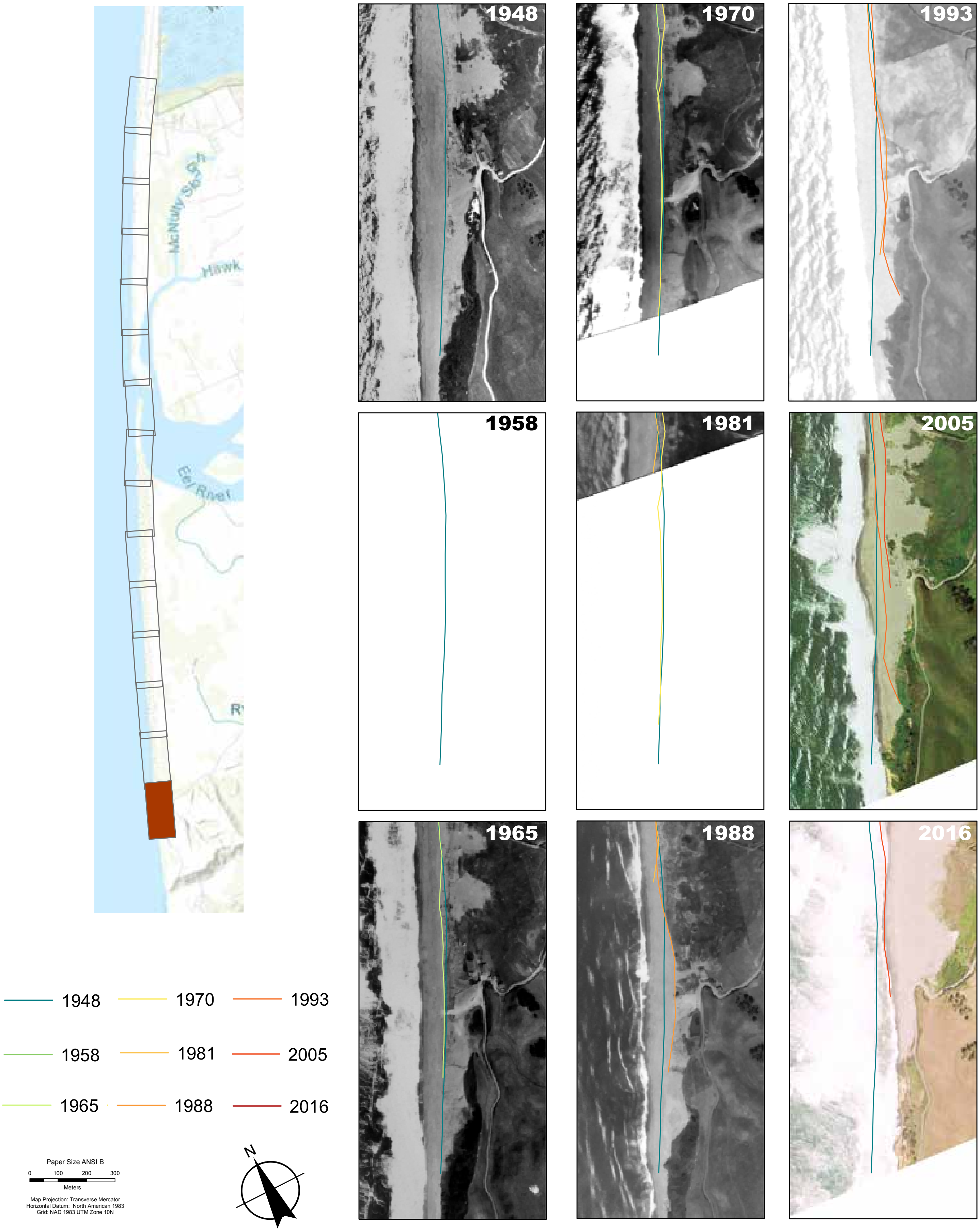


Figure 40: Enlargements of shoreline segments from 1998 (left) and 2016 (right) showig subtantial erosion over time.

