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Sea Level Rise and Coastal Erosion: A Cost-Benefit Analysis of Three Leading Management Techniques for San Luis Obispo County

Introduction:

This study investigates the most effective means of combatting sea level rise (SLR) and coastal erosion in San Luis Obispo County (SLOC). We will propose viable options for SLOC based on similar case studies and various cost-benefit analyses. Climate change is widely accepted by the scientific community and is a direct cause of SLR (Nicholls & Cazenave 2010). There are two main contributing factors to rising sea levels: thermal expansion of seawater due to an increase in ocean temperature, and water inputs from land ice melts (glaciers) and land water reservoirs (Nicholls & Cazenave 2010). The global mean sea level increased by approximately 20 cm in the 20th century alone and is expected to accelerate in the coming century (Russell 2014). The warming climate due to greenhouse gases could result in a global SLR of about two-to-seven feet (50-200 cm) in the next century (Titus et al. 2008). Consequences of SLR include but are not limited to: saltwater intrusion, habitat destruction and disappearance of coastal wetlands, coastal erosion, property damage, and infrastructure collapse leading to negative economic impacts (Nicholls & Cazenave 2010). These issues are of critical importance for human populations because ~10% of the world population reside in low-elevation coastal zones (<10m in elevation) (Nicholls & Cazenave 2010).

At present, ~80-90% of sandy beaches in the U.S., including those on the coast of Central California, are experiencing erosion due to rapid SLR (Leatherman 2007). Much of the Central Coast is coastal rocky cliff. Coastal cliff erosion rates are estimated at ~15-30 cm/year for sedimentary rocks similar to those seen in San Luis Obispo County (Committee on Sea Level Rise in California, Oregon, and Washington et al. 2012). Coastal cliff and bluff erosion is caused primarily from wave energy and wave impact. Tidal range, sea level variations, rainfall, runoff, groundwater seepage, and/or landslides also contribute to cliff erosion (Committee on Sea Level Rise in California, Oregon, and Washington et al. 2012). SLR leads to waves breaking closer and closer to the coastline and reaching the bases of coastal cliffs more frequently, thereby increasing the rate of cliff retreat (Committee on Sea Level Rise in California, Oregon, and Washington et al. 2012). Cliff retreat is an episodic and irreversible process in which large blocks suddenly fail under heavy rainfall, large waves during a storm event, or earthquakes (Committee on Sea Level Rise in California, Oregon, and Washington et al. 2012). Specific to San Luis Obispo County, there are ~4600 people vulnerable to a 100-year flood (at the sea-level in the year 2000) and ~6300 people vulnerable to a 100-year flood with a 1.4m increase in sea-level (Heberger et al. 2011). A 100-year flood is a term applied to a flood that has a 1% chance of occurrence in any year. These calculations were made with projections from NOAA and IPCC that indicate the sea level will rise as much as 1.4m by the year 2100.

Currently, there are three viable options for combating coastal erosion. (1) Seawalls, or physical barriers made of concrete or rock constructed to protect private or public property and infrastructure. (2) Beach nourishment, a method of pumping, dredging, or transporting sand from offshore sites or other sites with a surplus of sand to areas that are suffering from coastal erosion. (3) Managed retreat, an adaptation strategy that is usually employed as a last-ditch effort in which property and infrastructure are relocated and moved inland with the rising sea level. This paper will explore these three options for coastal erosion management and attempt to provide a means for determining the most economic and environmentally sound strategies for combatting SLR and coastal erosion on the Central Coast.

Seawalls:

Seawalls offer immediate, although relatively short term, protection for coastal properties. They are favored by many private property owners because they are relatively cheap and follow traditional permitting processes of local permitting agencies (Collaboration: Sea-level Marine Adaptation Response Team (C-SMART) et al. 2015). However, seawalls tend to modify natural processes by introducing exotic and more stable habitats (concrete) into formerly dynamic areas (sandy beach) (Nordstrom 2013). In other words, they alter the natural flow of sediment in sandy beach habitats. These manmade structures reduce the capability of many species to settle on them due to their flat vertical surface, and they decrease the overall area of intertidal habitats (Nordstrom 2013). While seawalls offer spatially precise quick-fixes, they do not solve many of the long-term effects of SLR. These long-term impacts include but are not limited to: increased erosion, decrease in sandy beach habitats, and a disappearance of coastal wetlands (Nichols, Cazenave 2010).

