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August 21, 2017

__Via E-Mail and U.S. Mail__

Santa Barbara County Board of Supervisors
County Administration Building
105 East Anapamu Street
Santa Barbara, California 93101
E-Mail: sbcob@co.santa-barbara.ca.us

Re: Goleta Beach

Dear Members of the Board of Supervisors:

We are submitting the attached report on behalf of Surfrider Foundation with regard to Goleta Beach.

Very truly yours,

SHUTE, MIHALY & WEINBERGER LLP

Ellison Folk

Attachment

ESA

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August 21, 2017

Everett Lipman
Vice Chair
Surfrider Foundation Santa Barbara Chapter
P.O. Box 21703
Santa Barbara, CA 93121-1703
Via email - surfrider@lipman.org

Subject: Goleta Beach

Dear Everett :

Per your request and ESA's Agreement with the Surfrider Foundation (Surfrider), ESA provides this letter for your use in communicating with the County of Santa Barbara.

Background

Goleta Beach County Park is an important coastal access and recreational place used by many residents and visitors. Coastal processes have resulted in a landward shore migration that has eroded into the earth fill supporting the park area. Quarry stone were placed to protect the upland park, with little beach remaining, despite efforts to rebuild the beach in front of the rock. There is an ongoing question as to whether there is an alternative approach that would facilitate formation of a wider beach, and concerns about the performance of such alternatives in terms of maintaining the Park "as-is" or in a different configuration. Alternatives have been developed for the County that entailed a "managed retreat" approach that would realign park development landward and allow more space for beach formation. ESA (formerly PWA) has worked on several of these alternative plans. Consequently, Surfrider has requested that ESA provide information about these alternative approaches prior to the County's next hearing, scheduled for August 22.

Prior Work

ESA has assisted with alternatives at Goleta Beach with reports in 2005, 2008 and 2011 summarized below. These reports address alternatives to coastal armoring in order to facilitate existence of a beach while maintaining the other services provided by Goleta Park. Each report identified feasible managed retreat / shoreward realignment approaches which can be reconsidered in lieu of the proposed rock revetment project.

"2005 study". Master Plan Goleta Beach County Park, Shoreline Management Alternatives, *Prepared for Santa Barbara County Parks, Prepared by Philip Williams & Associates, Ltd. June 14, 2005, PWA REF. # 1743.01. (See Attachment 1):*
Several alternatives were evaluated to provide for continuation of existing park uses for at least 20 years. All alternatives included maintaining the shore protection at the restaurant concession, while allowing a range of

approaches at other locations. The lowest construction and annual costs were found to be associated with the Managed Retreat Alternative. This alternative realigned the park facilities landward, with 550 parking places, thereby providing more room for shoreline migration and beach formation, identifying a “buffer zone” of 1.3 acres for a rock revetment “backstop” to limit shore erosion extents, while reducing the area available for lawn from 4 acres to 3.2 acres.

“2008 Study”. Goleta Beach County Park - Park Reconfiguration Alternative*, Prepared for The Coastal Fund at UCSB Surfrider Foundation – Santa Barbara Chapter Environmental Defense Center, Prepared by Philip Williams & Associates, Ltd., November 24, 2008, PWA REF. #1940.00. (See Attachment 2):*
A new “Park Reconfiguration” alternative was developed as a refinement of the 2005 PWA-County Parks recommendation (2005 Study, above), to avoid confusion with an inferior managed retreat alternative by others. The 2005 PWA-County Alternative was revised to conform with other alternatives for comparative purposes, and resulted in greater performance in terms of more lawn space (4.2 acres) and a greater number of parking spaces (594).

“2011 Study” Goleta Beach Technical Memo on Erosion Mitigation Alternatives*, Prepared for Penfield and Smith, Prepared by ESA PWA February 28, 2011, Project Number 2051 (See Attachment 3):*
Multiple erosion mitigation alternatives were developed based on direction from Penfield & Smith (P&S), who was working for Santa Barbara County on the “Goleta 2.0” Project. These alternatives included retreat (similar to the 2008 and 2004 alternatives), retreat only on the west side of the Park, and a range of shore armoring approaches elsewhere. However, these alternatives were more constrained in their scope than those considered in the 2005 and 2008 studies, ultimately limiting retreat to only the western section of Goleta Beach Park.

Findings Selected from Prior Studies

The 2005 study quantifies the range of shore positions to be expected at Goleta Beach and called the area of shoreline excursions the “coastal erosion hazard zone” (Figure 1). The zone was refined in the 2011 study and called the “coastal processes zone” (Figures 2,3 and 4). Note that much of the lawn and a portion of the park amenities are within the coastal erosion hazard / processes zone” and are therefore subject to damages resulting from coastal erosion and flooding. This is, of course, why armoring was installed and why retreat alternatives were developed. However, the retreat alternatives realign (relocate, reconstruct) park amenities landward of the coastal processes / hazard zone thereby reducing the risk of damages.

Goleta Beach park was constructed when the beach was wide and the shore was in a more extreme seaward location. This is also obvious, because it is doubtful that the existing conditions would have been an expected outcome of the initial design. However, considering sea-level rise and other factors, it is doubtful that the shore will return to that seaward extreme location. Therefore, the proposed armoring will result in a reduced beach relative to that which historically existed, and probably less beach than desired when the Park was first designed.

All of the prior studies included a rock revetment, to protect the restaurant, pier landing and sewer outfall junction box. Most of this revetment already exists although we expect that renovation will be required in the future owing to increased loadings associated with higher sea levels. The 2005 study indicated a location for a “backstop” revetment in response to community concerns about erosion beyond that landward extent of the coastal erosion hazard zone. This proposed “backstop” is landward of the existing proposed armor location.

All of the retreat plans include removal of the western parking lot and relocation of utilities inland. The 2008 study identified a phased retreat of the fill used to form the Park, as depicted in Figure 5. A portion of the fill would be removed and sloped (cut to slope seaward rather than have a vertical scarp) so that wave runup would rush up and dissipate rather than reflect and scour the beach. This would allow the fill to be eroded, maintain a wider “lawn” area for as long as possible, and improve safety relative to the vertical erosion scarp.

The 2011 study developed a preliminary design for a cobble berm that would slow erosion while being more compatible with beach formation and public access. The cobble berm design mimics natural deposits of coarse sediment found on the California shore. These cobble berms are found at river mouths (for example, Surfers Point, Ventura) and as a “lag” deposit below beaches near bluffs (for example, in the vicinity of Goleta Beach). The term ‘lag’ refers to the process of the coarser sediments being deposited below the typical beach elevation. The coarse sediment deposits consist of cobble with some larger boulders and smaller gravels delivered by the rivers and creeks or eroded directly from adjacent bluffs by waves. These coarser sediments tend to coalesce and move landward under wave action, forming berms with slopes steeper than sand beaches. The preliminary design for Goleta Beach included a cobble berm with a crest elevation of +10’ NAVD and a seaward slope of 5:1 (horizontal:vertical). Note that the berm crest elevation is below the existing Park surface (elevation around +13 to +14 feet NAVD). The berm crest elevation was selected to conform with wave runup elevations that shape the lag deposits and beach berms in the vicinity of Goleta Beach, as shown in a picture of an adjacent shore in Figure 6. Wave runup would exceed this elevation about 1% of the time and extreme wave runup would impinge upon the earth fill and lawn behind the cobble. This configuration (a low berm) is consistent with the managed retreat approach exemplified in Figure 5: The cobble would migrate landward with the eroding scarp but would slow the rate of erosion, reduce wave reflection, facilitate beach formation, improve vertical and lateral access, and have a more natural morphology, ecology and aesthetic relative to the quarry stone revetment. Extreme wave runup elevations associated with events that happen about once every two years or less frequently would reach the lawn surface, especially if impinging on the existing near-vertical scarp or shore armoring which deflect runup higher[1]. Larger and higher berms exist naturally and have been constructed, such as at Surfers Point, Ventura where a berm crest of elevation 13.5 feet (NAVD) was constructed. However, these larger berms are best designed where there is adequate space and therefore typically require some retreat of the backshore, such as at Surfers Point where the artificial shore was realigned about 70 feet landward. This “scale” of cobble berm is larger than observed in the vicinity of Goleta Beach, but is consistent with natural formations elsewhere in California including surfing areas such as El Capitan, Rincon, and Surfers Point – California Street – Ventura River mouth. In summary, our prior analysis indicates that a cobble berm can be employed to limit erosion at Goleta Beach. Attachment 4 provides additional information about use of cobble for shore management and erosion control[2].