From 1948 to 1970 this site has been relatively stable. In 1988 erosion at the center of the site moving south can be observed, as can the washover. In 2005 and 2016 extensive washovers can be seen. In 2016 the shoreline has eroded substantially with the dune feature from 1948 in the swash zone.

Figure 41 (Facing page): Compilation of the shoreline mapping for the segment by year. Each photograph includes mapped shoreline for the year of the photograph, 1948 and the prior year.


McNulty Slough
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Paper Size ANSI B
0 100 200 300
Meters
Map Projection: Transverse Mercator
Horizontal Datum: North American 1983
Grid: NAD 1983 UTM Zone 10N
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5. CONCLUSION

This study focused on documentation of shoreline change, as a means of understanding large scale coastal processes, sediment transport and dune building processes along the coast. Measuring any sediment movement across the boundaries of the shoreline helps understand past coastal patterns and inform future coastal behavior. We defined the coastal compartment (or beach cell) for the Eel River shoreline and undertook a review of aerial photograph and shoreline analysis.

This review and analysis indicates that the southern segment of the Eel River shoreline is prone to erosion, and the northern segment accretes at a low to moderate rate. Overall the statistical assessment has shown that the highest rate of accretion for both the north and south segments occurred between 1948--1958; whereas the interval between 1958-1965 saw the most erosion for both north and south.

An extended period of accretion and erosion, albeit at a lower rate, began in 1988 and lasted through 2005, at which point the processes reversed for each segment.

Figure 42 illustrates these trends in shoreline movement for each segment by averaging the rate of change over each interval studied. When overlaid against ENSO cycles (Figure 44), no clear correlation emerges. A finer grained analysis (for example, on a year-by-year basis) might clarify any relationship between ENSO and shoreline movement trends.

6. NEXT STEPS

Triggers or correlations for patterns of accretion and erosion were beyond the scope of this study and not determined.

Moving forward the context of coastal climate change and future adaptation should be established. Taking action on coastal erosion and future adaptation is challenging. This approach of understanding sediment budgets, sources and sinks, and trends in erosion and deposition from aerial photographic analysis, provided opportunity to see how the shoreline responds to the existing coastal processes and assists in understanding future coastal process changes. It in turn provides a framework for evaluating the likely intervention options that may be required for a coastal system over time.

Future investigations could focus on a more detailed sediment budget analysis focusing on the large scale coastal behaviors and other coastal processes or influences including land use factors and trends in fluvially-transported sediment, bluff erosion, nearshore currents, and wind and wave energy. A study such as this would further progress the understanding of climate change and sea level rise impacts on the Eel River shoreline.

Furthermore, while prior sediment budget projects have not agreed on where the Eel River's substantial sediment contributions to the coast are depositing, anecdotal observations and photographs clearly show a northward plume following large storms. A photograph