Coastal wetlands are important ecological habitats (saltmarshes, mudflats, mangroves, estuaries, etc.) such as the large mudflat located in Morro Bay. These wetlands provide habitat for birds and juvenile fish, produce important organic materials, and provide crucial habitat for many specialized organisms (Titus et al. 2008). Saltwater intrusion, a process in which rising sea levels leads to an increase in salinity of wetland habitats, is harmful to many aquatic plants and animals, and could threaten human use of freshwater (Titus et al. 2008). This process is also a concern because of the potential for septic system failures and groundwater contamination from saltwater or sewage due to an increase in SLR that in turn increases the elevation of the water table (usgs.gov 2014). Coastal wetlands collect sediments and produce peat, a soil-like material of partially decomposed plant material that accumulates in water-saturated environments in the absence of oxygen (Titus et al. 2008). Because of the accumulation of peat and sediments from watersheds, wetlands can usually keep pace with SLR under natural conditions (Titus et al. 2008). Seawalls erected above wetlands squeeze them between the rising sea and the seawall itself, resulting in a loss of these ecologically significant habitats (Titus et al. 2008). This "squeeze" effect coupled together with the increasing rate of SLR could result in complete loss of coastal wetland habitats. (Figure 1)

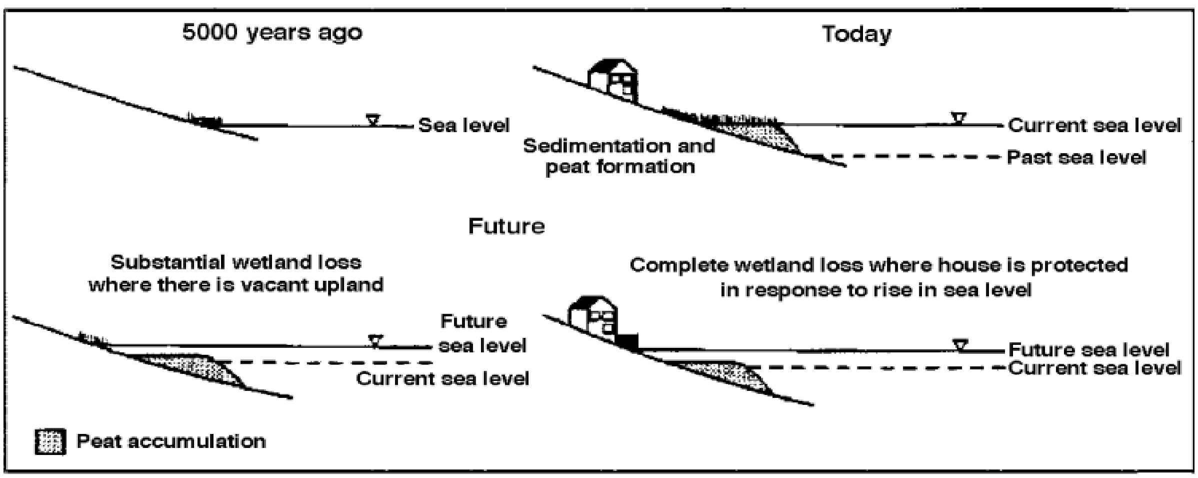

Figure 1. *Effect of SLR on wetland with and without a seawall. Coastal wetlands in the past have been able to keep pace with ambient SLR, however if future rates of SLR continue to increase, substantial loss of wetlands would occur. Construction of seawalls prevent new wetlands from forming inland as new lands are inundated by SLR, resulting in complete loss compared to substantial loss without seawalls. Figure taken from Titus et al. 2008.*

An estimated 10% of the California coastline has been armored, meaning these stretches of coastline have seawalls or similar hard structures in place to protect them against coastal erosion (Committee on Sea Level Rise in California, Oregon, and Washington et al. 2012). However, even with increased protection, coastal storm damage has increased over the past several decades due to intense development leading to the elimination of natural storm defenses (coastal wetlands, plant root structures, topographically complex coastline) and more frequent and severe storms, including major El Nino Southern Oscillation events. (Committee on Sea Level Rise in California, Oregon, and Washington et al. 2012). Seawalls and other hard structures may cause increased erosion on beaches down current from them because they impede the movement of sand via longshore transport (Speybroeck et al. 2006). Longshore transport is the overall net movement of sand parallel to the shore from tidal, wind, and wave energy (Seymour 2005). Active erosion is when seawalls prevent longshore transport and other beach-building processes, however, this was determined to be insignificant in a study of seawalls along the coast of Monterey Bay (Griggs 2010). Passive erosion is when the shoreline on either side of a protective structure naturally migrates inland, resulting in a loss of beach immediately in front of the structure (Griggs 2010). Passive erosion was considered a significant long-term effect in the Monterey Bay study (Griggs 2010). A similar effect would be expected along the coast of SLOC. Furthermore, seawalls are designed for a specific set of wave and (current) sea level conditions, if SLR continues to accelerate, overtopping of seawalls will become increasingly frequent (Titus et al. 2008). Overtopping results in damage to the structures that the seawalls are intended to protect, and may result in further structural damage to the seawall itself (Zviely et al. 2015).