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[1] Battalio, R. T., P. D. Bromirski, D. R. Cayan, L. A. White (2016). Relating Future Coastal Conditions to Existing FEMA Flood Hazard Maps: Technical Methods Manual, Prepared for California Department of Water Resources and California Ocean Science Trust, Prepared by Environmental Science Associates (ESA), pp. 114. http://water.ca.gov/floodmgmt/lrafmo/fmb/docs/Technical-Methods-Manual_FINAL_2016_12_02_clean.pdf last visited, August, 2017.

[2] Ocean Beach Master Plan, Appendix A: Technical Memoranda – Coastal Engineering, May 2012, http://issuu.com/oceanbeachmasterplan/docs/obmp_document_full/11 last visited August 2017.

Effect of Coastal Armoring on Beach

Figures 7-1 through 7-4 show a series of shore schematics developed to convey the effect of coastal armoring on fronting beaches when the armor is frequently reached by waves.

Figure 7-1 shows the natural shore, in this case with a bluff behind it rather than the slough at Goleta Beach. Note that the shore location and sandy beach geometry fluctuate in response to water levels and waves. For naturally wide beaches, the seasonal and extreme fluctuations do not impinge significantly on the back shore. For many California shores however, the backshore is impacted during extreme events, it erodes, and the beach recovers and persists. The amount of long-term change (typically erosion) and migration due to sea-level rise are important considerations.

Figure 7-2 shows a typical public works development on the California coast consisting of fill out onto the beach. This fill is then eroded when the beach reaches its more landward position. The erosion of the fill is permanent (unlike a beach or dune which can reestablish naturally and migrate landward as a component of the shore).

Figure 7-3 shows the approach recommended by many engineers and public works agencies, which is to armor the fill to prevent it from eroding. This results in a reduced beach width due to both the footprint of the structure, but also due to increased scour associated with wave reflection and turbulence at the base of the structure. Essentially, once wave runup impacts the structure frequently, the wave dissipation is changed and focused in a smaller area and the beach is lowered. This armored shore condition also adversely affects coastal ecology (Attachment 5)[3].

Figure 7-4 shows a managed retreat approach where the fill is removed and space created for future shore migration. The manifestation of the retreat (that is, the distance, rate, shore configuration, use of structures, sediment placement, etc.) is subject to site-specific design using coastal geomorphology and engineering methods. This approach (managed retreat) has been implemented successfully at Pacifica State Beach (Pacifica, CA) and Surfers Point (Ventura, CA) in 2005 and 2012, respectively, and neither location has experienced significant damages such as those that occurred pre-project, and both are exceptionally popular beaches for a wide range of activities. For example, the managed retreat project was the only portion of the surfers point vicinity to avoid damages during the large swells of December 11, 2015[4].

In summary, the Goleta Park fill extends into the coastal processes hazard zone, and construction of a rock revetment or other shore protection device will result in a narrower beach more often. Alternatively, realignment of infrastructure landward, removal of armor and re-establishment of natural coastal processes will reduce damages and result in a more resilient shore.

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[3] Dugan, J.E., Emery, K.A., Alber, M. et al. Estuaries and Coasts (2017). Generalizing Ecological Effects of Shoreline Armoring Across Soft Sediment Environments, https://doi.org/10.1007/s12237-017-0254-x DOI https://doi.org/10.1007/s12237-017-0254-x Publisher Name Springer US Print ISSN 1559-2723
Online ISSN 1559-2731
https://www.coastalreview.org/2017/08/study-predicting-how-seawalls-affect-ecology/ last visited August, 2017.

[4] Surfer's Point Shore Enhancement Project, Monitoring Report, Prepared for the City of Ventura, Prepared by ESA, July 19, 2016, ESA DW01708.05 2015-2016

Closing

The proposed armoring will reduce the size and persistence of the sandy beach. Alternatively, realignment of developed assets landward will alleviate the need for armoring and allow the beach to exist. Prior work provides actionable information to pursue renovation of Goleta Beach County Park in a more sustainable configuration.

Sincerely,

Robert (Bob) Battalio, PE
Vice President

Figures:

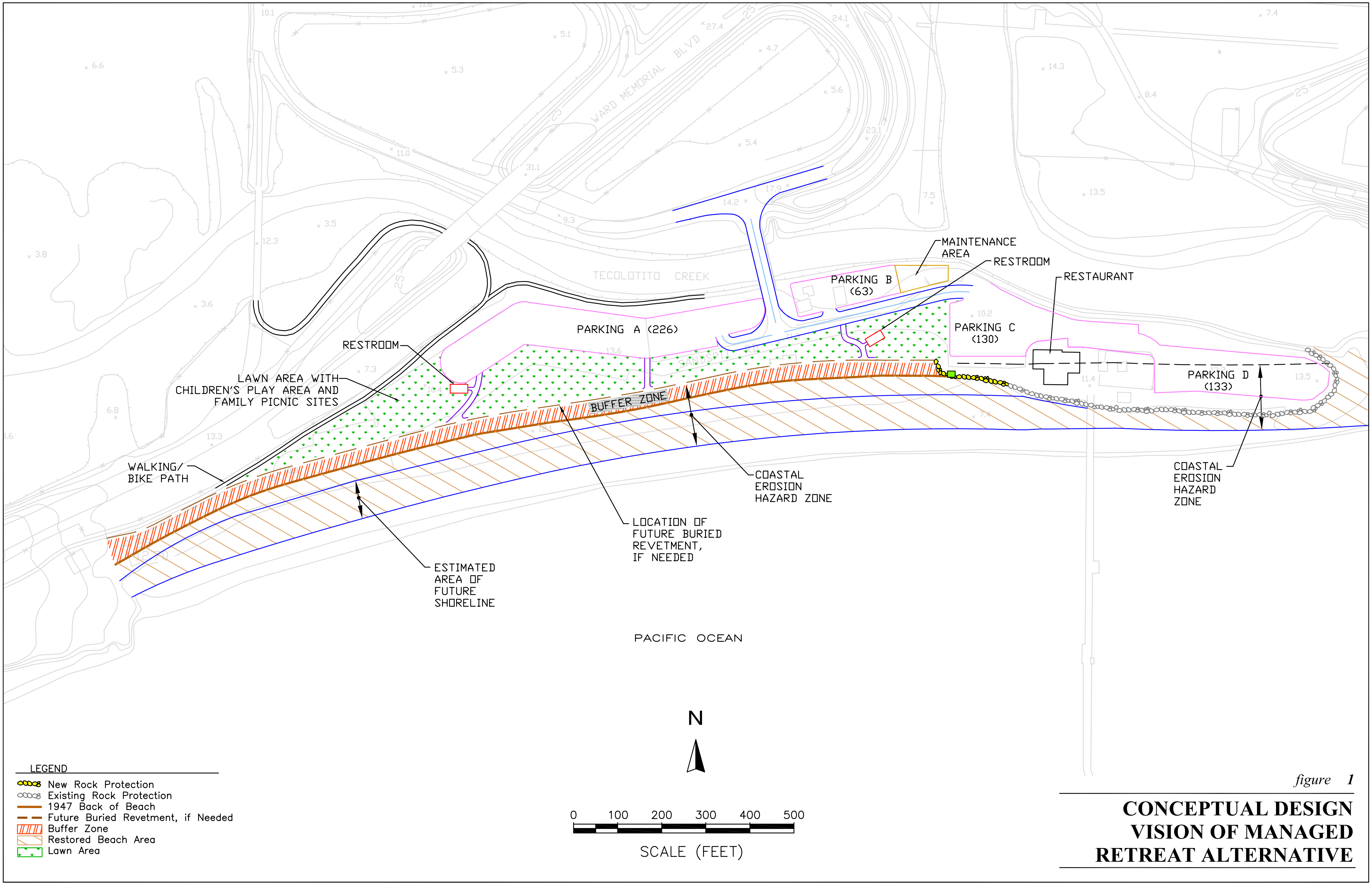
1. Conceptual Design Vision of Managed Retreat Alternative
2. Coastal Processes Zone, Goleta 2.0 – Infrastructure Protection Alternatives
3. Site Plan, Goleta 2.0 – Infrastructure Protection Alternatives
4. Profile Definition Sketch, Goleta 2.0 – Infrastructure Protection Alternatives
5. Evolution of Park Reconfiguration Alternatives, Goleta Beach
6. Photograph of cobble beach berm composed of lag exposed by erosion of sand, Goleta California (vicinity of 34.407344,-119.849926 , date August 14 2017). Source: Surfrider Foundation