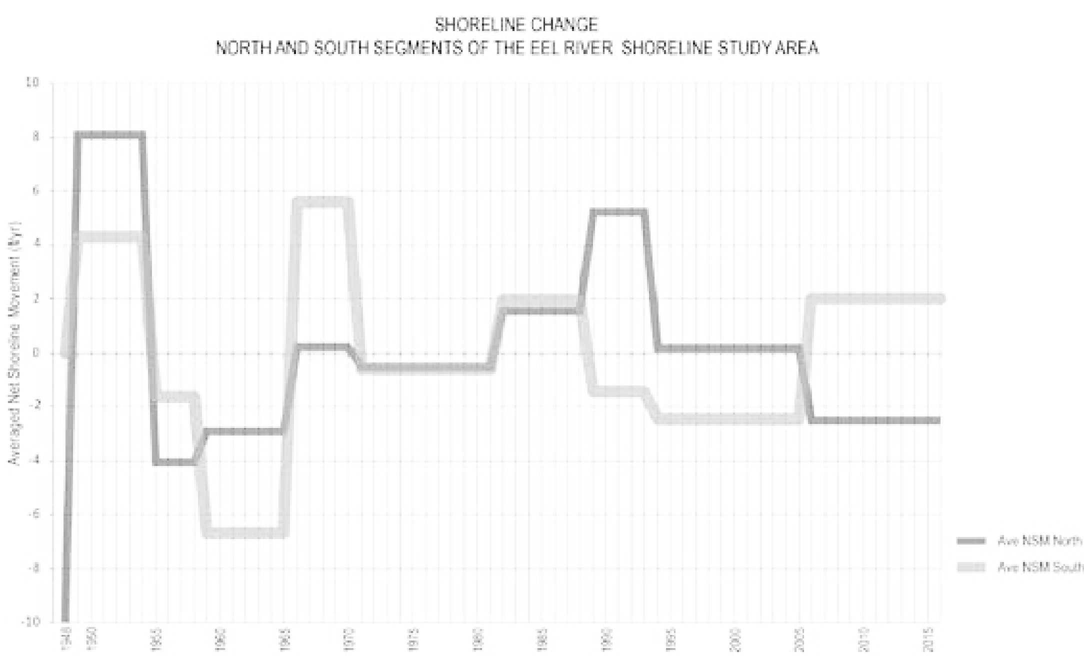

Figure 42: Rates of accretion and erosion averaged over intervals of reference aerial photorgraphs, by north and south segments.

taken on January 18, 2016 (Figure 6) demonstrates this. A study of the local wind and wave conditions at the mouth of the Eel River during significant discharge events would provide more detail on the direction of longshore sediment transport of the beach sized sediment component of the river's sediment load. This could be accomplished through numerical modeling of local wave conditions and sediment transport. Currents documented offshore (Figure 43) may also indicate sufficient velocity to mobilize sand (greater than 0.2 m/s along the bed) and also contribute to regional understanding of the patterns of sediment dispersal around the Eel River shoreline.

By considering change as part of a sediment compartment / littoral cell planning, reductions in vulnerabilities could be achieved, in particular if integrating these considerations across collaborative projects where the following is defined:

- The context of coastal climate adaptation
- Coastal climate adaptation within existing coastal management frameworks

Gurran et al., 2011, stated that the key issues of concern for coastal climate adaptation are:

- physical exposure (sea level rise, inundation)

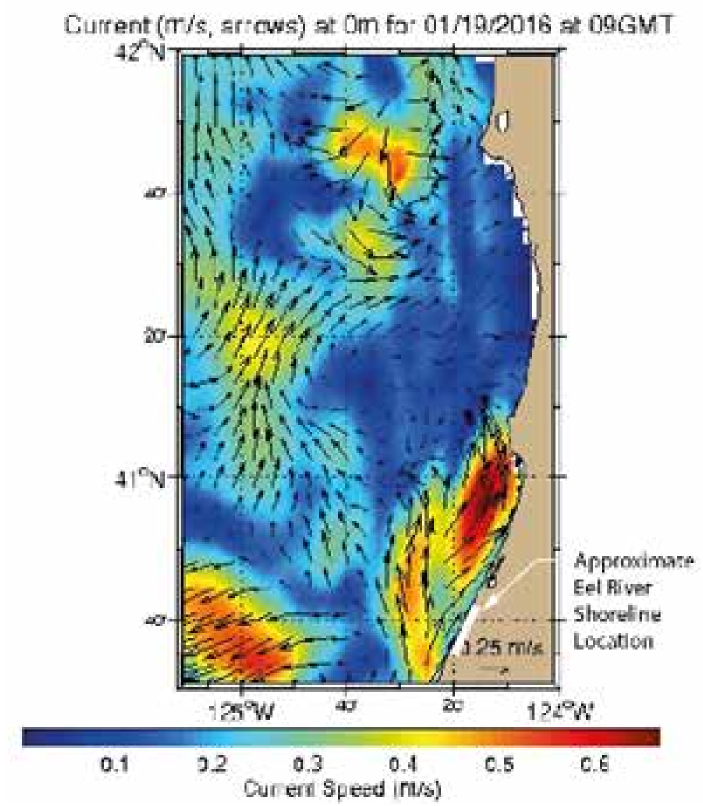

Figure 43: Modeling of currents, within 24 hours of date of photograph in Figure 6. Source: California Ocean Prediction System.

