CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

Relationship of Land Use Modification and Sediment Transportation to Transverse and Parabolic Dune Behavior in the Mussel Rock Dunes Complex, California

A thesis submitted in partial fulfillment of the requirements

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By

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Table of Contents

List of Figures

Abstract

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The Mussel Rock dunes complex, California, is experiencing continuous change owing principally to the variable influx of sediment delivered to it by the nearby Santa Maria River. In 1958, construction of the Twitchell Dam on the Cuyama River, a tributary of the Santa Maria River, interrupted the natural flow of sediment to the coast. The entrapment of considerable amounts of sediment behind the dam, significantly altered the long-term natural rates of fluvial sediment delivery to the coastline. In order to understand how a coastal dune system will behave when starved of sediment, aerial imagery from 1954 to 2016 was examined. The active transverse and stabilized parabolic dunes within the Mussel Rock dunes complex were evaluated to determine changes in their extent resulting from sediment starvation caused by the dam, beach erosion and sand mining. Vegetation cover response to drought, rainfall, and reduced sediment load was also examined. This study revealed that the reduction in sediment has resulted in an increase in the extent of vegetation within the stabilized parabolic dune region along with a decrease in area within the nearby active transverse dune region. The results demonstrate that the transverse dunes most likely migrated into the vegetation, transformed into parabolic dunes owing to the lack of sediment, and became more stabilized as the vegetation increased. Additionally, the Santa Maria River to the north has migrated and removed some of the transverse dune field (reduction in area) while there is an eastward migration of the dune field in the southern section (increase in area). Overall, the net result in dune field extent was shown to be a decrease in area. The eastward migration may be the result of dune sands being eroded by waves and contributing to the beach (in a reverse flow of sediment), where it would become available for aeolian transport back into the dune field.

Introduction

Coastal dune systems provide a significant contribution to the protection of coastlines, acting as barriers to storm surges and thereby providing protection for low-lying inland areas. These dune systems are sedimentary deposits created by the wind-driven onshore transport of sediment from beaches to inland areas (Davidson-Arnott 2010) with the nature, form, and dimensions of the coastal dunes reflecting the character and volume of sediment available on nearby beaches (Orme 1988). The Mussel Rock dunes complex is part of the Guadalupe-Nipomo Dunes Complex on the central California coastal edge of the Santa Maria Basin (Figure 1), and is one of the largest

Figure 1. *Location of the Mussel Rock dune complex (Esri, Digital Globe 2017)*

coastal dune landscapes in North America. It is comprised of transverse paleodunes, parabolic, lobate, and transverse dunes. The transverse dunes are closest to the coast and active; whereas the vegetation-covered parabolic, lobate and transverse paleodunes are further inland and largely stabilized. The dune complex is believed to have been formed within the Quaternary (2.6 ma to present) through alternating periods of tectonic uplift and subsidence, as well as fluvial deposition (McCrory et al. 1995). It has then been modified throughout the Holocene (second epoch of Quaternary period from ~11 ka to present) by sea level fluctuations, erosion and changing sediment budgets (Orme 1992).

The nearby Santa Maria River delivers a variable influx of sediment to the offshore zone, where it is moved south by longshore transport, then subsequently deposited onshore by wave activity. Strong, prevailing winds from the northwest then transport the sediment from the beach into the dune complex. For the past six decades, however, there have been changes in the extent and vegetation cover of the transverse and parabolic dunes. From 1958 to present, sediment delivery to the system has been reduced owing to the construction of Twitchell Dam on the Cuyama River, a tributary of the Santa Maria River. Sand mining, which has taken place within the Mussel Rock complex, and upstream on the Santa Maria and Sisquoc Rivers, may have also influenced sediment delivery, although there are little quantitative data available to evaluate the veracity of this assumption.

The Twitchell Dam was constructed to protect the Santa Maria Valley from flooding. Like all dams, however, considerable amounts of sediment were trapped, thus significantly altering the long-term natural rates of fluvial sediment delivery to the coastline (Slagel and Griggs 2006). Water releases from the dam are managed for groundwater recharge, and released at a rate that ensures percolation into the aquifer (Science Applications International Corporation 2004). Although no dams exist on the Sisquoc River, the second major tributary to the Santa Maria River, sediment delivery from this stream only occurs during episodic flooding events (Patsch and Griggs 2007).

The purpose of this study is to analyze the morphological changes to the transverse and parabolic dunes within the Mussel Rock dunes complex in the period following the construction of the Twitchell Dam. This study examines the sediment budget of the dune field, comparing the fluvial and aeolian sediment inputs to sediment losses from the dam to determine (1) if there has been an overall net increase or reduction of sediment input to the dunes complex, (2) if alterations in sediment input are consistent with morphologic changes observed in the areas of the dune field dominated by transverse and parabolic dunes, and (3) if there have been long- or short-term fluctuations in vegetation cover.

Scientific Background

Aeolian Sediment Transport

Aeolian sediment transport is the driving process in the redistribution of sand within coastal dune systems. Johnson (1963) determined that three elemental conditions are necessary for the development and persistence of a coastal dune system: (1) a large supply of sand from a nearby stream and/or reservoir of dune-forming sediment in the nearshore zone, (2) a shoreline orientation approximately parallel to the crests of the prevailing waves, thus creating a favorable condition for a littoral current, and (3) low lying topography inland from the beach so that the prevailing onshore winds can easily move the sand from the region of accumulation towards the dune system.

Sediment transport from the beach to the dunes occurs when the wind blowing over a sand surface initiates forces that act on an individual grain, thus overcoming the gravitational and frictional forces that are holding the grain in place (Davidson-Arnott 2010). The threshold friction velocity is affected by numerous factors, such as grain size and shape, particle size distribution, surface slope, sediment moisture content, rain, and crusts resulting from salt or algae (Van Dijk et al. 1999). Wind speeds must reach the "fluid threshold," defined as the wind speed necessary for sediment to start saltating under the impact, drag, and lift of the wind (Bagnold 1941). The fluid threshold varies in direct proportion to the predominant grain size of the sediment surface and the amount of moisture present (Mangimeli 2007). Three modes of sediment particle transport (Figure 2) take place within dunes, depending primarily on the grain size. Very small particles (fine sand and silt (<60-70 μm)) are transported in suspension, larger particles (medium sand- coarse gravel (60-1000µm)) are transported by saltation, and larger or less exposed particles (500 µm) are pushed or rolled along the surface in creep (Nickling and

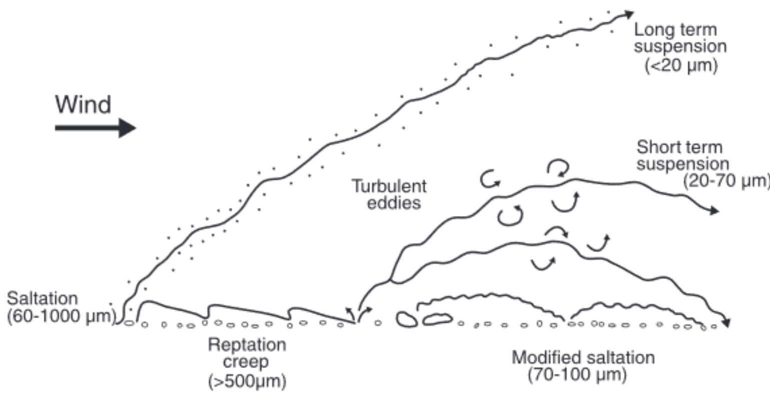


***Figure 2**. Processes of sand movement (Davidson-Arnott 2010)*

Davidson-Arnott 1990). Studies on sediment grain size in coastal dunes have shown that dune sand is composed of fine particles between 125-250 µm (Nickling and Davidson-Arnott 1990, Tsoar 2001, Aagaard et al. 2004). Transportation of beach sediment occurs at relatively high wind speeds usually over 6 m/s $^{-1}$ (Bagnold 1941, Bauer et al. 2009, Davidson-Arnott 2010), with approximately 75% of sediment transport taking place by saltation and the remaining 25% moving by creep (Bagnold 1941). Wind speed within the Mussel Rock complex has not been directly measured. In a 2013 study on airborne particulate matter (Etyemezian and Gillies 2013), anemometers were placed in the Oceano Dunes State Vehicular Recreation Area (approximately 10 km north of the Mussel Rock complex) from May- July 2013. Average wind speeds between 5.7- 8.8 m/s $^{-1}$ from the west and northwest were recorded suggesting wind speeds are capable of aeolian sediment transport within the dune region.

Inputs of sediment to coastal dune systems are largely derived from beach sands (Patsch and Griggs 2006). Beach surface moisture is an important variable controlling the dynamics of sediment transport, increasing the sediment entrainment threshold and thereby reducing the overall rate of transport (Bauer et al. 2009). The process of saltation is affected as the number of grains ejected by wind stress and the number of grains dislodged by saltation impact are reduced (Aagaard et al. 2004). Principal moisture sources acting to reduce sediment transport on beaches include: 1) precipitation during or just prior to a wind event; 2) spray blown onshore from breaking waves; 3) pore water derived from the beach water table through capillary rise or where the water table outcrops on the beach during low tide; and 4) inundation due to wave run-up and storm surge (Nickling and Davidson-Arnott 1990). The sediment entrainment threshold depends primarily on the wind speed (Bauer et al. 2009). When the threshold is met, surface moisture is no longer the dominant control on saltation, and the sediment transport system switches to being controlled by wind speed (Wiggs et al. 2004). Field studies (Nickling and Davidson-Arnott 1990, Wiggs et al. 2004, Davidson-Arnott et al. 2008, Delgado-Fernandez 2011) have attempted to measure surface moisture content and sediment entrainment thresholds on moist coastal dunes, however, the results have not been consistent and generally accepted, thus signifying that the effect of moisture on coastal dune transport is still not well understood (Dong et al. 2007). The complex interaction of aeolian sand transport across beach and dune systems is affected by highly variable surface conditions (grain size and sorting, moisture content), beach-dune geometry (slope, roughness, vegetation), and wind conditions (speed and angle) in ways that are not easy to decipher (Bauer et al. 2009).

Longshore and River Sediment Transport

Primary sources of sediment supply to beaches include longshore transport and river discharge. Longshore transport of sediment (Figure 3) results from the operation of three sets of processes: (1) longshore drift on the swash (run-up) slope which is driven primarily by oblique wave action; (2) wave-generated long-shore currents in, and just seaward of the surf zone; and (3) transport seaward of the breaker zone by residual tidal and wind-driven currents (Davidson-Arnott 2010). Longshore transport typically includes

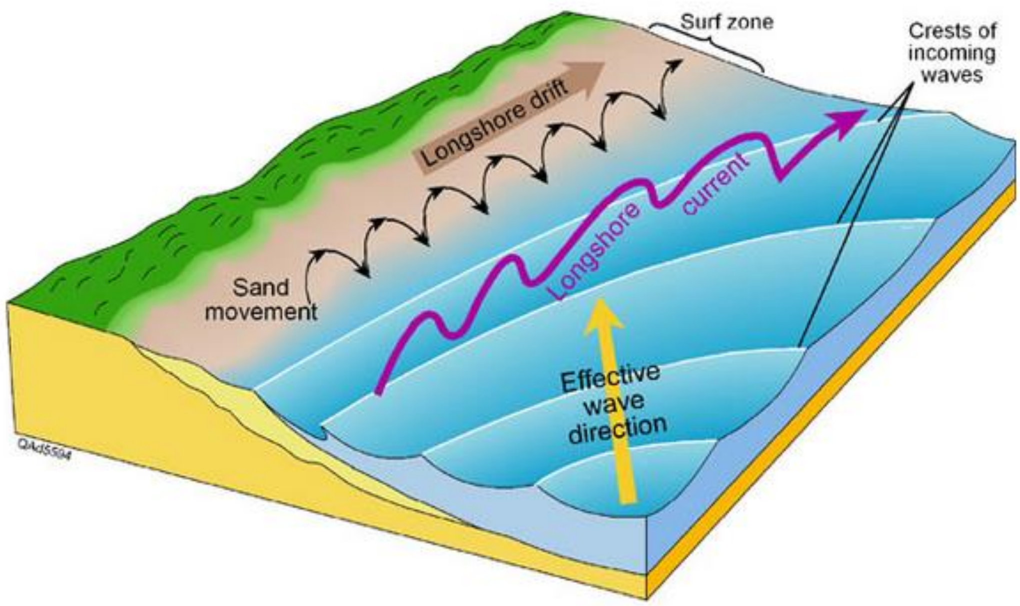


***Figure 3**. Diagram depicting longshore sediment transport (The University of Texas at Austin 2006).*

both upcoast and downcoast directions and varies seasonally depending on the dominant angle of wave approach (Patsch and Griggs 2007). Most beach sediment along the coast of California is transported from north to south because of dominant waves approaching the shoreline from the northwest, though periods of alongshore transport to the north occurs in response to seasonal waves from the south (Patsch and Griggs 2006). Sediment moved through longshore transport along the Mussel Rock complex is largely from north to south. In 1966, the rate was estimated to be approximately 47,402 m^3/yr. and takes into account losses from Twitchell Dam (Bowen and Inman 1966). However, accurate sediment transport rates for longshore drift are difficult to determine owing to near shore bathymetry and seasonal variations in the direction of wave approach (Patsch and Griggs 2007). Submarine canyons can also affect sediment transport rates for longshore drift by trapping sediment and channeling it offshore. However, there is no submarine canyon near the Mussel Rock complex.