7.1 Schematic profile of California beach
7.2 Schematic profile of California beach with erosion of fill for parking and access
7.3 Schematic profile of California beach with Revetment / Seawall Solution
7.4 Schematic profile of California beach with Realignment / Retreat Solution.

Attachments:

1. **Master Plan Goleta Beach County Park, Shoreline Management Alternatives,** Prepared for Santa Barbara County Parks, Prepared by Philip Williams & Associates, Ltd. June 14, 2005, PWA REF. # 1743.01
2. **Goleta Beach County Park - Park Reconfiguration Alternative**, Prepared for The Coastal Fund at UCSB Surfrider Foundation – Santa Barbara Chapter Environmental Defense Center, Prepared by Philip Williams & Associates, Ltd., November 24, 2008, PWA REF. #1940.00.
3. **Goleta Beach Technical Memo on Erosion Mitigation Alternatives**, Prepared for Penfield and Smith, Prepared by ESA PWA February 28, 2011, Project Number 2051.
4. **Cobble Berms: A Brief Summary in Support of the Ocean Beach Master Plan**, Prepared by Bob Battalio, PE ESA PWA January 20, 2012, Ocean Beach Master Plan, Appendix A: Technical Memoranda – Coastal Engineering, May 2012, http://issuu.com/oceanbeachmasterplan/docs/obmp_document_full/11 last visited August 2017.
5. **Generalizing Ecological Effects of Shoreline Armoring Across Soft Sediment Environments**, Dugan, J.E., Emery, K.A., Alber, M. et al. Estuaries and Coasts (2017). https://doi.org/10.1007/s12237-017-0254-x DOI https://doi.org/10.1007/s12237-017-0254-x Publisher Name Springer US Print ISSN 1559-2723 Online ISSN 1559-2731 https://www.coastalreview.org/2017/08/study-predicting-how-seawalls-affect-ecology/ last visited August, 2017.

Figure 1



PWA

Figure 1: Conceptual Design Vision of Managed Retreat Alternative: Source 2005 Study

Figure 2

Goleta Beach 2.0 – Infrastructure Protection Alternatives

Coastal Processes Zone

PWA Ref# 2051.00

ESA PWA

Figure 2.Coastal Processes Zone,
Goleta 2.0 – Infrastructure Protection Alternatives.
Source 2008 study.

Figure 3

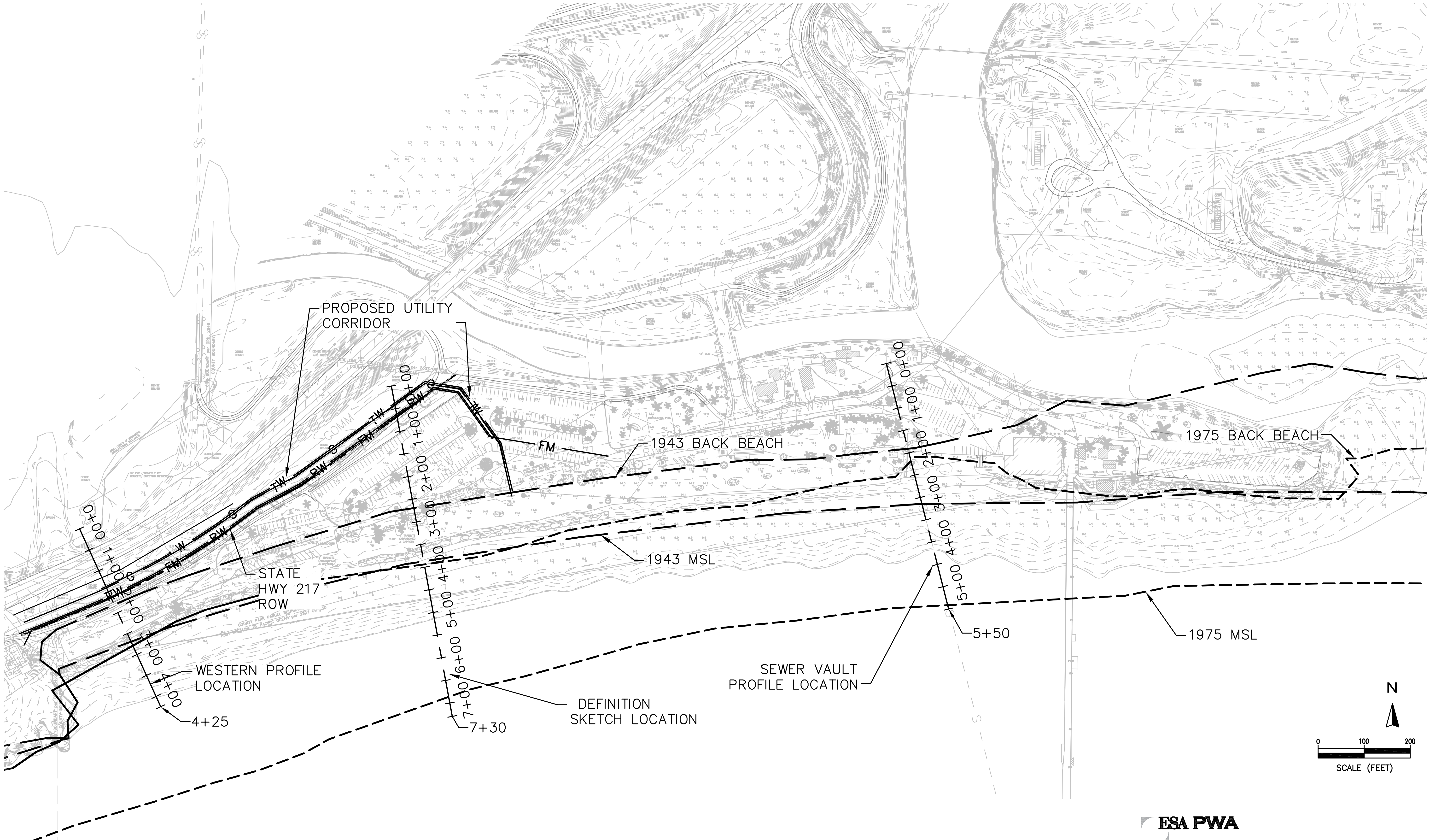


Figure 3: Site Plan - Coastal Processes Zone, Goleta 2.0 – Infrastructure Protection Alternatives
Source: 2008 study