Seawalls can be altered to add habitat complexity and minimize negative effects on native habitats such as limited settlement area and increased exposure. Adding surface complexity by building seawalls out of rough or pitted materials instead of smooth and flat materials increases total habitat surface area and leads to an increase in biodiversity on the structure (Nordstrom 2013). These pits and crevices in the seawall surface prove increasingly significant to intertidal species as they create refuges from desiccation and predation, provide insolation from environmental stresses, and increase overall surface area for fauna to inhabit as natural intertidal habitats are destroyed by SLR (Nordstrom 2013). Although these strategies minimize the ecological impact of seawall construction, the disappearance of intertidal and sandy beach habitats is a similar process to that of the loss of wetlands. Existing habitats are flooded by SLR and have no means to migrate inland as they are squeezed against seawalls resulting in total loss (Titus et al. 2008). These consequences result in financial losses due to a decrease in recreational activity and natural resources, as observed in the disappearance of beaches along the Malibu coastline in Southern California during winter beach conditions (Griggs 2010). These observed decreases in coastal access contradict the Coastal Act passed in 1976, a major proponent in preserving public coastal access in the face of increasing beachfront developments (Griggs 2010).

In conclusion, seawalls protect against wave damage and erosion, can be constructed in small spaces, and can be made to blend into natural surroundings. They can be easily implemented because they follow traditional permitting processes of local permitting agencies such as the California Coastal Commission (C-SMART et al. 2015). Costs of seawalls and similar hard structures are site-specific and have been estimated to cost, on average, $5300 per linear foot (King et al. 2011). Annual maintenance costs may range from ~1-4% of the initial cost of construction (King et al. 2011). Seawalls tend not to be favored by regulatory agencies and other stakeholders that prioritize natural resources as they can result in a negative net cost from the loss of recreational and natural value (when compared to the cost of construction of the structures). Seawalls also represent visual impacts, could negatively impact public coastal access, accelerate coastal erosion up to the structure, and require frequent maintenance or even reconstruction (C-SMART et al. 2015).

Managed Retreat:

Another strategy to dampen the effects of SLR and damage to infrastructure and habitat by coastal erosion is managed retreat. Managed retreat, sometimes referred to as managed realignment/adaptation, is a policy in which property and infrastructure are methodically migrated inland as the coastline retreats with rising sea levels. Managed retreat provides a soft and, in many cases, more sustainable technique for flood defense. As existing seawalls are deliberately breached and the sea left free to flood the land behind, recreating salt marsh habitats, the construction of a new inland secondary defense could follow depending on the topography of the area (Turner et al. 2007). The policy is an attempt to prevent as much damage as possible to property and avoid ecosystem squeeze between development and the advancing sea (Burket et al. 2001). Projects are currently underway in San Mateo and Ventura Counties, as well as a proposed project being considered for Santa Barbara County (King et al. 2011). Managed retreat can be divided into three main strategies for new coastal developments. (1) Setbacks, or minimum distances from the coastline for new developments. (2) Density restrictions that put limits in place on new coastal developments. (3) Rolling easement policies that establish conditional agreements for new developments, provided they be removed to allow inland migration of new coastal wetland habitats (Burket et al. 2001).

These policies have already been implemented in multiple nations worldwide, including various forms of rolling easement policies in Maine, Massachusetts, Rhode Island, and South Carolina (Burket et al. 2001). In developed countries, where experience of managed retreat is greatest, the main cost of managed retreat is that of purchasing the land to be flooded. This may differ in developing countries where land prices are relatively low and may already be owned by the state. Land costs can vary widely depending on the current land use and as such, so too will realignment costs. For example, agricultural land is less costly than land used for housing or industry, largely due to the presence of infrastructure (Rupp & Nicholls 2002). If land is used for housing or industry, it may also be necessary to provide additional compensation for relocation. Costs may increase further if it is necessary to dismantle human-made infrastructure present in the realignment zone (Rupp & Nicholls 2002). This may include structures such as buildings and roads, underground pipes for gas delivery or wires for electricity, internet or television (Rupp & Nicholls 2002). Costs are likely to be lowest if existing defenses are left to breach naturally. This saves money which would have been spent on the creation of artificial breaches and creates new intertidal areas (Rupp & Nicholls 2002).