Rivers and streams contribute the great majority of sediment to California beaches where it ultimately becomes available for aeolian transport into the dune system. Coastal rivers in central California have exceptionally high sediment loads because of the steep topography, the geologically young and tectonically active terrain, and the relatively sparse vegetative cover (Willis and Griggs 2003). Physical and chemical weathering breaks down rocks from coastal mountains into smaller fragments which are transported in streams either as suspended load (finer-grained sediment), in saltation (medium grains bounced along by force of the water), or as bedload (coarser material transported along the stream bed) (Patsch and Griggs 2006). Approximately 85-95% of all sediment is carried as suspended load while bedload typically ranges from 5-10% of the total sediment load (Willis et al. 2002). Sediment transport by rivers will be stored within the basin (in the stream channel, flood plain, or estuary at the stream mouth), or delivered directly to the ocean where it will be deposited near the river mouth as beach deposits (Willis et al. 2002). Delivery of sediment to rivers is highly episodic with much of the sediment being discharged during short periods of high flow during the winter months (Patsch and Griggs 2007). Additionally, the natural rates and magnitudes of fluvial sediment delivery have been significantly altered by 1) land use changes that have modified sediment production, 2) the reduction of stream discharges, and 3) the construction of barriers to sediment transport (Willis and Griggs 2003).

Beach erosion can contribute to a reduction in sediment available for transport into the dune system. In California, this primarily occurs in response to short-term events such as increases in storm activity; long-term events such as sea-level rise; or human activities (i.e., dam construction) that disrupt the natural sediment supply (Hapke et al. 2006). A 2006 USGS study (Hapke et al.) measured coastal erosion along the California coast using historical maps and lidar (Light Detection and Ranging) to determine long-term rates (1800s to present) and short-term rates (1950s-1970s to present) of change. At the Guadalupe Dunes region, the maximum long-term erosion rate was -1.1 m/yr^{-1} while the maximum short-term erosion rate was -6.7 m/yr^{-1}; this was the highest short-term rate in California and is likely related to flood control projects upstream on the Santa Maria River (Hapke et al. 2006).

To counteract the narrowing of beaches resulting from erosion and human activities, beach nourishment projects have been implemented along the California coastline to widen beaches where the natural supply of sediment has been significantly reduced (Patsch and Griggs 2006). Sources of sediment for beach nourishment may come from dredging, inland areas, and harbor construction and ultimately represents a means of restoring a more natural system (Hearon et al. 2002). This process has not been initiated along the beach at the Mussel Rock dunes complex.

Transverse and Parabolic Dune Behavior

The amount of sediment available has a profound effect on long-term dune field patterns (Eastwood et al. 2011). Coastal dune development results from the complex interaction of several factors including the type and influx of sediment, and the presence of vegetation (Parteli et al. 2006). Transverse and parabolic dunes dominate the Mussel Rock dunes complex. Coastal parabolic dunes (Figure 4) develop in a unidirectional onshore wind regime (Yan and Baas 2015), and are high, U-shaped migrating dunes with an active slip face at the landward margin and an elongate erosional basin on the

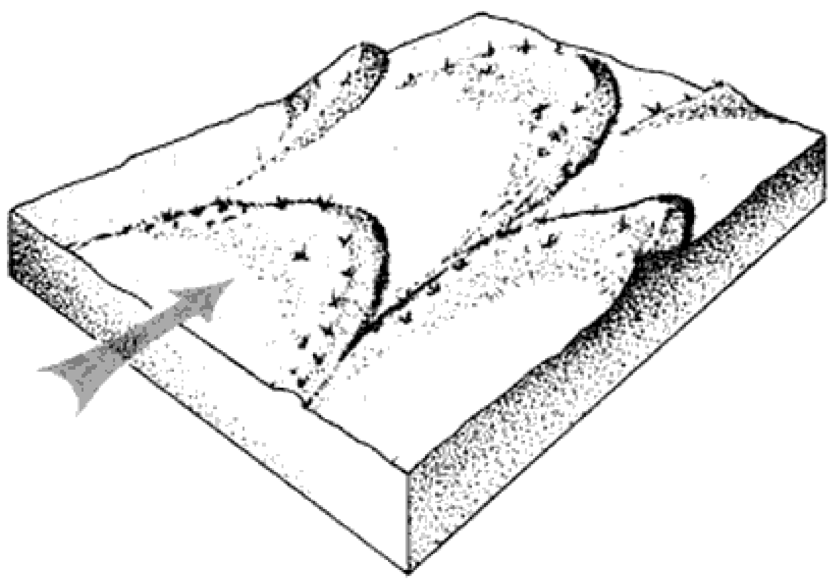


Figure 4. *Parabolic dune formation. Arrow indicates wind direction (McKee 1979).*

upwind (coastal) side which supplies sediment to the active depositional lobe (Davidson-Arnott 2010). In their initial, simplest form, they are referred to as lobate dunes. Parabolic dunes are mostly located in humid coastal areas where vegetation is more easily established at the base of the dune near the water table (Tsoar 2001). Dune vegetation limits the capacity of winds to transport sand as it partitions shear stresses and decreases particle saltation and erosion potential. Only finer grains with lower threshold shear velocities can be dislodged and transported by winds (Yan and Baas 2015). Transport of sediment effectively ceases when vegetation cover reaches ~20 %, although the threshold depends on the plant species, geometry and structure, and spatial distribution (Yan and Baas 2015). The density and distribution of vegetation also fluctuate, with seasonal growth rates strongly influencing patterns of sediment transport and deposition (Hesp 2002). Furthermore, the migration patterns of parabolic dunes vary from place to place because of different local environmental settings, which affect moisture content (atmospheric and water table), sediment availability, vegetation cover, and human activities (Yan and Baas 2015).

Transverse dunes (Figure 5) are long, asymmetrical migrating ridges that advance by erosion on the windward slope and deposition on the leeward slope with little or no change in shape or dimension (Tsoar 2001). These formations tend to develop in

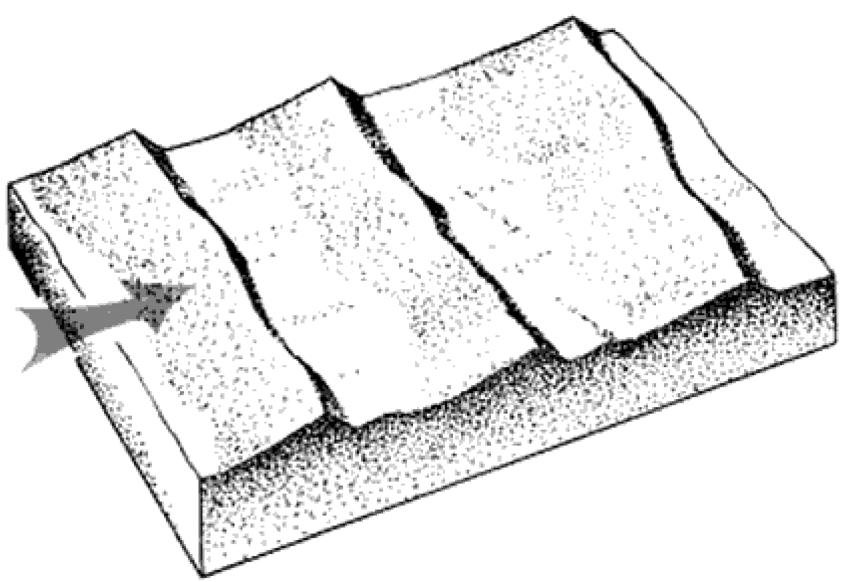


Figure 5. *Transverse dune formation. Arrow indicates wind direction (McKee 1979).*

environments with a plentiful supply of sediment. Transverse dunes are unvegetated and mobile, with sediment transport dominating over other processes (Rust and Illenberger 1996), and attain a maximum height where there is a balance between wind strength and available sediment (McKee 1979). They are dynamic, often display rapid changes in position depending on the wind regime, and tend to systematically move sediment inland, away from the beach (Rust and Illenberger 1996). As transverse dune fields migrate into vegetation, parabolic dunes are formed, and the parabolic development becomes more pronounced as the dune field begins to stabilize (Hesp 2013). It is quite possible that many stabilized coastal dune fields that are presently dominated by parabolic dunes, originally evolved as transverse dunes (Hesp 2013). The transformation has been attributed to a progressive increase in vegetation cover caused by climatic changes or human disturbances however, the exact transformation process and the underlying mechanism remain unclear (Yan and Baas 2015).

Effects of Dams on Sediment Transport

The largest reduction in sediment to coastal regions takes place through dam construction on rivers. Dams affect sediment transport by 1) altering the annual hydrograph and typically reducing peak discharges and sediment transport downstream, 2) trapping sediment and reducing the amount of upstream sediment that reaches the downstream river network (Willis and Griggs 2003), and 3) altering channel incision rates and channel morphology (Gordon and Meentemeyer 2006). Coastal dams disrupt the long-term balance of sediment gains and losses to the coast, ultimately tipping the balance toward a long-term net loss (Willis et al. 2002) as they isolate a significant proportion of sediment load, which would normally be delivered downstream via the river (Petts and Gurnell 2005) .

Twitchell Reservoir catches runoff from the Cuyama, Husana and Alamo watersheds (Figure 6). Water is stored and slowly discharged into the Santa Maria River, which, in turn, supplies about 24,669,600 m^3 of recharge to the Santa Maria Groundwater Basin annually (Twitchell Management Authority 2010). The dam has greatly reduced the effective area of the drainage basin (Bowen and Inman 1966). Willis and Griggs (2003) estimated that the annual sand and gravel flux for the Santa Maria River was

Figure 6. *Map showing location of the Santa Maria, Cuyama and Sisquoc Rivers, and Twitchell Reservoir in relation to the study area (outlined in red) (Esri, Digital Globe 2017)*

620,000 m^3 under conditions of natural unrestricted flow, but has been reduced to 199,368 m^3 by the dam. Such losses are probably the cause of the very high erosion rates documented along the coastline in the Guadalupe Dunes region (Hapke et al. 2006).

Sand Mining

Sand and gravel are often removed from riverbeds, beaches, and dunes for construction and commercial purposes representing a substantial loss of sediment that would otherwise be transported to the coast (Patsch and Griggs 2007). Attempts to gather information on specific practices are constrained by the proprietary nature of mining and therefore the volumes removed are difficult to quantify (Patsch and Griggs 2007). Although sand mining does not take place on the Mussel Rock complex beach, there currently are a few operations that exist along the Santa Maria and Sisquoc Rivers and on the edge of the Mussel Rock complex itself. A sand mine facility has been processing sand from the Mussel Rock complex southwest of the entrance kiosk to the Rancho Guadalupe Dunes Preserve since 1967 (Science Applications International Corporation 2004), although no data on the volume of sand that has been removed can be accessed. Nonetheless, it can be surmised that sand mining reduces the input of sediment to the Mussel Rock dunes complex.

Study Area

General Description

The Mussel Rock dunes complex is located within the southern portion of the Guadalupe- Nipomo Dunes Complex; this 29 km long expanse of coastal dunes in the Santa Maria Valley extends from Pismo Beach southward to Point Sal and encompasses nearly 90 km^2 making it one of the largest remaining coastal dune systems in California (Figure 1). The Guadalupe- Nipomo Dunes Complex spans two counties, with the Santa Maria River forming the boundary between San Luis Obispo County to the north and Santa Barbara County to the south. Designated as a National Natural Landmark, the Guadalupe- Nipomo Dunes Complex (Figure 7) protects several areas, including the

***Figure 7**. Map of Guadalupe-Nipomo Dunes Complex, with study area outlined in red (Esri, Digital Globe 2017)*

Pismo Dunes Natural Preserve, Oso Flaco Lake Natural Area, Guadalupe-Nipomo Dunes National Wildlife Refuge, and the Rancho Guadalupe Dunes Preserve County Park. It is also home to sites with considerable human impact, notably the Oceano Dunes State Vehicular Recreation Area (ODSVRA), the only California State Park where vehicles may legally drive on the beach, and the Guadalupe oil field, a controversial former oil exploration and development site.