ESA PWA

Goleta Beach 2.0 - Infrastructure Protection Alternatives

SITE PLAN

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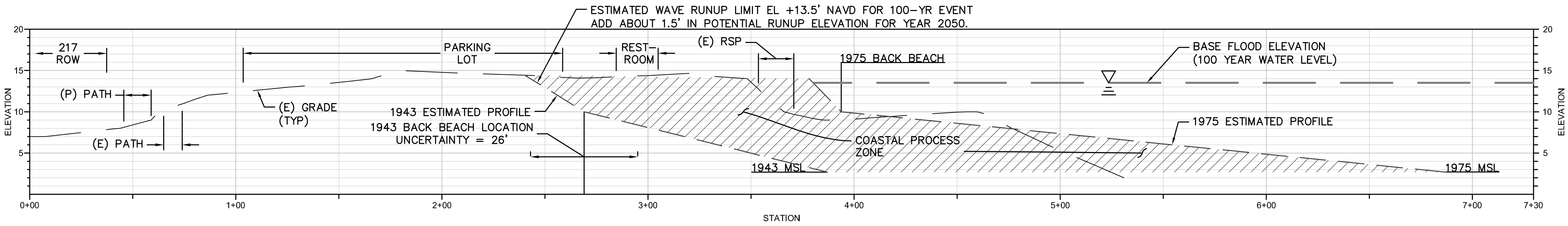
Figure 4



NOTES
1. SCALE IS 1" = 50', 4X VERTICAL EXAGGERATION
2. VERTICAL DATUM IS NAVD 88
3. MSL = 2.69' NAVD. (ASSUMED CONSTANT OVER TIME)

Figure 4: Site Plan - Profile Definition Sketch,
Goleta 2.0 – Infrastructure Protection Alternatives
Source: 2008 study

ESA PWA

Goleta Beach 2.0 - Infrastructure Protection Alternatives
PROFILE DEFINITON SKETCH

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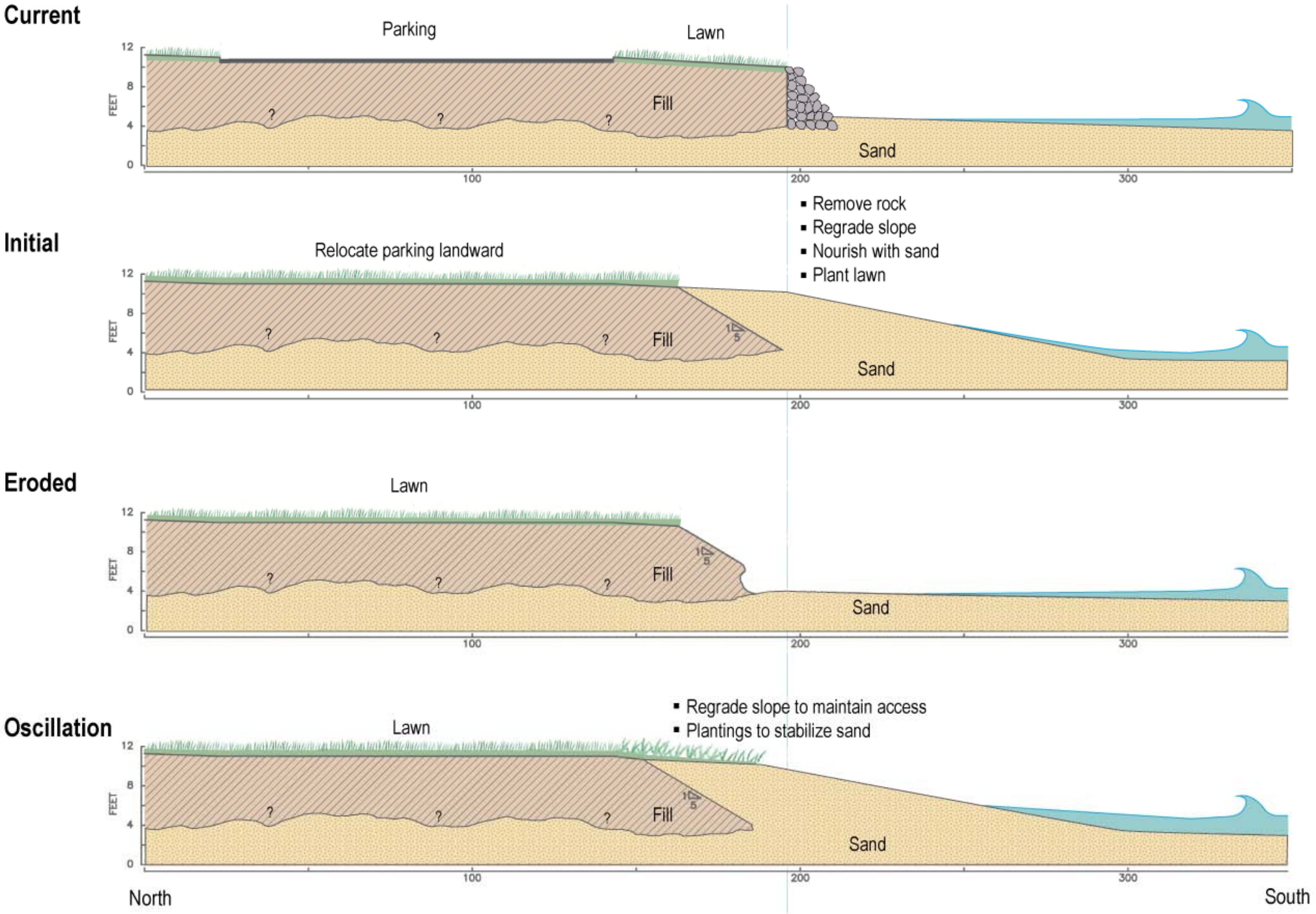
Figure 5



Goleta Beach

Evolution of Park Reconfiguration Alternatives

#1940

PWA

Figure 5. Evolution of Park Reconfiguration Alternatives, Goleta Beach. Source: 2008 study

Figure 6

Photograph of cobble beach berm composed of lag exposed
n of sand, Goleta California (vicinity of 34.407344,-119.849926 ,
ust 14 2017). Source: Surfrider Foundation