Among the 20 coastal counties in California, San Luis Obispo County is 15th out of the 20 in terms of predicted monetary loss from buildings and contents after a 100-year flood at a 1.4m increase in sea level (Heberger et al. 2011). Under the assumption that sea level will rise 1.4m by 2100 provided by NOAA and IPCC projections, Heberger et al. (2011) estimates that San Luis Obispo County would lose ~$360,000 with a 100-year flood and ~$220,000 at the sea level for the year 2000 (Heberger et al. 2011). Because the dollar amount was given under conditions seventeen years ago, the value for property loss under current conditions is probably higher than $220,000 but we can confidently say that it will be less than the $360,000 loss given in a worse-case scenario by Herberger et al. It is also important to keep in mind that this study did not take population dynamics into account, and it was conducted under the “do nothing” premise. This means that the actual cost for a “do nothing” strategy for San Luis Obispo county is probably higher than the reported financial loss in the study and may rise to even higher values if policies to control coastal development are not put in place. The study also did not consider the process of relocation and rebuilding. Further complications arise in implementation of managed retreat due to coastal property owners being generally affluent and politically organized (King et al. 2011). This can result in significant pushback if an area is identified as a potential managed retreat site. Public pushback can be lessened through education and outreach programs that provide information about managed retreat. Another major drawback to implementation is the California Coastal Act (CCA) passed in 1976. Although the CCA tends to be in favor of managed retreat because it protects public coastal access, it also limits managed retreat because it allows private landowners to protect existing structures when property loss is "imminent" (King et al. 2011). This enables property owners to implement whichever strategy they feel is the most effective way to immediately protect their property, most likely the construction of a seawall.

Beach Nourishment:

Background erosion rates increase with SLR, and sand is lost naturally through storms, wave and tidal impacts, and longshore transport. Beach nourishment slows down background erosion and offers some storm protection (Speybroeck et al. 2006). This strategy is often coupled with the construction of seawalls to help dampen the effects of down current erosion caused by hard structures. Beach nourishment can be defined as deliberately placing sand on an eroding beach or creating a beach where no beach or only a narrow beach was once present (Speybroeck et al. 2006). This strategy is less ecologically damaging than the construction of hard structures. However, little is known about long-term cumulative physical and ecological effects of repeated nourishment projects (Speybroeck et al. 2006).

Beach nourishment replenishes existing, damaged, or nonexistent beaches. This is a favored strategy because the average value of California beaches has been valued at ~$4000 per hectare per year in economic benefits excluding recreational value (King et al. 2011). This strategy may also increase real estate value for coastal properties by protecting beachfront property from SLR and increasing recreational and ecological value of damaged or wiped out beaches (Dixon et al. 1996). However, because the large-scale projects alter a highly complex and dynamic habitat, many of the physical and biological effects of sustained nourishment are hard to predict. One of the main drawbacks to the beach nourishment strategy is the fact that effectiveness depends on repeated nourishment projects as coastal erosion carries away the sand that has been placed on the beach of interest. These projects are often viewed as unsustainable short-term fixes vulnerable to wave energy, storm events, and other effects of SLR (King et al. 2011). Many of these issues are the same problems experienced with hard structures (seawalls), although beach nourishment is not plagued with the ecological consequences associated with seawalls.

Short-term effects are most damaging to native interstitial flora and fauna (organisms that live between sand grains) as the addition of a thick layer of sand smothers many benthic invertebrates (Speybroeck et al. 2006). To minimize the known short term and unknown long-term effects of repeated beach nourishment, certain precautions should be considered. Chosen sediment should be as similar as possible to the composition and characteristics of the natural sediment (Speybroeck et al. 2006). The majority of California nourishment projects over the past fifty years have used sand taken from harbors and marinas (Griggs & Runyan 2005). The accumulation of sand in harbors and marinas offers a sediment supply for nourishment projects. Harbors and marinas should be chosen based on sediment similarities between the dredge and deposit sites to minimize ecological effects (King et al. 2011). Toxic substances should be completely avoided, which may be difficult in marina and harbor areas such as Morro Bay, and the projects should be completed within a single winter (late October to around March) (Speybroeck et al. 2006). This time window is optimal for nesting birds in the northern hemisphere and coincides with periods of low beach use by other mobile/migrating organisms (Speybroeck et al. 2006). Multiple small projects (<800m of beach) are favored over a single large-scale project because they allow for quicker re-colonization of local species (Speybroeck et al. 2006). However, full recovery of ecological value of beaches after a nourishment project may take years or decades in certain cases, depending on the replacement sand characteristics (Peterson et al. 2006).