Three extensive dune fields comprise the Guadalupe-Nipomo Dunes Complex (Figure 8): the Callender dune sheet, resting mainly on the Nipomo mesa; the Guadalupe

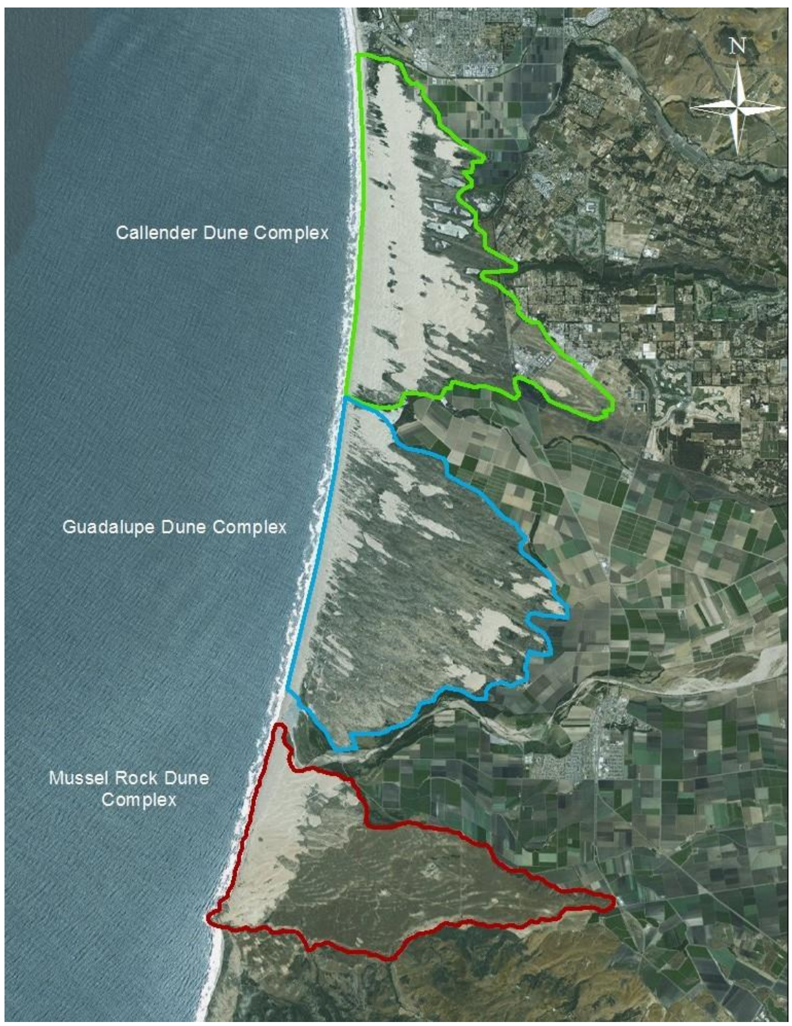


Figure 8*. Map of the three dune fields within the Guadalupe-Nipomo Dunes Complex (Esri, Digital Globe 2017)*

dune sheet, on the Santa Maria flood plain; and the Mussel Rock dune complex, which lies partly on the floodplain of the Santa Maria River (along its northern border) and partly on Orcutt Mesa at the southern edge (Cooper 1967, Orme 1992). The area bordering the Callender sheet to the north is largely urbanized, while agricultural fields and pastures occupy the land immediately east of the Callender and Guadalupe sheets (Smith 1976). To the north of the Mussel Rock dunes complex lie agricultural fields and the Santa Maria River wetlands, while the Casmalia Hills border the southern extent of the dunes.

The Mussel Rock dunes complex (Figure 9) includes some of the most remote and least disturbed habitats within the Guadalupe- Nipomo Dunes Complex (U.S. Fish & Wildlife Service 2009). It is one of the largest and most important breeding sites in California for the western snowy plover (*Charadrius nivosus*), a federally listed threatened species (MacDonald et al. 2010). The Rancho Guadalupe Dunes Preserve County Park is contained within the northern region of the Mussel Rock dunes complex and is closed to

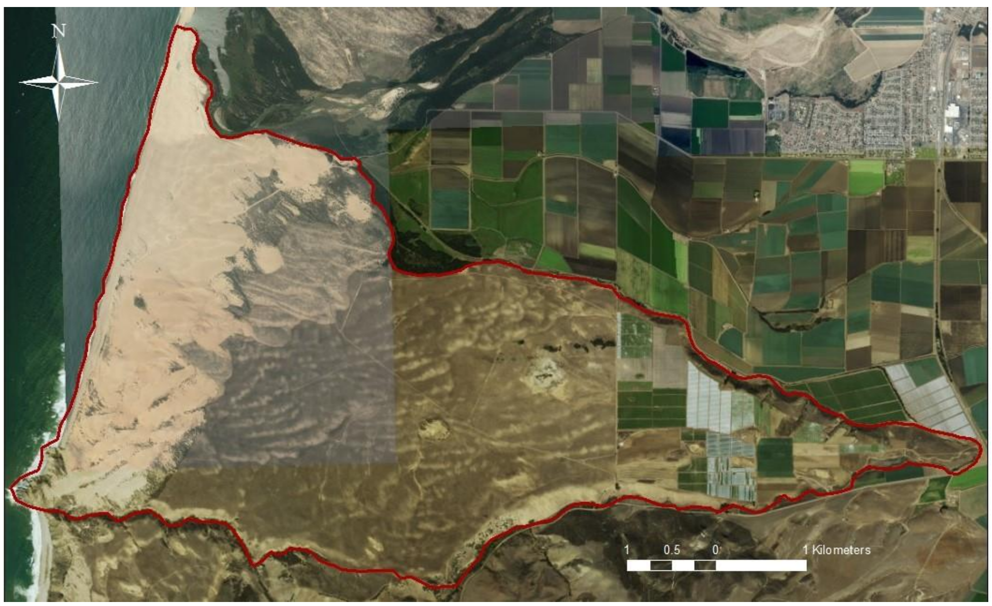


Figure 9. *Mussel Rock dunes complex- study area outlined in red (Esri, Digital Globe 2017)*

the public from February 1st to October 1st every year to protect the plover's nesting habitat. Due to the seasonally limited entry into the Dunes Preserve County Park, and the remote and difficult-to-access region around Mussel Rock, I chose to study the central Mussel Rock dunes complex because it is the least affected by human activity. The Callender dune sheet is affected by off road vehicle impacts, and the Guadalupe dune sheet is impacted by agriculture and disturbance from oil exploration and infrastructure.

Climate

The climate of the region is characterized as Mediterranean with warm, dry summers and cool, moist winters. Temperatures range from average winter lows in December of 4℃ to average summer highs in September of 24℃ (Tetra Tech 2010). Precipitation occurs in the late fall through the early spring and averages around 304mm per year along the coast (National Climactic Data Center 2017). Coastal fog is an additional important source of moisture and more prevalent during the summer months as warm, moist air contacts cooler surface air, and water vapor condenses to create fog (U.S. Fish & Wildlife Service 2009, Rutledge et al. 2011). Winds measured at the Santa Maria Municipal Airport (KSMX) are predominantly from the northwest with an average speed of 2.9 m/s^{-1} (National Climactic Data Center 2017).

Geomorphology

The Mussel Rock dune complex is a triangular shaped area extending 4.9 km southward from the Santa Maria River to Mussel Rock and inland to Corralitos Canyon (Figure 10). Elevation in the dune complex fluctuates from 4m (13 ft.) to around 30m (100 ft.) along the Santa Maria River floodplain, then gradually rises onto Mussel Rock and the Orcutt Mesa (168m), a marine terrace to the south (Figure 11).

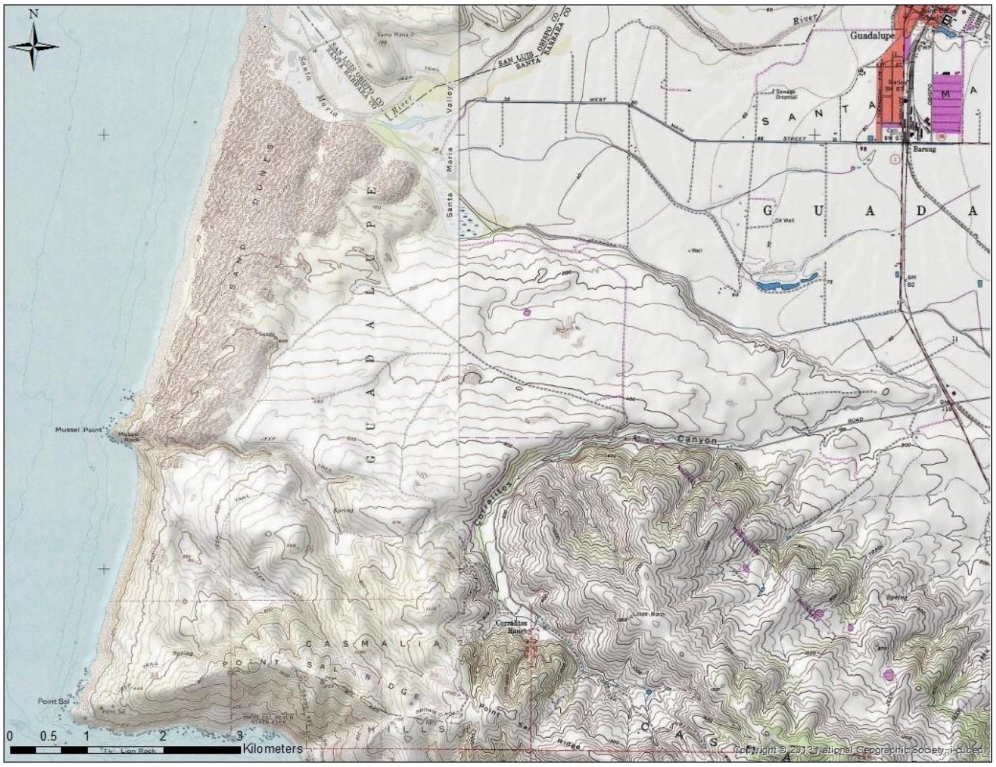


Figure 10. *Topographic map of Mussel Rock dunes complex (Esri, USGS 2017)*

Figure 11*. Aerial view of dune complex looking to the east from the Pacific Ocean (Google 2016)*

The dune complex is primarily comprised of transverse and parabolic dunes, although four dune types are present. Orme (1992, 2012) categorized the dune forms into active transverse (Qe_5), parabolic (Qe_3) and lobate dunes (Qe_4) and transverse paleodunes (Qe_2) (Figure 12). Located closest to the coast, the active transverse dunes (Qe_5) parallel