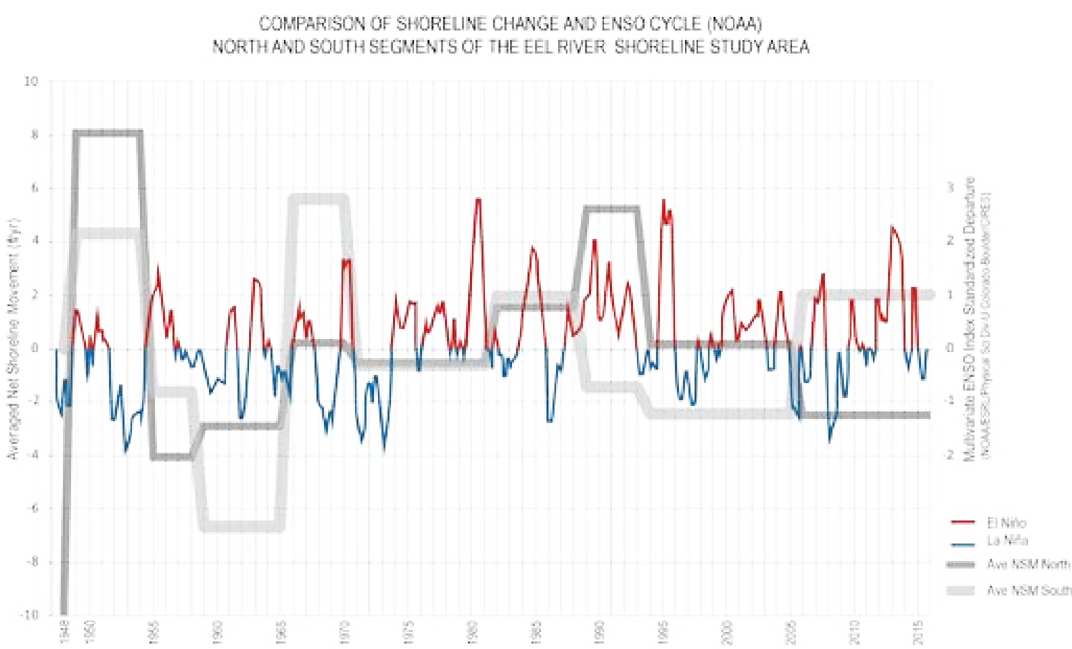

Figure 44: Average rates of accretion and erosion juxtaposed with ENSO cycles do not indicate clear correlation, demonstrating more detailed study of sediment and coastal processes is needed.

- potential development in vulnerable locations, loss of foreshores/recreational areas, impact on existing public infrastructure
- legal liability in planning decisions
- impact on existing private homes
- capacity of emergency response systems
- economic impacts
- increased population and
- lifestyle impacts.

Strategies for sea level rise adaptation are broadly characterized as “defend, accommodate, retreat” (IPCC, 2001). Approaches to addressing climate change impacts to dunes including both sea level rise and changes in geomorphic processes can fall within similar categories. To a limited degree, dune-building processes (“protect”) can be supported with dune fencing and other techniques. An adaptation response may allow dunes to migrate inland in accordance with sea level rise. The degree to which dunes re-establish would depend upon the availability of land and adequate sediment supply, the latter of which may also be impacted by changes in nearshore currents, and wave and wind energy. Retreat scenarios may be either planned or forced relocation of infrastructure away from natural hazards. In the case of dunes, the adaptation response and retreat response both require movement of structures away from the shore.

As the coastal dunes of the Eel River continue to evolve the main goal of dune management in light of climate change will be to build resilience by protecting or reinstating natural coastal ecosystems, which perform as a natural buffer to avoid and reduce coastal risks for landward infrastructure or by adapting existing development to accommodate identified coastal risks and timeframes (Gates et al, 2012).

Changes in climate may have diverse implications on the coastal environment and localized land uses.

Greater understanding of the coastal processes within the littoral cell could be achieved through numerical modeling of wave processes and sediment transport along with more detailed analyses of dune evolution. This will assist in identifying dune and beach management stabilization options.

With an understanding of this, in concert with climate change predictions for sea level rise and ocean temperatures, the detail needed to not just assess the vulnerability of the Eel River shoreline, but adequately prepare for its future will be in hand.

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