Figure 7-1

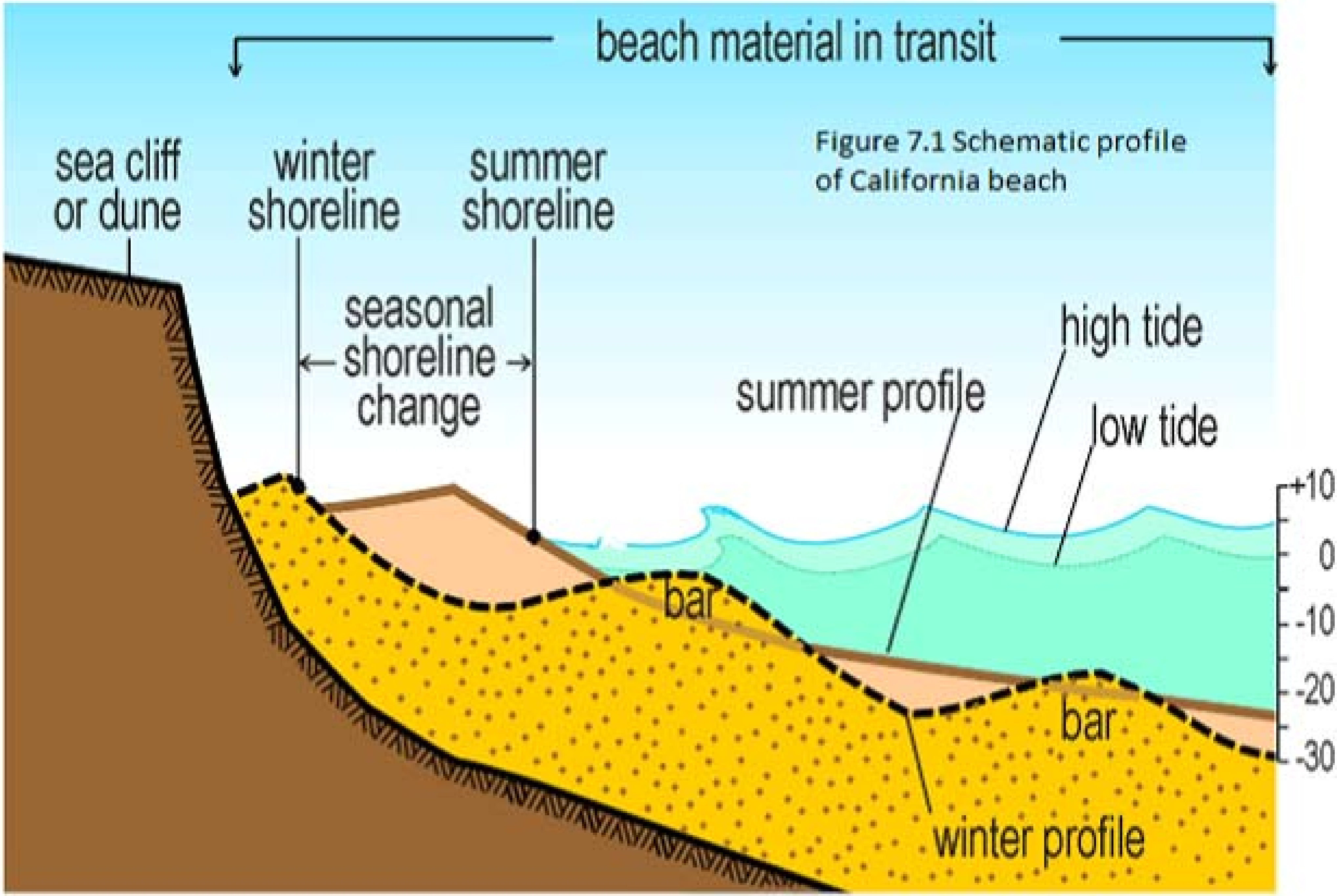


Figure 7.1 Schematic profile of California beach

Figure 7-2

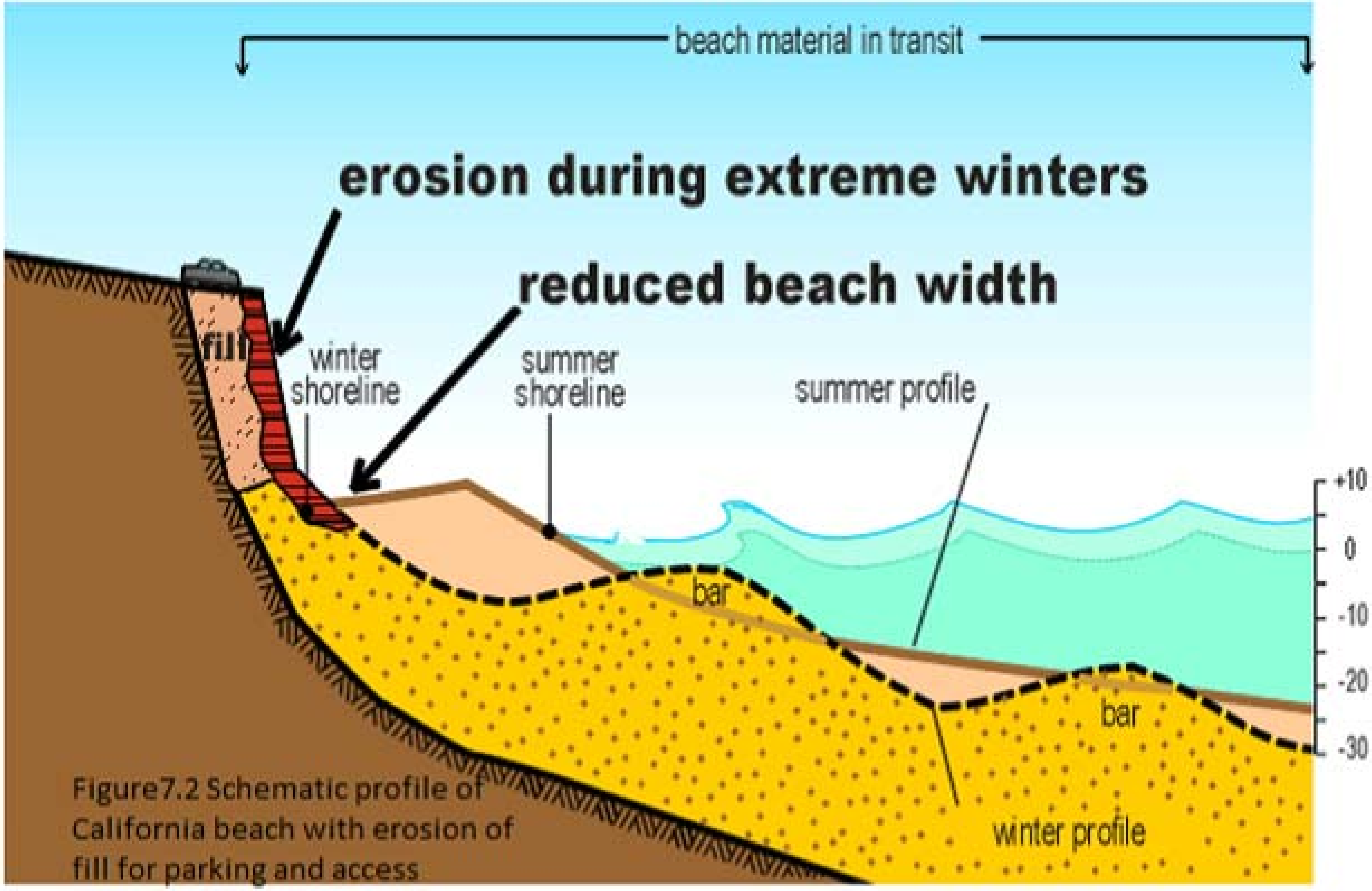


Figure7.2 Schematic profile of California beach with erosion of fill for parking and access