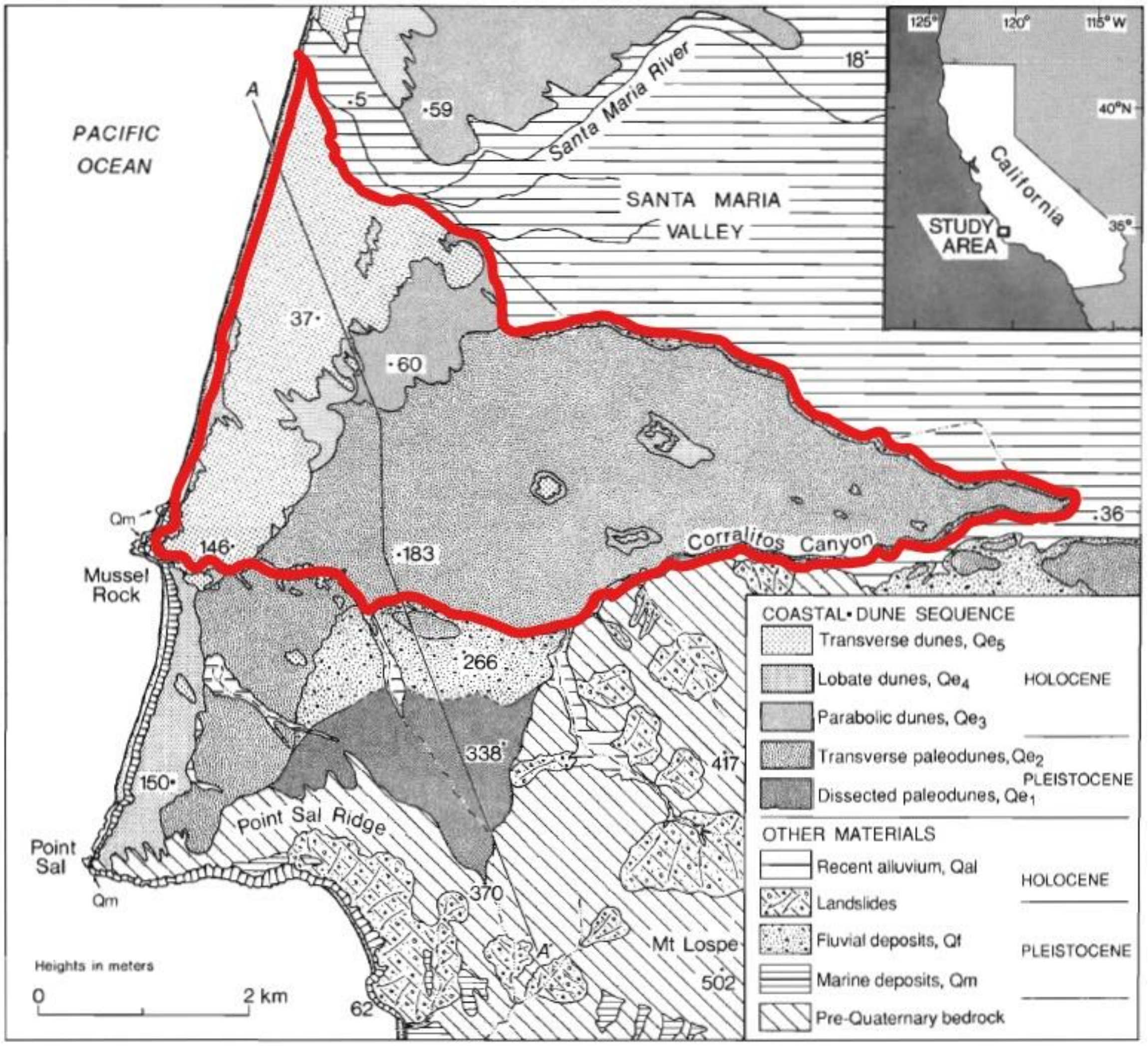


***Figure 12**. Map demonstrating late Quaternary coastal dune sequence with study area outlined in red. The transverse, parabolic and transverse paleodunes will be referenced within this study (Orme 1988)*

the shoreline from the mouth of the Santa Maria River south toward Mussel Rock. Mostly devoid of vegetation, these dunes are migrating southeast at a rate of 2-5 m/yr^{-1} and are composed largely of sand derived from the beach (Orme, 1992). Located between the active transverse dunes (Qe_5) along the coast and the more inland transverse paleodunes (Qe_2), the partially vegetated parabolic dunes overlap the transverse paleodunes near the Santa Maria River and extend 1 km inland (Orme 1992, Eley and Knott 2006). The stabilized transverse paleodunes are more vegetated than the parabolic dunes, constitute the largest portion of the dune field, and may contain as much as 1.3 km^3 of sand (Orme 1992); they first appear about 0.5-1.5 km inland from the coast and extend landward as a wedge until they terminate at Corralitos Canyon to the south and Orcutt Creek to the north.

Radiocarbon dating of the transverse, parabolic, and transverse paleodune sands by Orme (1992) has provided the most accurate representation of their ages. Formation of the transverse paleodunes began after 26 ka with sand deposition between 26 and 23 ka (Orme 1992). The parabolic dunes developed from new and reactivated sand masses during the Flandrian transgression (period of rapid sea-level rise between ~18 ka to ~4 ka b.p.), stabilizing before 3 ka; lobate dunes around Mussel Rock yielded uncorrected ages of 1,120 to 850 yrs b.p.; and the present transverse dunes were most likely activated within the past 200 years (Orme 1992).

Vegetation plays a critical role in determining the dynamics and morphology of coastal dune environments (Lancaster and Baas 1998). Although sparse in coverage, coastal strand plants such as sand verbena (*Abronia maritima*), sea rocket (*Cakile maritima*) and beach morning glory (*Ipomoea pes-caprae*) grow nearest the beach in the transverse dunes (California Coastal Commission 1987). Coastal dune scrub including mock heather (*Ericameria ericoides*), dune lupine (*Lupinus chamissonis*), surf thistle (*Cirsium rhothophilum*), and soft-leaved paintbrush (*Castilleja mollis*) occupy the parabolic dunes, lobate dunes and in greater concentration, the transverse paleodunes (California Coastal Commission 1987). The sandy soils of coastal dune scrub vegetation have a high accumulation of organic matter, a low salt content, greater water-holding capacity (LFR 2006), and have been stable long enough to have developed a soil profile (Cooper 1967). These soil conditions may help to explain the growing presence of agricultural fields established on the furthest inland region of the transverse paleodunes (Figures 13A-C). Although fields were initially plowed in 2009, more have been added in subsequent years. Polygons were created for the entire transverse paleodune and agricultural fields in Google Earth, and total area was calculated using Earth Point. The results demonstrate that the agricultural fields now account for approximately 2.4 km^2 (20%) of the entire transverse paleodune region. However, it is unlikely that the agricultural fields would affect the sediment supply to the contemporary active dunes as aeolian sediment delivery comes largely from beaches and the transverse paleodunes are stabilized and inactive. Furthermore, the prevailing winds direct sand away from the dunefield, not towards it. A review of the aerial imagery did not show any sand streaks

***Figure 13a**. 2008 image of the Mussel Rock dunes complex showing the absence of agricultural fields within the transverse paleodunes (Esri, Digital Globe, 2017)*

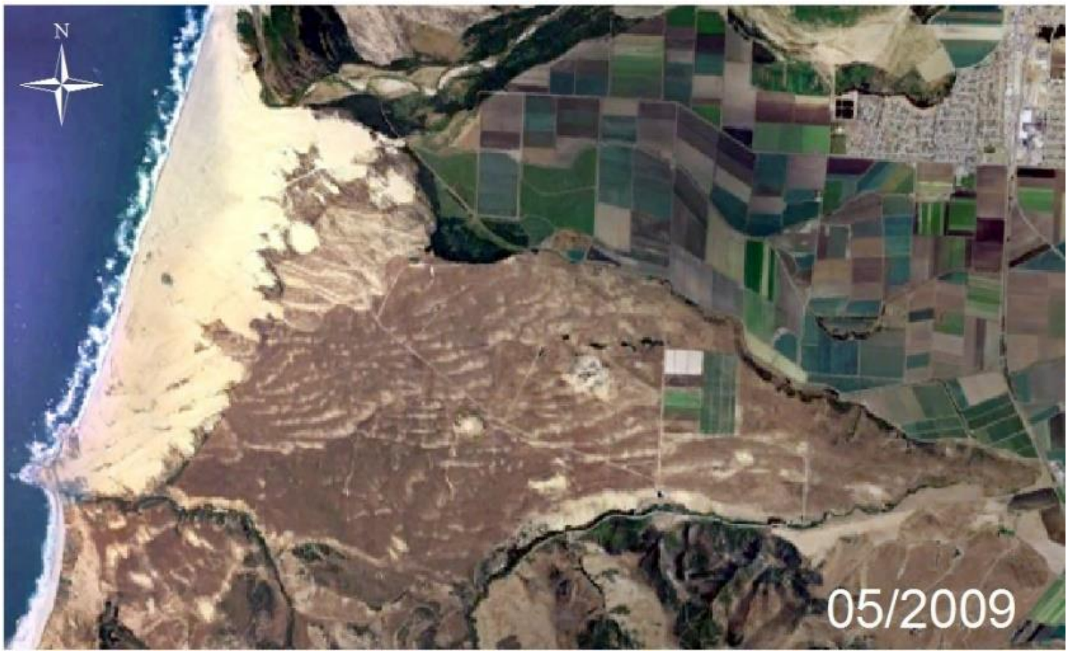


***Figure 13b**. 2009 image demonstrating the first agricultural fields plowed (Esri, Digital Globe, 2017)*

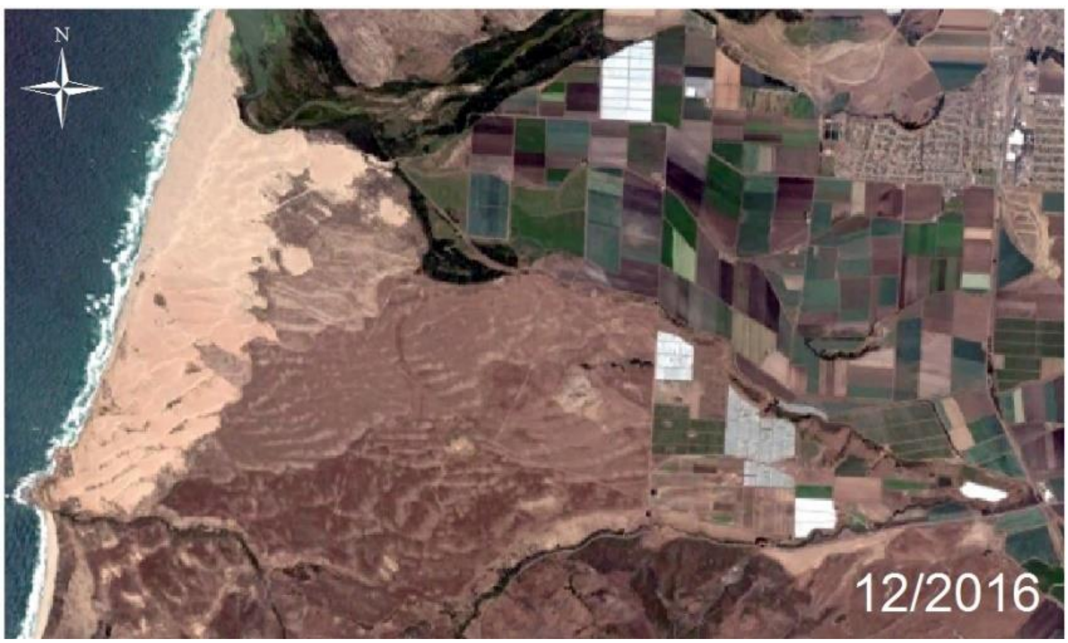


***Figure 13c**. 2016 image demonstrating most recent extent of agricultural fields (Esri, Digital Globe, 2017)*

across the agricultural fields, indicating that the paleodunes to the west are largely stabilized. They are also constrained in size by the Corralitos Creek to the south and the Orcutt Creek to the north.

Methodology

This study utilized aerial imagery to determine the areal extent of the active transverse and stabilized parabolic dune fields. Sea level data were obtained to observe overall trends in sea level patterns. Climate data including precipitation and drought, wind velocity, and wind direction, were collected to determine possible effects on dune morphology and parabolic dune vegetation. Sediment budget data on aeolian sediment transport, and average annual sediment transport with and without Twitchell Dam, were obtained to determine their effect on the extent of the parabolic and transverse dune regions.

Dune Field Measurements

The aerial extent of the active transverse and stabilized parabolic dune fields was estimated using aerial imagery of the dune complex obtained from the University of California Santa Barbara, Google Earth, and the California Coastal Records Project. A total of seven images were selected: the first was from 1954, with one image from each decade examined thereafter until, 2016. The 1954 image allowed for a baseline measurement of dune area to be taken prior to the construction of the dam in 1959. Polygons outlining the transverse and parabolic dune regions were created in Google Earth. The polygon data, consisting of a series of latitude and longitude points, were imported into Earth Point, formatted, and then converted to display the total area. Area measurements for the corresponding years were graphed in Excel. Polygons for the years 1984, 1994, 2006, and 2016 were created directly from Google Earth. Aerial photos from 1954, 1961, and 1970 were imported into Google Earth using the overlay feature, superimposed onto the earliest image available through Google Earth, and spatially adjusted using reference points. Although steps were undertaken to create the best alignment between the polygon edges and actual ground differences, the area calculations are necessarily approximations.

Sea Level Measurements

Changes in sea level may alter location of the shoreline and ultimately the long-term littoral sediment budget (Nickling and Davidson-Arnott 1990). Mean sea level data were obtained from the Permanent Service for Mean Sea Level, Port San Luis Station. The station is located just north of Pismo Beach along the San Luis Obispo Bay and is approximately 25 km north of the Mussel Rock complex. Yearly data were collected from 1946 to 2016 (no data were available for the years 1960, 1968-1969, 1971, 1996 and 2010) to allow a greater time frame for observation. The data were graphed to demonstrate the overall trend in sea level patterns.

Climate Data

Changes in climate can affect fluvial sediment transport in rivers and streams, dune moisture patterns, and vegetation growth. Precipitation and drought information were obtained from the Santa Barbara County Flood Control District. Data showing the five driest and wettest years during the time frame of this study were compiled from yearly rainfall measurements taken from 1970-2016 at station #380 in Santa Maria using an ALERT storm monitoring system. The results were compared to the aerial extent of the transverse and parabolic dunes to determine if heavy precipitation or drought years coincided with changes within the dune fields.