Beach nourishment is more ecologically sound than construction of hard structures such as seawalls, however, the process is much more expensive. The minimum cost for such projects ranges from $1-$2 million and can range from $100 million-$1 billion for larger, longer projects (Barber). Nourishment restores and widens recreational beaches, protects structures if the added sand remains intact, and does not leave hazards on beaches as erosion continues like hard structures do (Barber). However, the new sand often erodes faster than the natural sand (two-to-three times faster), the process is expensive and must be repeated periodically, the beach turns into a construction zone during nourishment projects, and the projects themselves often damage or destroy local fauna (Barber). Nourishment projects alter the natural morphology of the underwater shoreline as far as tens of kilometers away from the project site (Slott et al. 2010). Altered shoreline topography effects natural wave morphology and could potentially have detrimental results on favored surf spots. Overall, the beach nourishment strategy, although more expensive, is more effective than hard structures in terms of keeping beaches recreationally and ecologically intact. Seawalls would be the preferred method if the only goal is to protect specific structures from coastal erosion over a relatively short term period.

Discussion:

Each strategy has its own set of benefits and drawbacks as displayed in Table 1. The most efficient way to implement them would be to use any combination of the three based on the characteristics of specific sites. Coastlines, especially the California central coast, are highly dynamic with many different habitats often in close proximity. Seawalls would work best in discrete locations in which the primary goal is to protect private property. They can be used in concert with beach nourishment to help diminish some of the recreational and environmental impacts of increased erosion through longshore transport. Beach nourishment works well in areas that have high recreational value and are seasonal. Seasonality is ideal for beach nourishment because of the complete shutdown of sites during the project. Although beach nourishment is less ecologically damaging than hard structure defenses, the cumulative effects of long-term repeated projects is still unknown. Managed retreat is ideal for areas in which SLR has already made huge impacts and environmental value is relatively high. Retreat is usually most effective in areas in which other coastal defense systems have failed or in areas that are not well developed with small coastal populations. This strategy will likely meet heavy local resistance without compensation for lost property and adequate relocation of infrastructure. It results in a more natural way of allowing coastal erosion to stay its course and claim any property or infrastructure near the shoreline.

Along the SLOC coastal areas, sites should be examined to determine which strategy best fits each potential site. Areas in which large recreational value is associated with beach area would be a good fit for nourishment. Developed areas, especially those with a relatively low amount of sandy beach and coastal wetland (coastal cliff/bluff areas) would be best suited by construction and maintenance of seawalls and similar structures. Sites that have high ecological value and relatively low development would work well in a managed retreat scenario. This would allow for the natural habitats to adapt to SLR and migrate inland as necessary, while property and infrastructure can be dealt with accordingly.

	Advantages	Disadvantages
Managed Retreat	- Encourages the development of beaches and salt marshes. - Initial costs are high but long term savings are likely. - Provides a more sustainable long term solution - Sediment flow is restored to its natural state. - Most environmentally friendly approach	- A certain amount of land will be inevitably lost in this process while beaches are being built up resulting in settlements, farmland and other property being destroyed. - May be legally and financially complex - May have to compensate private property owners
Seawalls	- Protect against wave damage and erosion - Can be constructed in small spaces - Relatively cheap - Can be made to blend into natural surroundings - Can be easily implemented	- Leads to increased erosion at immediate area and possibly in habitats down-current of site - Can result in a negative net cost from the loss of recreational and natural value - Public coastal access and visual impacts - Require frequent maintenance or reconstruction
Beach Nourishment	- Relatively ecologically friendly - Restores damaged or lost beaches with no impacts to public access when project is completed - Does not leave dangerous debris when eroded - May increase real estate values of coastal properties	- Expensive and must be repeated periodically - Does not stop erosion - Must adhere to site specific guidelines to maintain ecological friendliness - Shuts down beach during project times - Has immediate impacts on local interstitial fauna - May effect natural wave morphology - Unknown long-term cumulative effects

Table 1: *Table displaying the various pros and cons of each strategy discussed. Each different policy has strengths and weaknesses that may be better suited for specific sites.*

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