Figure 7-3

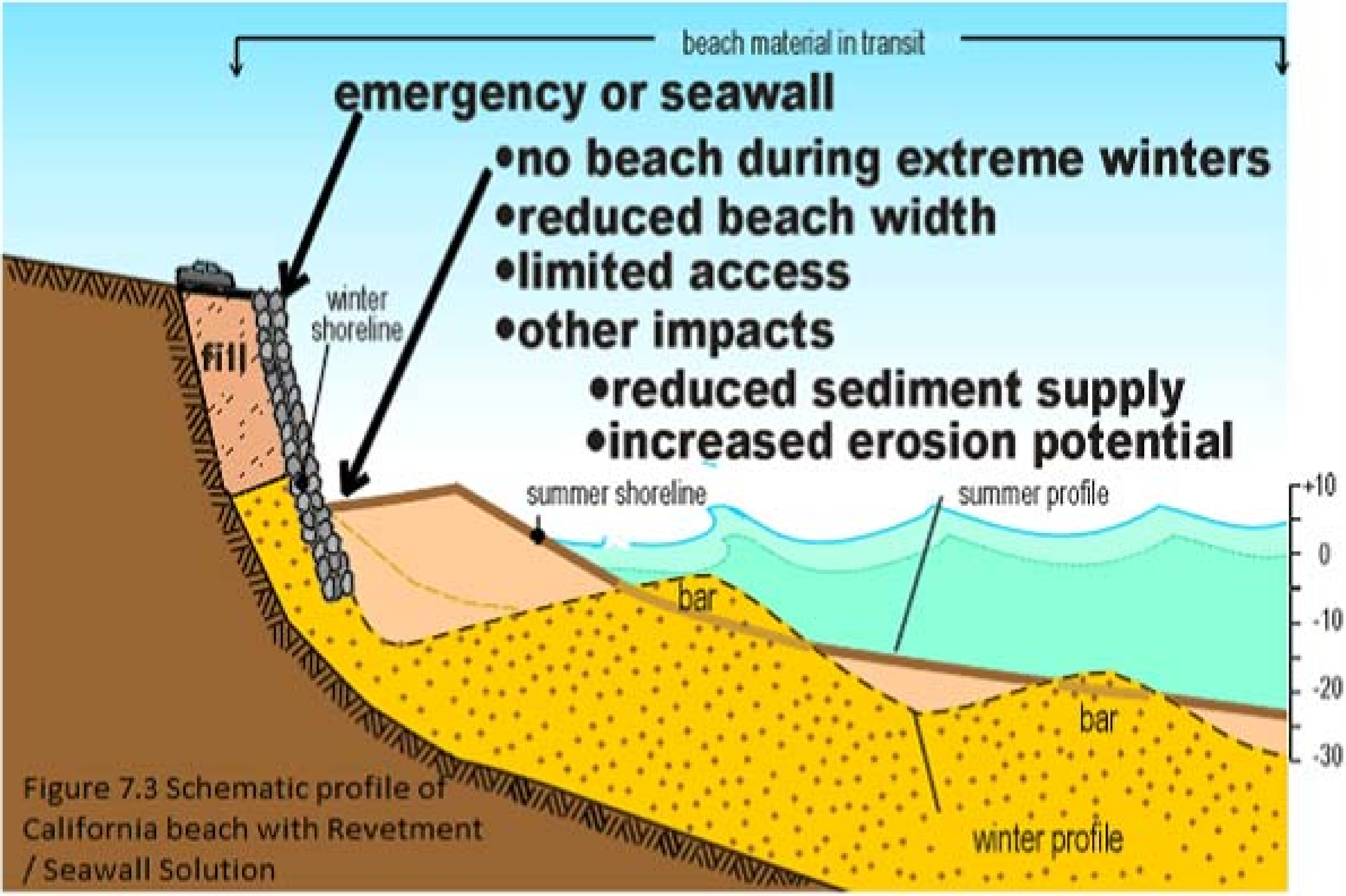
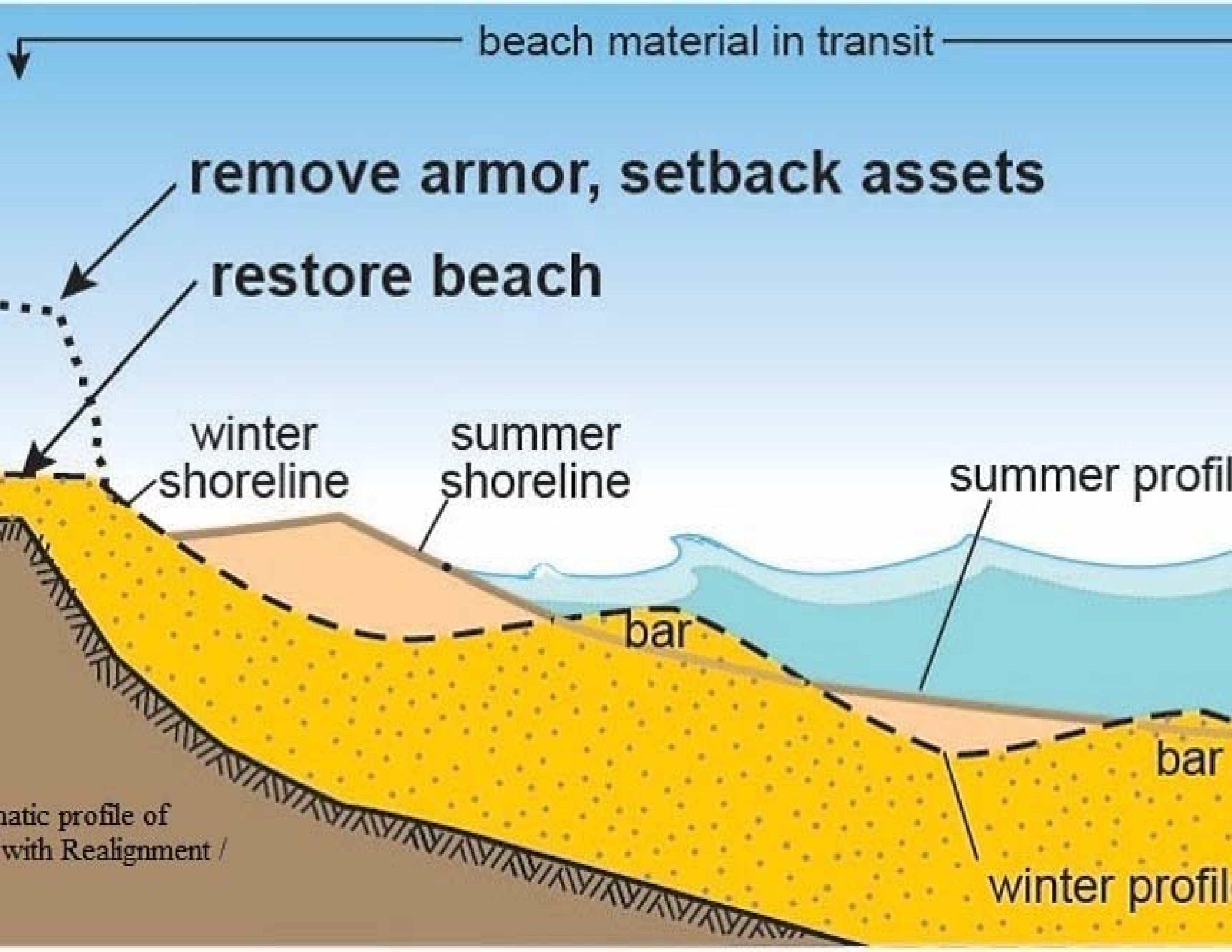


Figure 7.3 Schematic profile of California beach with Revetment / Seawall Solution

Figure 7-4



natic profile of
with Realignment /

Attachment 1

Exhibit 1: 2005 Study

Master Plan Goleta Beach County Park
Shoreline Management Alternatives

Prepared for

Santa Barbara County Parks

Prepared by

Philip Williams & Associates, Ltd.

June 14, 2005

PWA REF. # 1743.01

Services provided pursuant to this Agreement are intended solely for the use and benefit of the Santa Barbara County Parks.

No other person or entity shall be entitled to rely on the services, opinions, recommendations, plans or specifications provided pursuant to this agreement without the express written consent of Philip Williams & Associates, Ltd., 720 California Street, 6th Floor, San Francisco, CA 94108.

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1. INTRODUCTION

The Goleta Beach Master Planning and Community Visioning Process is developing a plan for Goleta Beach County Park. . PWA was commissioned by Santa Barbara County Parks to provide information on the recent and likely future evolution of the shoreline and provide a conceptual design for a Managed Retreat alternative.

A primary driver for the process has been the threat posed to park facilities by recession of the shoreline. The visioning process has identified facilities that may be relocated to allow the beach to continue to evolve and those facilities for which relocation is not desired and for which some form of protection may be required. The key issues resulting from the visioning process are:

- Protection of the west end of the park
- Continuing protection of the restaurant
- "Softer" solutions for the mid area of the park
- Modification of the parking lot layout
- Relocation of utilities

2. FACTORS AFFECTING THE SHORELINE

The major issue to consider is where should the shoreline be located in relation to the rest of the park. Some functions of the park (the restaurant, parking lots, utilities corridor etc) have to be located landward of the shoreline. Other functions, such as wave dissipation, some ecological and some recreational functions have to be located seaward of the line. The long-term management of the park depends on understanding the interaction of the shoreline with the various functions of the park and how these will change in the future.