Wind velocity and direction data were obtained from the National Climactic Data Center to correspond with the years of the aerial imagery (1954, 1961, 1970, 1984, 1994, 2006, 2016). The meteorological station is located at the Santa Maria Public airport, which is approximately 18 km inland from the coastal dune areas. Using Excel, the data was formatted, and input into WRPLOT to create a wind rose showing wind speed and direction. Wind speed categories were chosen to reflect those from a 2013 study 10 km up the coast at the Oceano Dunes State Vehicular Recreational Area (Etyemezian and Gillies 2013).

Sediment Budget Data

In order to determine if there is a deficit, surplus, or equilibrium in sediment for the dune complex, sediment budget data for the dunes were obtained from several peer-reviewed reports: (1) an estimate of sediment transport by wind from beaches to the dunes (Bowen and Inman 1966); and (2) average annual sediment transport from the Santa Maria River under natural conditions (no dam) and as it occurs today (with dam) (Willis and Griggs 2003). The sediment data provided are estimates, as it is not possible to accurately measure the amount of sediment being transported by the longshore current, aeolian transport, river transport, or lost by accretion behind dams.

Results

Dune Field Measurements

Figures 14 and 15 demonstrate the areal extent of the active transverse and stabilized parabolic dune fields from 1954-2016. The transverse dune area occupied ~5 km^2 in 1954, increased to ~5.1 km^2 in 1961, stabilized (~5.2 $km^{2)}$ between 1970 and 1984, and decreased thereafter until 2016 (~4.4 km^2). The decrease in the extent of the active transverse dunes after 1984 was approximately 15%. By contrast, the parabolic dune area was ~1.4 km^2 for between 1954 and 1961, before decreasing slightly to

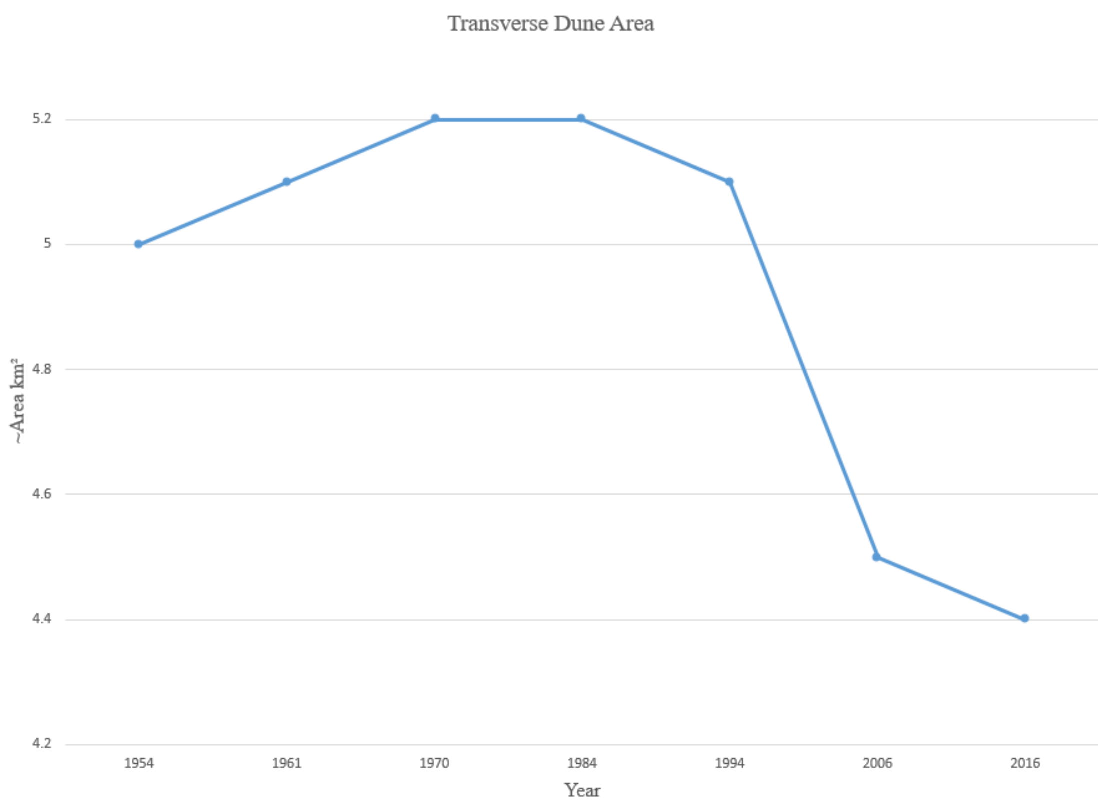


Figure 14. *Graph of approximate transverse dune field area*

~1.3 km^2 in 1970. The dune field began to expand in area thereafter, reaching ~1.4 km^2 in 1984, ~1.6 km^2 in 1994, ~1.8 km^2 in 2006, and ~1.9 km^2 in 2016. Thus, the parabolic dune field increased in area 31% between 1970 and present. Overall, the transverse dune field decreased ~0.6 km^2 while the parabolic dunes increased ~0.5 km^2. The 0.1 km^2

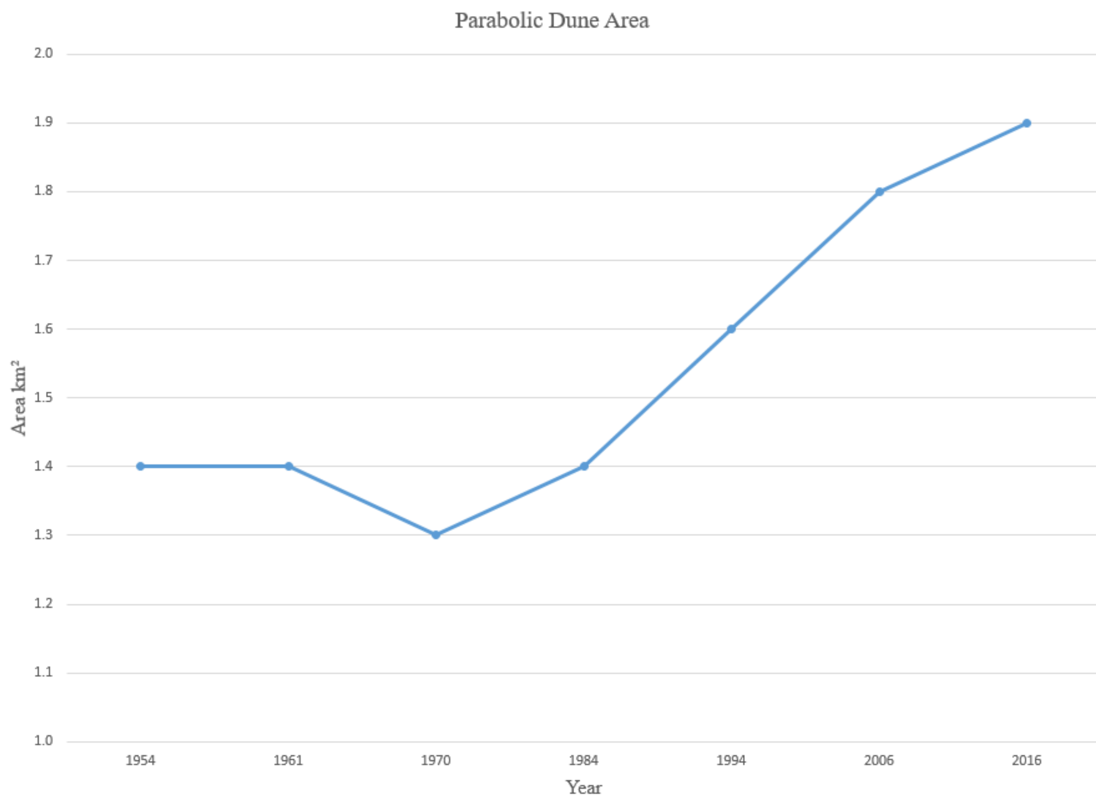


Figure 15. *Graph of approximate parabolic dune field area*

difference in area may be the result of an error in measurement due to spatial alignment differences with the aerial photos, but may also be the result of a difference in inherent dune volume, and hence extent, between the two dune types.

Figures 14 and 15 demonstrate that whereas the transverse dune field began to stabilize in 1970, the parabolic dune field began to increase in size. In 1984, the transverse dune field began to decrease in extent while the parabolic dunes continued to gain in size. Given that there was no increase in the overall size of the Mussel Rock dune complex, it is likely that the source of sediment for the vegetated parabolic dunes was the migrating transverse dunes.

Sea Level Measurements

Fluctuations in sea level have a profound effect on sediment availability for

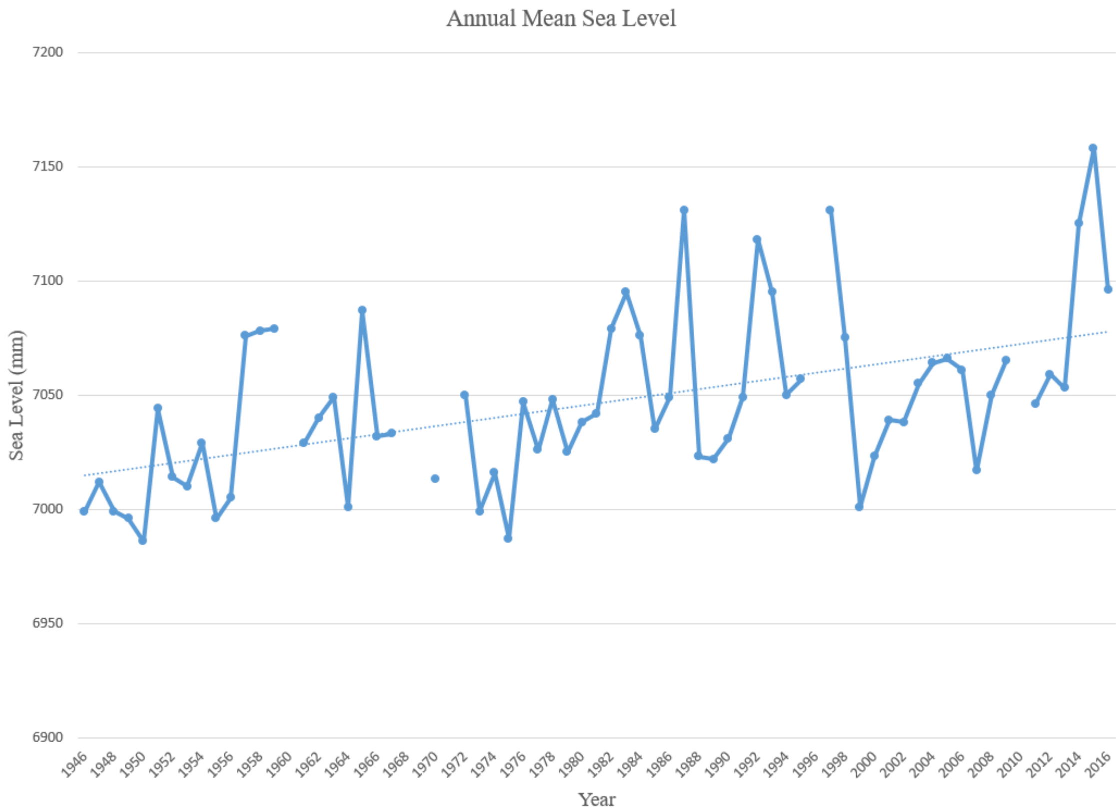


Figure 16. *Graph demonstrating mean sea level from 1946- 2016. Gaps in the graph represent years in which data was not collected for unknown reasons (Permanent Service for Mean Sea Level, National Oceanography Center, UK)*

aeolian transport. The formation of coastal dunes reflects the volume of sand on nearby beaches, with sediment levels dependent on whether sea level is rising or falling relative to the land (Orme 1988). When sea level falls, large quantities of sediment are exposed on emergent continental shelves thus becoming available for the development of thick and extensive coastal dunes (Orme 1988, 1992). During periods of sea level rise, beaches migrate up continental shelves and erode material, thus restricting the amount of sediment available for dune building (Orme, 1988). Mean sea level data for the California coast shows an average increase of 172 mm from 1946 to 2016 (Figure 16). While this change is relatively small, it does indicate that there may have been a minor reduction in available sediment over this period. This trend has probably been further exacerbated by the very rapid short-term losses of beach. In 2006, a USGS study reported the maximum short-term erosion rate along the coast of Guadalupe Dunes at -6.7 m/yr^{-1}, which was the highest short-term rate in California (Hapke et al. 2006).