We usually think of the shoreline as a line drawn on a map but this is an artificial line drawn by man. It represents some time averaged high water mark and is used to represent the landward limit of wave activity and of the dynamic beach – structures and assets land ward of the shoreline would not normally be in danger from erosion. In reality, the shoreline is not static, it is continually moving, and so over time it describes not a single line but a zone:

- In the short term (months), during a storm the shoreline may move landward as sand is dragged offshore to form bars. In calmer weather, the same sand may move onshore and build up the beach so the shoreline moves seaward. This rhythmic movement of the shoreline can be clearly seen when comparing summer and winter profiles.

- In the medium term (years), the shoreline may be influenced by particular events. A large amount of sand arriving at that part of the coast due to erosion in the watersheds or along the coast may deposit sand on the beach that brings the shoreline seaward. Similarly if the sand supply is reduced (by structures, dredging etc) the shoreline may retreat. Changes in wave energy and water levels associated with El Nino may also cause the shoreline to move.

- In the long term (decades), trends in sea level and earth movements may cause the shoreline to migrate. In the case of sea level rise, the shoreline will tend to migrate landward, which has been the general history for the last ten thousand years.

The natural position of the shoreline is not random – it is a response to a number of environmental variables and the beach is continually adjusting itself to accommodate changes in these variables:

- Wave energy – a beach dissipates wave energy in a number of ways – by providing a long rough surface over which energy is used to overcome friction, by breaking the waves and converting the wave energy into sound and heat. During a period of large waves the beach profile will tend to flatten and sand will move offshore and form bars. These changes increase the beaches ability to dissipate energy. The size of the waves affecting the beach is governed by the strength and frequency of storms and ocean swell waves, the shape of the seabed for several miles offshore and the shelter provided by headlands and islands.

- Sand supply – sand does not just move onshore and offshore, it also moves along the coast. Waves approaching a beach at an angle will tend to 'push' sand along the coast. The larger the angle and the larger the waves, the greater the transport of sand. The angle the waves approach is governed by the direction of storms and ocean swell waves, the shape of the seabed for several miles offshore and the shelter provided by headlands and islands. If the average angle between the coast and waves is small, the longshore transport will be lower and the shoreline may be more stable. The shoreline may be relatively stable even though lots of sand is being transported provided sufficient sand is arriving from further up the coast. If there is an interruption to the supply, the waves will still be capable of transporting sand and then erosion will occur.

- Sea level rise – the position of the shoreline is set where the beach profile and the surface of the sea intersect. With rising sea levels, associated with climate change, the point of intersection will tend to move landward, moving gradually over decades. If tectonic movements cause the land levels to rise then the shoreline may move seaward, however unlike sea level rise this will be in discrete events and much more rapidly.

The key is to understand the width and location of the zone in which the shoreline will move in the future and to accommodate this zone with the other functions of the park. Accommodation may mean allowing more space for the zone to move in or it may mean changing the environmental conditions to move the zone to a new location or reduce its width or a combination.

3. OVERVIEW OF CONCEPTUAL MODEL FOR GOLETA BEACH

Goleta Beach lies within a hook-shaped or equilibrium bay whose updrift end lies at Campus Point and stretches westward to Santa Barbara Point. This type of coastal formation is typical of sandy shores exposed to wave action between erosion-resistant headlands. The bay is one of a series along this part of the coast.

A hook-shaped bay consists of two parts:

- A curved section adjacent to the upcoast headland (Campus Point)
- A nearly tangential straight beach segment at the downcoast end (towards Santa Barbara Point)

A similar shaped bay can be seen further to the east at Coal Oil Point.

In static hook-shaped bays, the shoreline is parallel to the incident wave crests. A wave at the curved upcoast section will first diffract and then refract as it propagates in the lee of the headland; it will arrive almost normal to the beach. Thus, wave breaking will occur simultaneously in all locations in a static equilibrium bay. This means there is no longshore component of breaking wave energy and hence no longshore sand transport within the embayment.

However, the bay is not likely to achieve a static equilibrium form in the near future as:

- the assumption of a static equilibrium bay is that there is no net longshore transport whilst for the Santa Barbara littoral cell estimates of eastward movement in the range of 250,000 yd^3 per year have been made (USACE, 1986; Noble Consultants, 1989).

- the response of parts of the bay backed by bluffs is limited by the erosion rate of the bluffs. The whole bay may be moving towards an equilibrium shape but at a slow rate. Where there is easily erodible material, for example the sand of Goleta Beach, the retreat rate is much quicker.

The embayment defined by Campus Point is not in static, but rather, dynamic equilibrium; there is a net longshore transport of sand driven by waves. The bay responds to changes in sediment supply and wave conditions.

In the shorter-term (decades), we see sediment arriving on the coast in pulses due to the intermittent nature of the sediment supply from the watersheds (Willis and Griggs, 2003). The latest such pulse appears to have been in the 1950s with a corresponding rapid widening of the beach and subsequent slower erosion to the present day. The supply of sediment may therefore vary widely depending upon events further up the sediment pathway.

Sediment is transported from the beach and moved eastward by the process of longshore transport. The rate of transport is a function of both the power and direction of the waves. Wave power can vary considerably over a period of decades between the calmer La Niña and stormier El Niño conditions.

The net result of a low correlation between sediment supply and sediment loss is that the net budget of sand in the embayment may vary from year to year. If the annual input is dominated by a pulse of sediment this will result in a large positive budget for the bay, sand will likely be deposited in the bay and beaches will rapidly widen (which occurred in the 1950's). The sand from these pulses will be transported out of the system during stormier periods of higher wave (such as the El Niño of 1983) and beaches will gradually narrow. This will continue until either the static equilibrium form of the embayment is achieved or another pulse of sediment enters the embayment.

In summary:

1. Increasing sand supply

   This corresponds to a large pulse of sediment entering the bay. In this situation, there will be net gain of sand to the beach, the indentation of the beach is reduced and beach widths will increase.

2. Decreasing sand supply

   This corresponds to the periods between large pulses of sediment entering the bay. In this situation, there will be net loss of sand from the beach. The indentation of the beach increases. The curved section closest to the headland responds slowest as transport rates are lower than on the tangential sections.

In an embayment that is in dynamic equilibrium, the net longshore transport rate is not zero. This is due to the waves approaching the beach at an angle, driving sediment along the beach. Not all the sand in the pulse can be transported through the embayment and so some is deposited. Beaches will widen and the indentation of the embayment will reduce. This will result in an increase in the angle of wave to the beach and the transport rate will increase. The tendency will lead to the removal of beach material and narrowing of the beaches. As the beaches narrow, the angle of waves to the beach decreases and the longshore transport rate decreases. The beaches will therefore gradually return to their 'pre-pulse' width and orientation.

The bay can reestablish an equilibrium form by this feedback mechanism. Within the embayment there are other, more localized, influences on the shape of the bay and local beach orientation that can change the local transport rate and hence the width of the beach.

3.1 OBSERVATIONS OF SHORELINE EVOLUTION

These periodic changes in the shape of Goleta Beach have been observed over the past 70 years and reported in the work undertaken by David Revell (Revell and Griggs, 2005). The shorelines as indicated by the wet/dry/line were identified from aerial photographs. The wet/dry line provides a general indication of the location where the Mean High Water Mark lies on the beach profile. It gives a general indication of the shape, position of the shoreline. These shorelines are ‘snapshots’ of the beach position, and together give a long term picture of the evolution of the beach. David Revell of UCSC undertook rectification and original digitization of the shorelines; these have been subsequently reprojected, and beach transects drawn to calculate beach widths.