Climate Data

The mobility of sand dunes may be related to short term changes in weather and climate. Mobility increases during periods of aridity (drought), while stability is encouraged by vegetation growth which occurs during wet phases (Tsoar 2001). Precipitation and drought data were used to depict the five wettest and driest years for Santa Maria from 1954 until 2016 (Table 1). Strong El Niño conditions occurred in 1982-83 and 1997-98, which coincided with the two wettest years. Historic drought conditions

Santa Maria Station #380

Rank	Year	Rain		Rank	Year	Rain
1	1997-98	32.61"		1	2013-14	4.97"
2	1982-83	25.26"		2	2006-07	5.60"
3	2010-11	24.48"		3	1971-72	5.69"
4	1977-78	22.95"		4	1989-90	5.94"
5	1994-95	21.66"		5	2012-13	6.52"
	Normal	13.31"			Normal	13.31"
	Wettest Years				Driest Years	

***Table 1**. Graph depicting the wettest and driest years for the period of 1954 to 2016 with rainfall amounts for Santa Maria. A water year is from September to August. (County of Santa Barbara Public Works 2014)*

occurred in 1987-92, 2007-09, and 2012-2016 (California Department of Water Resources 2015).

A wind rose depicting wind speed and direction for Santa Maria is shown in Figure 17. The dominant wind direction is primarily from the northwest with average speeds in the 2.10 -3.60 m/s^{-1} range. These measurements are taken at a station 18 km inland of the dunes complex, and are thus not very representative of coastal wind speeds

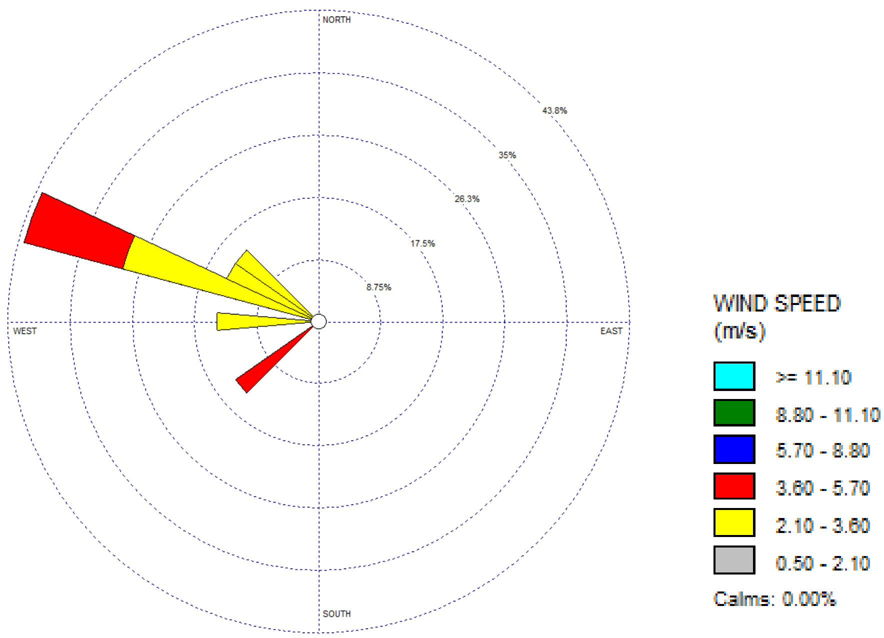


Figure 17. *Wind rose depicting average wind speed measured at the Santa Maria Municipal Airport (WRPLOT)*

although the dominant wind direction is accurate. Dune shape is a manifestation of a long-term average of wind conditions; transverse and parabolic dunes are prevalent in regions with a unimodal wind direction, depicted in Figure 18 (Tsoar 2001).

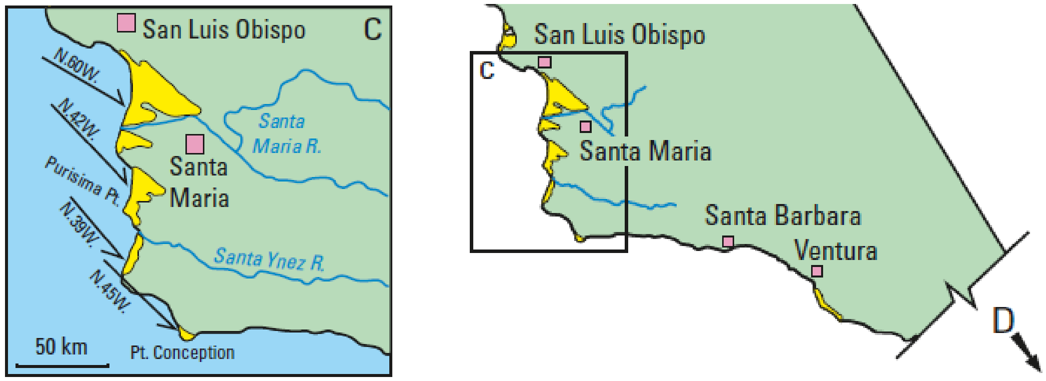


***Figure 18**. Map showing wind direction in relation to the Mussel Rock dunes complex (Hapke et al. 2006)*

Sediment Budget Data

Annual aeolian sediment transport from the beaches to the dunes is 19,878 m^3 (Bowen and Inman 1966). The annual sediment discharge from the Santa Maria River (with dam) is 199,000 m^3/yr. (Hapke et al. 2006). An estimated 620,000 m^3/yr. (Willis and Griggs 2003) of sediment would naturally flow to the coast if the dam was not present. Taking the 19,878 m^3/yr. (Bowen and Inman 1966) of annual sediment transport from the beaches to dunes and combining it with the 199,000 m^3/yr. (Hapke et al. 2006) of annual sediment discharge from the Santa Maria River (with dam), results in a possible annual estimated 218,878 m^3/yr. of sediment coming into the dunes. Attempts to quantify sediment movement between offshore areas and beaches is one of the more difficult parameters to measure accurately and no data exists for the study area (Bowen and Inman 1966, Patsch and Griggs 2006). The difference between the annual amount of sediment

	Santa Maria River	Beaches to Dunes	Total
Sediment into dune field with dam	199,000 m^3/yr.	19,878 m^3/yr.	218,878 m^3/yr.
Sediment into dune field without dam	620,000 m^3/yr.	19,878 m^3/yr.	639,878 m^3/yr.
		Difference	421,000 m^3/yr.

***Table 2**. Table demonstrating estimated annual sediment deficit into the dune complex (Bowan and Inman 1966, Willis and Griggs 2003, Hapke et al. 2006)*

coming into the dunes with and without Twitchell Dam (Table 2) leaves an estimated deficit of 421,000 m^3/yr., or 66% of the original sediment supply. This represents a substantial overall net loss of sediment into the dune field.

Aerial Imagery Analysis

The region of the transverse and parabolic dunes are where the most noticeable changes have taken place within the study time frame is highlighted within the red circle on the images (Figures 19a-g). Blue arrows further indicate the areas where the transverse dune area is decreasing and the parabolic dune area is increasing. This is evident through observation of the areas of bare sand (transverse dunes) and the areas of vegetation (parabolic dunes).

Figure 19a. *1954 baseline image (University of California, Santa Barbara Map & Imagery Library)*

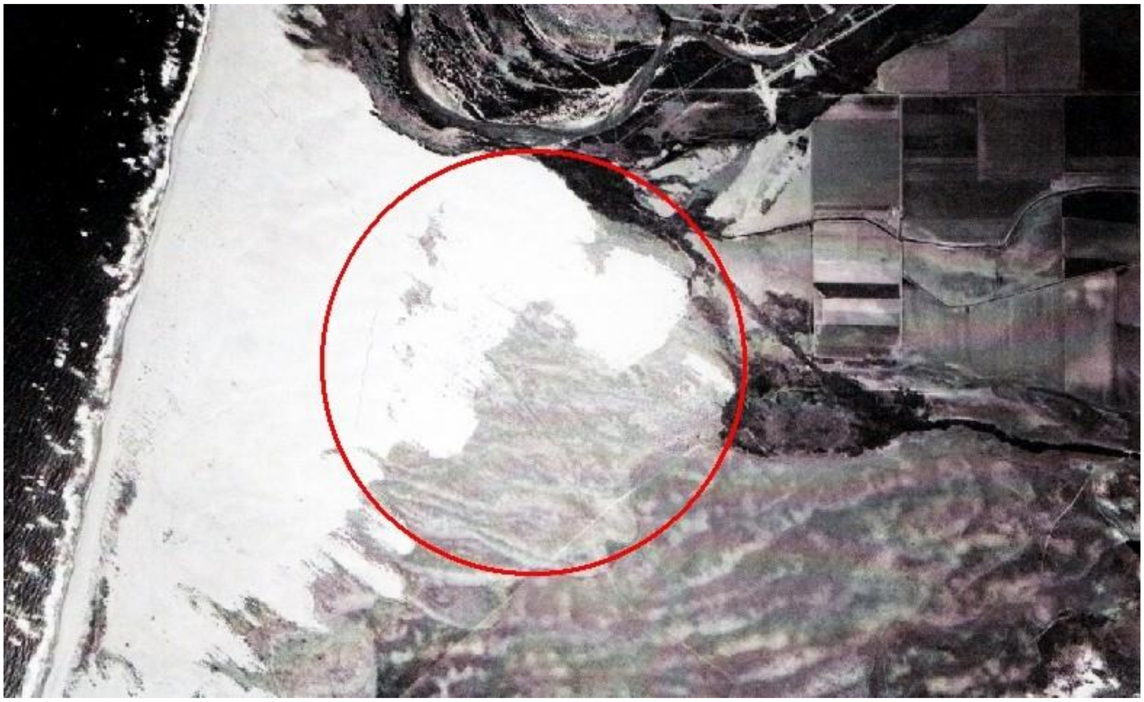


Figure 19b. *1961 image (University of California, Santa Barbara Map & Imagery Library)*

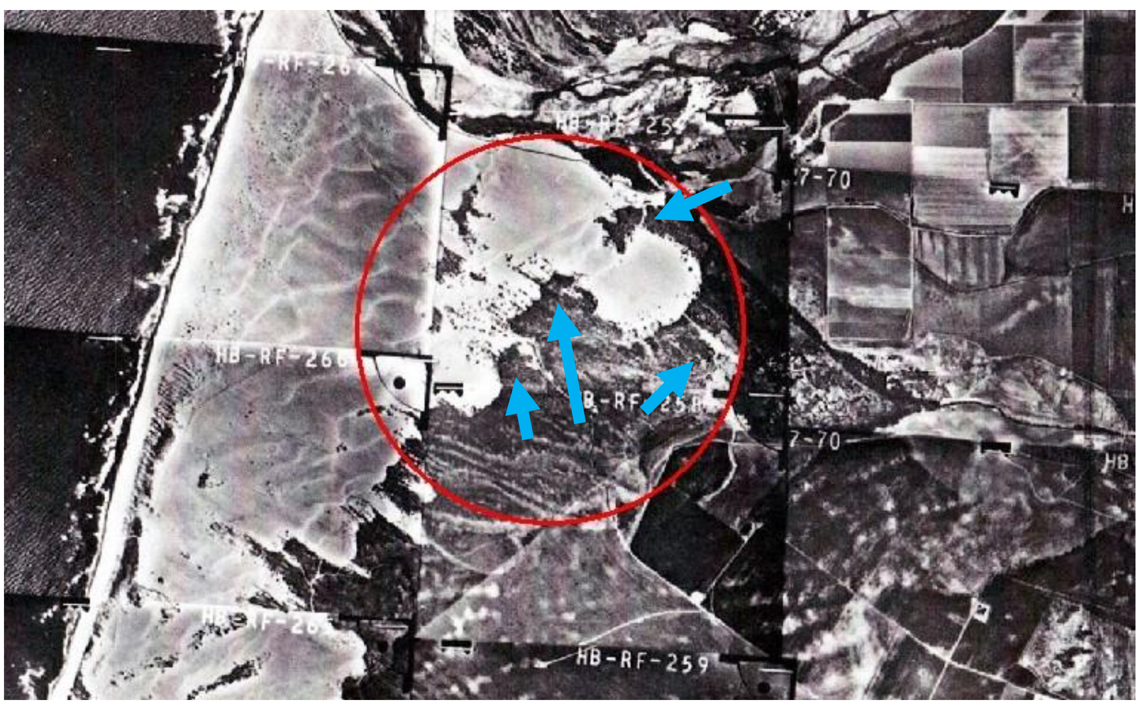


Figure 19c. *1970 image with blue arrows demonstrating initial areas of change (University of California, Santa Barbara Map & Imagery Library)*

Figure 19d. *1984 image showing continued increase in the parabolic dune region (Google Earth)*

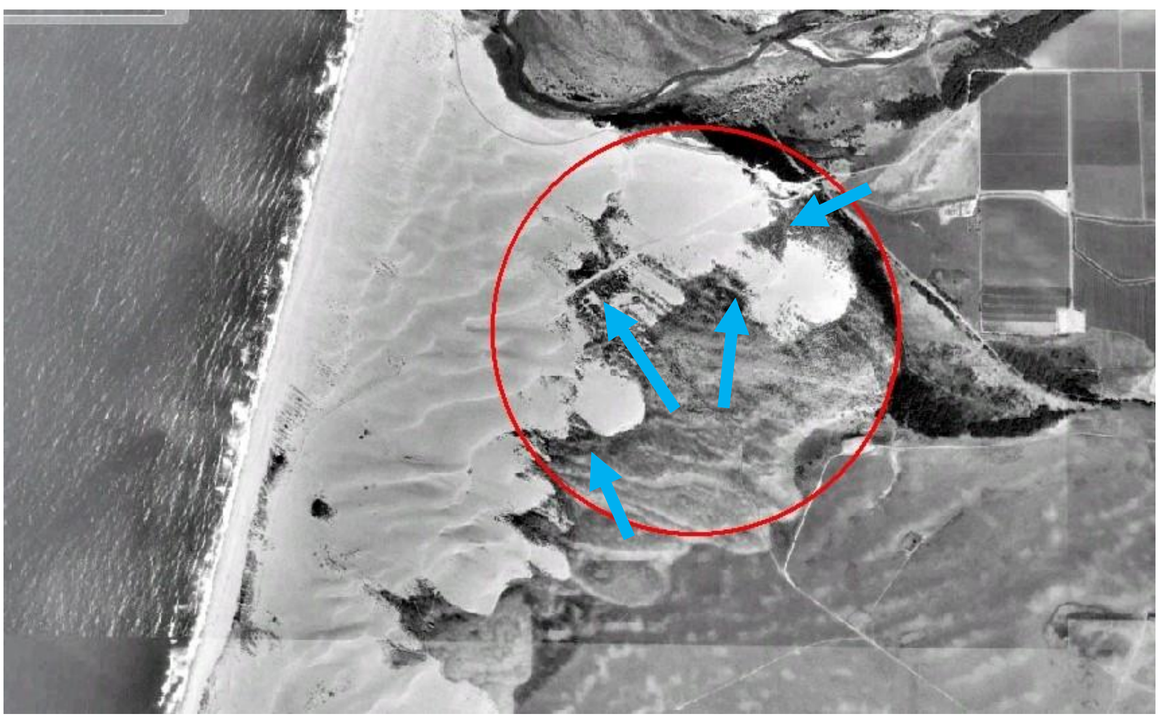


Figure 19e. *1994 image showing more parabolic advancement in the lower and central study area (Google Earth)*

Figure 19f. *2006 image showing greater changes in the central area (Google Earth)*

Figure 19g*. 2016 image. The transverse dunes have significantly decreased in area (Google Earth)*

Discussion

Analysis of the dune field measurements and aerial imagery revealed findings consistent with the sediment deficit caused by the construction of the Twitchell Dam. In the active transverse dunes, an increase of 0.1 km^2 was noted post-dam from 1961 to 1970. This increase could have resulted from pre-dam sediment remaining in the lagoon at the mouth of the Santa Maria River (sediment transport by rivers can be stored in the stream channel, flood plain, or estuary at the stream mouth (Willis et al. 2002), where it ultimately became available for transport back into the littoral sediment budget. Total transverse area remained at 5.2 km^2 in the 1984 photo, but began decreasing steadily in 1994, 2006 and 2016. Transverse dune systems grow by accumulation of sediment and tend to systematically transport sediment inland, away from the beach (Rust and Illenberger 1996). A side by side comparison of the 1954 and 2016 images (Figure 20) revealed changes in the transverse dune field outside of the circled study area. Green

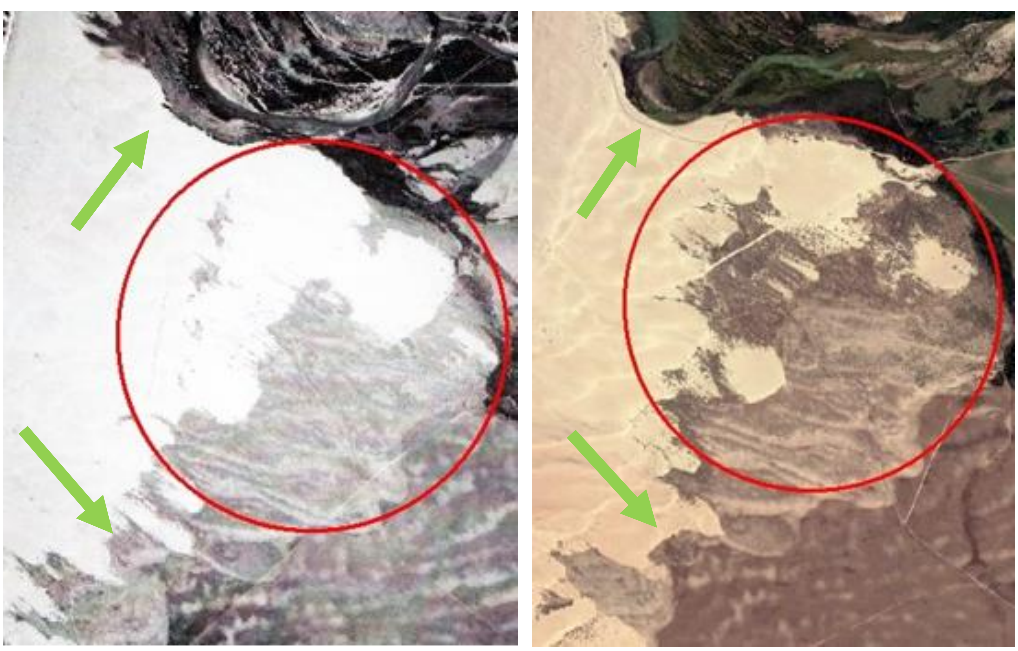


***Figure 20**. Comparison of the 1954 (left) and 2016 (right) images (University of California, Santa Barbara Map & Imagery Library, Google Earth)*

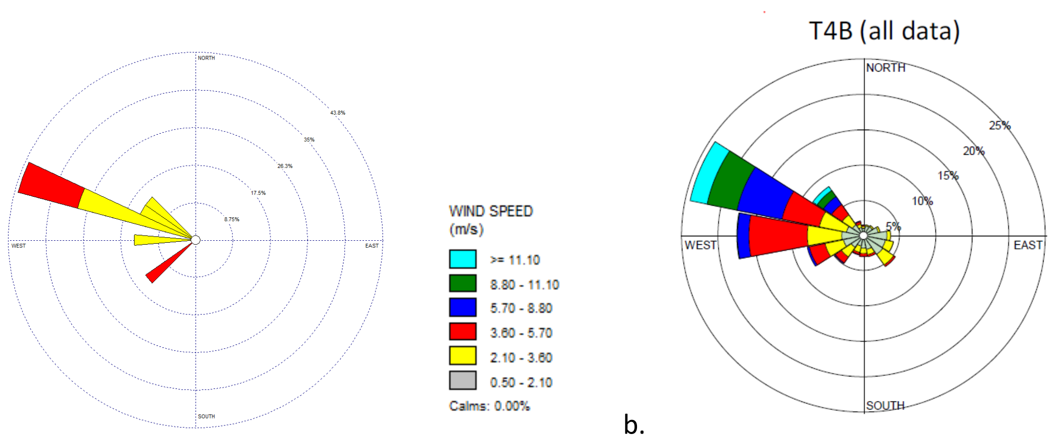
arrows indicate the areas of change. The Santa Maria River to the north has migrated and removed some of the transverse dune field (reduction in area) while there is an eastward migration of the active dune field in the southern section (increase in area). Based on areal measurements, the overall net result was shown to be a decrease in dune extent. Transverse dunes tend to develop in environments with a plentiful supply of sediment. The eastward migration may be the result of dune sands being eroded by waves and contributing to the beach (in a reverse flow of sediment), where it then becomes available for aeolian transport back into the dune field (Hapke et al. 2006).

In the parabolic dunes, total area remained steady between 1954 and 1961 and there does not appear to be a noticeable difference in vegetation cover and extent within the aerial imagery during this time. An 0.1 km^2 decrease of total parabolic dune area was noted in 1970, before total area began to rise steadily. This change was not clearly identifiable on the aerial imagery and could most likely be an error in measurement of the dune field. Vegetation cover within the parabolic dune field also began to increase and is evident in all subsequent photos. The increase in parabolic dune area is consistent with vegetation growth resulting from a lack of available sediment; its response to aeolian activity will ultimately dominate the dune development (Van Dijk et al. 1999). This could also signify that the transverse dunes are migrating inland into the vegetation, transforming into parabolic dunes from lack of sediment, and becoming more stabilized as the vegetation increases (Hesp 2013). It has been shown that dune dimensions reflect the proportion of wind velocities above the threshold values (speeds usually over 6 m s^{-1} (Bagnold 1941, Bauer et al. 2009, Davidson-Arnott 2010)) for the sediment available and, as sediment supplies decrease, dune form changes from transverse to parabolic (Orme 1988).

A 172mm (6 in.) increase in mean sea level was noted over the 70-year period of the study. Most short-term sea level changes to coastal beaches are the result of seasonal tidal cycles and wave action from intense storms as the width of exposed beach narrows, and sediment supply becomes restricted (Patsch and Griggs 2006). Although long-term sea level changes (over thousands of years) are an important factor in large-scale dune development or suppression (Cooper 1967, Orme 1992), the amount of rise within the time frame is not significant enough to have generated the differences observed within the transverse and parabolic dune regions.

The precipitation data did not reveal any clear identifiable events that would influence parabolic and transverse dune area. No major precipitation or drought events occurred between 1954 and 1970, although transverse dune area increased. Parabolic dune area remained the same until 1970, when it decreased by 0.1 km^2. A dry year occurred in 1971-72, followed by two wet events in 1977-78 and 1982-83. In 1984, transverse area remained steady but the parabolic dune area increased. In 1994 through 2016, transverse area decreased, while parabolic area increased despite heavy rains in 1994-95, 1998-78, 2010-11; and dry periods in 1989-90, 2012-13, and 2013-14. Two major El Niño conditions occurred in 1982-83 and 1997-98; however, the increase in precipitation from these events is unlikely to have been a factor for the increase of vegetation cover in the parabolic dunes as vegetation can grow on dunes in arid areas with very minimal rainfall (Tsoar 2001).

Wind speed data obtained at the Santa Maria Airport station may not be highly representative of that within the Mussel Rock dune complex, although the direction is reasonably accurate. Average yearly wind speed data obtained for 1954, 1961, 1970, 1984, 1994, 2006 and 2016, showed wind speeds of 2.10-3.60 m/s^{-1} out of the west and northwest. Bagnold (1941) demonstrated that sediment transport in dune systems takes place at wind speeds of 6 m/s^{-1} and greater. The Oceano Dunes State Vehicular Recreational Area (ODSVRA) study (2013), which was referenced earlier, placed anemometers directly in the Oceano Dunes (approximately 10 km north of the study area) from May to July, and reported average wind speeds above 5.7m/s^{-1} and directions from the west and northwest. A comparison of the wind speeds between the Santa Maria Airport (a) and the ODSVRA study (b) is shown in Figure 21.



a. b.

Figure 21*. Wind roses for the inland Santa Maria Airport (a) and for the coastal ODSVRA study (b) demonstrating differences in wind speeds. T4B stands for transect 4B which was the closest anemometer location to the Mussel Rock complex (WRPLOT, Etyemezian and Gillies 2013)*

Although the average wind speeds at ODSVRA are more reflective of coastal wind speeds, the topography where the station was located is relatively flat as compared to the steeper slopes of the transverse dune field at Mussel Rock. Winds can show a tendency to speed up as they move from west to east, most likely due to compression of the streamlines over the dunes that force the wind to accelerate (Etyemezian and Gillies 2013). The Mussel Rock complex lies partly on the floodplain of the Santa Maria River, but gradually increases in elevation onto Mussel Rock and Orcutt Mesa. To properly analyze the effect of aeolian sediment transportation within the Mussel Rock Dune Complex, future studies should measure wind speed and direction from directly within the dunes and take into account topographic acceleration and variability within the field.

Conclusion

The transverse and parabolic dunes within the Mussel Rock dunes complex are undergoing continuous changes brought on by the construction of Twitchell Dam, sand mining, and high rates of short-term beach erosion (Hapke et al. 2006). Multiple studies (Willis et al. 2002, Petts and Gurnell 2005, Slagel and Griggs 2006, Gordon and Meentemeyer 2006) have demonstrated that dams along coastal rivers significantly reduce the long-term natural rates of fluvial sediment delivery to the coastline and littoral cells and, ultimately on the beach. Thus, aeolian transport from the beaches into the dune system may be greatly reduced. Additionally, under conditions of rising sea level, it is also possible that the dune sands may be eroded by waves and contribute to the beach, in a reverse flow of sediment (Hapke et al. 2006). Aerial imagery analysis indicates that the transverse dune region is decreasing in area, consistent with these changes in sedimentary supply and loss. By contrast, the region of vegetated parabolic dunes appears to be increasing in area.

Research on coastal dunes in other areas of the world indicates that transverse dunes dominate where there are large amounts of sediment, while parabolic dunes are more prevalent where less sediment is available (Goudie 2011). There is evidence at the Mussel Rock complex to suggest that transverse dunes are migrating into vegetated areas and forming parabolic dunes, with the parabolic development becoming more pronounced. It is likely that the original parabolic dunes located inland within the Mussel Rock complex were derived from previously active transverse dunes (Yan and Baas 2015). The eastward migration of dunes in the southern transverse dune section may be related to an increase in sediment; as the Santa Maria River meandered southward, it removed sand from the northern fringe of the transverse dune field. Transported southward by littoral drift, this sand may have been moved back onto the beach, and become available for aeolian transport back into the dune field (Hapke et al. 2006). Over time, it is likely that continued sediment entrapment from the Twitchell Dam, sand mining, river and beach erosion, and sea level rise will further reduce the area of transverse dunes. The impact of these factors on parabolic dunes is less clear, as this vegetation-dependent dune form is also affected by available moisture, both from precipitation and ground water systems. Short-term changes to water availability, either through drought or drawdowns in the water table, are more difficult to anticipate.

Works Cited

Aagaard, Troels, Robin Davidson-Arnott, Brian Greenwood, and Jorgen Nielsen. 2004. "Sediment Supply from Shoreface to Dunes: Linking Sediment Transport Measurements and Long-Term Morphological Evolution." *Geomorphology* 205-224.

Adelman, Kenneth, and Gabrielle Adelman. 2017. *California Coastal Records Project.* Accessed March 10, 2017. http://www.californiacoastline.org/.

Bagnold, R.A. 1941. *The Physics of Blown Sand and Desert Dunes.* London: Methuen.

Bauer, B. O., R. G.D. Davidson-Arnott, P. A. Hesp, S. L. Namikas, J. Ollerhead, and I. J. Walker. 2009. "Aeolian sediment transport on a beach: Surface moisture, wind fetch, and mean transport." *Geomorphology* 106-116.

Bowen, A. J., and D. L. Inman. 1966. *Budget of Littoral Sands in the Vicinity of Point Argello, California.* Berkeley: University of California.

California Department of Water Resources. 2015. *California's Most Significant Droughts: Comparing Historical and Recent Conditions.* Sacramento: Department of Water Resources.

Clark, Bill. 2017. *Earth Point.* Accessed March 15, 2017. http://www.earthpoint.us/Default.aspx.

Commission, California Coastal. 1987. *California Coastal Resource Guide.* Berkeley: University of California Press.

Cooper, William S. 1967. *Coastal Dunes of California.* Boulder: The Geological Society of California.

County of Santa Barbara Public Works. 2014. *County of Santa Barbara Public Works Historical Rianfall Information.* February 28. Accessed April 13, 2017. http://cosb.countyofsb.org/pwd/pwwater.aspx?id=3772.

Davidson-Arnott, Robin G.D., Yanqi Yang, Jeff Ollerhead, Patrick A. Hesp, and Ian J. Walker. 2008. "The Effects of Surface Moisture on Aeolian Sediment Transport Threshold and Mass Flux on a Beach." *Earth Surface Processes and Landforms* 55-74.

Davidson-Arnott, Robin. 2010. *Introduction to Coastal Processes and Geomorphology*. Cambridge: Cambridge University Press.

Delgado-Fernandez, Irene. 2011. "Meso-scale modelling of aeolian sediment input to coastal dunes." *Geomorphology* 230-243.

Dong, Zhibao, Qingsong Mu, and Xiaopiu Liu. 2007. "Defining the Threshold Wind Velocity for Moistened Sediments." *Journal of Geophysical Research* 1-10.

Eastwood, Erin, Joanna Nield, Andreas Baas, and Gary Kocurek. 2011. "Modelling controls on aeolian dune-field pattern evolution." *Sedimentology* 1391-1406.

Eley, Donald S., and Jeffrey R. Knott. 2006. "Early to Middle Holocene Coastal Dune and Estuarine Deposition, Santa Maria Valley, California." *Physical Geography* 127-136.

Esri, Digital Globe. 2017. *World Imagery.* March 20.

Esri, USGS. 2017. *World Topographic Map*. March 30.

Etyemezian, V., and J. A. Gillies. 2013. *Wind and PM10 Characteristics at the ODSVRA from the 2013 Assessment Monitoring Network.* Las Vegas: Division of Atmospheric Sciences, Desert Research Institute.

Gordon, Eric, and Ross K. Meentemeyer. 2006. "Effects of dam operation and land use on stream channel morphology and riparian vegetation." *Geomorphology* 412-429.

Goudie, Andrew. 2011. "Parabolic Dunes: Distribution, Form, Morphology and Change ." *Annals of Arid Zone* 1-7.

Hapke, Cheryl J., David Reid, Bruce M. Richmond, Peter Ruggiero, and Jeff List. 2006. *National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast.* Open-File Reoprt 2006-1219, Washington, DC: U.S. Geological Survey.

Hearon, Greg, Craig Leidersdorf, and Peter Gadd. 2002. *California Beach Restoration Study*. sacramento: California Department of Boating and Waterways and State Coastal Conservancy.

Hesp, Patrick A. 2013. "Conceptual models of the evolution of transgressive dune systems." *Geomorphology* 138-149.

Hesp, Patrick. 2002. "Foredunes and blowouts: initiation, geomorphology and dynamics." *Geomorphology* 245-268.

Johnson, J. W. 1963. *Sand Movement on Coastal Dunes.* Berkeley: University of California.

Lancaster, Nicholas, and Andy Baas. 1998. "Influence of Vegetation Cover on Sand Transport by Wind; Field Studies at Owens Lake, California." *Earth Surface Processes and Landforms* 69-82.

LFR. 2006. *Morro Bay Harborwalk- Coastal Dune Scrub Restoration and Enhancement.* Morro Bay: The City of Morro Bay.

MacDonald, Beau, Travis Longcore, and Shawna Dark. 2010. *Habitat Suitability Modeling for Western Snowy Plover in Central California.* Los Angeles: The Urban Wildlands Group.

Mangimeli, John. 2007. "Geology of Sand Dunes." *Geology od Sand Dunes.* September 10. Accessed March 13, 2017. http://www.nps.gov/whsa/naturescience/upload/Geology%20of%20Sand%20Dunes.pdf.

McCrory, Patricia A., Douglas S. Wilson, James C. Ingle, and Richard G. Stanley. 1995. "Neogene Geohistory Analysis of Santa Maria Basin, California, and Its Relationship to Transfer of Central California to the Pacific Plate." *U.S. Geological Survey Bulletin* 1-35.

McKee, Edwin D. 1979. *A Study of Global Sand Seas.* Geological Survey Professional Paper, Washington, D.C.: U.S. Government Printing Office.

National Climactic Data Center. 2017. *Local Climatological Data Publication.* March 8. https://www.ncdc.noaa.gov/IPS/lcd/lcd.html?_page=1&state=CA&stationID=23273&_target2=Next+%3E.

National Oceanography Centre. 2017. *Permanent Service for Mean Sea Level.* February 02. Accessed March 10, 2017. http://www.psmsl.org/data/obtaining/stations/508.php.

Nickling, William G., and Robin G.D. Davidson-Arnott. 1990. "Aeolian Sediment Transportation on Beaches and Coastal Sand Dunes." *Proceedings Canadian Symposium on Coastal Sand Dunes.* Guelph: University of Guelph, Department of Geography. 1-35.

Orme, Antony R. 1988. "Coastal Dunes, Changing Sea Level, and Sediment Budgets." *Journal of Coastal Research* 127-129.

Orme, Antony R. 1992. "Late Quaternary Deposits Near Point Sal, South-Central California: A Time Frame For Coastal-Dune Development." *Society for Sedimentary Geology (SEPM)* 309-315.

Parteli, E. J.R., V. Schwammle, H. J. Herrmann, L. H.U. Monteiro, and L. P. Maia. 2006. "Profile measurement and simulation of a transverse dune field in the Lencois Maranheses." *Geomorphology* 1-26.

Patsch, Kiki, and Gary Griggs. 2007. *Development of Sand Budgets for California's Major Littoral Cells.* Santa Cruz: Institute of Marine Sciences, University of California, Santa Cruz.

Patsch, Kiki, and Gary Griggs. 2006. *Littoral Cells, Sand Budgets, and Beaches: Understanding California's Shoreline.* Santa Cruz: Institute of Marine Sciences, University of Californis, Santa Cruz.

Petts, Geoffrey E., and Angela M. Gurnell. 2005. "Dams and geomorphology: Research progress and future directions." *Geomorphology* 27-47.

Rust, Izak C., and Werner K. Illenberger. 1996. "Coastal dunes: sensitive or not?" *Landscape and Urban Planning* 165-169.

Rutledge, Kim, Melissa McDaniel, Diane Boudreau, Tara Ramroop, Santani Teng, Erin Sprout, Hilary Costa, Hilary Hall, and Jeff Hunt. 2011. *Fog- National Geographic Society Encyclopedia.* January 21. Accessed April 12, 2017. http://www.nationalgeographic.org/encyclopedia/fog/.

Science Applications International Corporation, Moffatt & Nichol Engineers, Swanson Hydrology and Geomorphology, MNS Engineers. 2004. *Santa Maria River Estuary Enhancement and Management Plan.* Santa Maria.

Service, U.S. Fish and Wildlife. 2016. *Guadalupe-Nipomo Dunes National Wildlife Refuge Final Comprehensive Conservation Plan and Environmental Assessment.* San Luis Obispo: U.S.Fish and Wildlife Service.

Slagel, Matthew, and Gary Griggs. 2006. *Cumulative Losses of Sand to the California Coast by Dam Impoundment.* Santa Cruz: Institute of Marine Sciences, University of California, Santa Cruz.

Smith, Kent A. 1976. *The Natural Resources of the Nipomo Dunes and Wetlands.* California Department of Fish and Game, U.S.Fish and Wildlife Service.

Tetra Tech. 2010. *Santa Maria Valley Watershed Characterization for Hydromodification Management Within the City of Santa Maria.* Santa Maria: City of Santa Maria Utilities Department.

The University of Texas at Austin. 2006. *The Texas High School Coastal Monitoring Program.* November 13. Accessed April 3, 2017. http://www.beg.utexas.edu/coastal/thscmp/fg_mustang_3.htm.

Tsoar, H. 2005. "Sand dunes mobility and stability in relation to climate." *Physica A* 50-56.

Tsoar, H. 2001. "Types of Aeolian Sand Dunes and Their Formation." *Lecture Notes in Physics* 403-429.

Twitchell Management Authority. 2010. *Twitchell Project Manual.* Santa Maria: Santa Maria Valley Water Conservation District.

U.S. Fish & Wildlife Service. 2009. *Guadalupe-Nipomo Dunes National Wildlife Refuge.* August 21. http://www.fws.gov/hoppermountain/GuadalupeNDNWR/GuadalupeNipomoDunesNWR.html.

Van Dijk, P. M., S. M. Arens, and J. H. Van Boxel. 1999. "Aeolian Processes Across Transverse Dunes. II: Modeling the Sediment Transport and Profile Development." *Earth Surface Processes and Landforms* 319-333.

Wiggs, G. F.S., A. J. Baird, and R. J. Atherton. 2004. "The dynamic effects of moisture on the entrainment and transport of sand by wind." *Geomorphology* 13-30.

Willis, Cope M., and Gary B. Griggs. 2003. "Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability." *The Journal of Geology* 167-182.

Willis, Cope, Brian Lockwood, and Doug Sherman. 2002. *California Beach Restoration Study*. Sacramento: Department of Boating and Waterways and State Coastal Conservancy.

Yan, Na, and Andreas C.W. Baas. 2015. "Parabolic dunes and their transformations under environmental and climatic changes: Towards a conceptual framework for understanding and prediction." *Global and Planetary Change* 123-148.