1938 to 1947 The shoreline is relatively stable in position. The largest changes are in the region of Goleta Slough which show that at least on one occasion the slough had broken through to the west of the 1938 position.

1959 to 1966 There is a large seaward movement of the shoreline along both the UCSB and Goleta beaches. This appears to be related to a large pulse of sediment that has entered the embayment and is spread fairly uniformly through the area. This may be related to a pulse of sediment moving westward from Devraux Slough and along Isla Vista. Sand was able to accumulate on Goleta Beach due to the calmer La Nina conditions that were typical of the period 1945 to 1978.

1966 to 1975 This period shows what appears to be a redistribution of beach material with a large seaward movement of the UCSB beach (there is no evidence of a pulse propagating from the west). 1969 shows the most seaward position the southern part of the UCSB beach will attain in the record. During this period, the shoreline at Goleta Beach retreated particularly in the west, retreating past the West Bluff. Some material from Goleta Beach may have moved westward to feed the UCSB beach.

1983 to present Coincident with a change from calmer La Niña to stormier El Niño conditions the beach at Goleta continues to narrow. The El Niño storms events of 1982-83 and 1997-98 were particularly significant (Revell and Griggs, 2005). The transport rate within the bay is greater than the supply of sand around Campus Point and the shoreline retreats. As the shoreline retreats beach reorients and the angle of the waves to the beach is reduced. This reorientation of the beach with retreat of the shoreline reduces the longshore transport rate and the rate of retreat diminishes over time. Looking further west a pulse of sand appears to be accumulating in the vicinity of Deveraux Slough and Coal Oil Point. Pulses appear to move at the rate of about a mile per year (Bruun 1954, Bailard 1982) in which case this material may reach Goleta in the next decade.

3.2 CHANGES IN EBB DELTA

A more localized, influences on the shape of the bay is the ebb delta of Goleta Slough, formed by the interaction of the tidal flow out of the slough with the open ocean. As the flow passes through the narrow constriction of the inlet and into the ocean it slows and deposits sediment. This forms an ebb delta characteristic of many inlets on the open coast. Waves will refract over the shallow ebb delta, changing the angle at which they approach the shore and so reducing the local transport rate. The net effect is for the delta to reduce the sediment transport rate and trap sand updrift of the delta.

The size of the delta is dependent upon the flow of water through the inlet, the tidal prism, and the ocean wave energy. Generally, for similar wave conditions, the volume of the ebb delta, and hence size, is proportional to the tidal prism (Walton and Adams, 1976).

The tidal prism of Goleta Slough has decreased by 60% by infilling over the last 150 years. Consequently, the size of the ebb delta is likely to have decreased by something like 70% in volume. Reducing the tidal prism would also make the inlet less stable becoming more prone to closing and more mobile. As the volume of the ebb delta has reduced so has its width and length. Consequently, the ebb delta has less impact on local wave refraction and so local wave approach angles will increase. Transport rates along Goleta Beach have therefore probably increased as the ebb delta volume has decreased.

3.3 IMPLICATIONS FOR FUTURE MANAGEMENT

1. The evolution of Goleta Beach appears to be a balance between occasional large pulses of sediment that widen the beaches in the embayment significantly and periods between pulses when the sediment is transported eastward, particularly during stormier El Niño conditions.

2. The present large embayment is in a state of dynamic equilibrium, with sediment passing through the embayment as well as erosion of the beaches.

3. Infilling of Goleta Slough and the consequent reduction in the ebb delta has reduced the stability and increased the longshore transport along Goleta Beach.

4. Managed retreat will provide some room for the equilibrium plan shape to evolve.

5. Another pulse of sand appears to be forming that would nourish Goleta Beach, however the timing of its arrival is uncertain.

6. It may be possible to mimic the short term effects of sediment pulses, which may allow the beach to maintain its present position by:

    a. offsetting the present longshore loss of material by renourishment, and/or,

    b. locally reorienting the shoreline to reduce the local longshore transport rate (perhaps by increasing the volume of the ebb delta).

4. MANAGED RETREAT ALTERNATIVE

A conceptual design for a managed retreat alternative has been developed that considers the goals of the Working Group and an understanding of future shoreline evolution. The design consists of a plan that incorporates a managed retreat approach including beach restoration, coastal armoring, and the relocation or removal, where necessary, of existing utilities and structures.

It is not intended that all the proposed changes in the conceptual design occur at once. Rather, proposed changes can be implemented in a phased manner to accommodate both the evolution of the beach and budgetary constraints.

To determine the extent of managed retreat, a coastal erosion hazard zone is defined. This is an area in which storm induced erosion and flooding can cause either a recession of the shoreline or damage to infrastructure that lies within the zone. The intention is to remove structures and utilities from this zone. Moving utilities and structures landward of the hazard zone would provide a setback from the existing shoreline and erosion hot spots.

The hazard zone was defined using the 1947 back beach shoreline, the most landward observed in the past 70 years, with an additional buffer of 30 feet to account for potential flood limits. The width of the additional buffer is a compromise between providing space for the beach to evolve, the constraints posed by existing utilities (in particular the high pressure gas line) and the desire to maintain lawn area and parking capacity. The area between the landward edge of the buffer zone and the existing shoreline approximates the coastal erosion hazard zone as shown in Figure 1.

In some places, the existing infrastructure would not be moved within the 20-year planning horizon of the Master Plan and some form of coastal armoring would have to be maintained for protection. Facilities behind the revetment would remain in the hazard zone and they may be subject to wave overtopping and flooding. Passive erosion of the beach in front of the revetment will continue and the revetment will require periodic maintenance.

Figure 1 shows the 20-year vision of the managed retreat alternative and Figure 3 the long-term vision (20 years plus) of the same alternative.

4.1 20-YEAR VISION OF MANAGED RETREAT ALTERNATIVE

Within 20 years, retreat would be allowed to the west of the restaurant. The restaurant and the spit to the east would remain in place. The area from the west bluff to the restaurant accommodates future coastal erosion within the hazard zone. The managed retreat alternative shows the hazard zone as a restored beach area..

Landward of the coastal erosion hazard zone is a beach park area that includes the existing park amenities reconfigured for the future shore conditions: space for a lawn, a playground, barbecue pits, public restrooms and paths that connect the beach to the parking areas. The approximate area of the proposed beach park is 3.2 acres.

Landward of the beach park area are Parking Areas A, B and maintenance area. In the design, Parking Areas A and B are shown connected to the restored beach area with paths.

Approximately 1000 feet of existing rock revetment at the west end of the park would be removed. The existing rock revetment in front of the restaurant and restroom would be extended by 150 feet, to protect Parking Area C and the sewer outfall vault.

4.2 PHASING OF 20-YEAR VISION

For the managed retreat alternative, existing utility lines, buildings, and parking lots would need to be reconfigured or removed to accommodate the conceptual design plan. It is anticipated that the buffer area would not be eroded in the next 20 years. Structures and utilities within the buffer area, such as the restrooms, need not be relocated immediately but gradually as budgets allow. Figure 2 shows prioritized elements in which either portions of utility lines or existing structures would need to have been relocated or removed as part of the managed retreat.

The only initial work suggested is to regrade the scarp in the fill material and add sand at the top end of the beach. The vertical scarp that forms in the winter in the eroded fill could be a safety issue and also presents a negative image of the park. It is suggested during the summer the scarp is reduced in slope and covered in sand from the debris basins. This sand would act as nourishment of the back beach. Alternatively the fill above MHHW could be removed to the seaward edge of the buffer and replaced with sand.

The actual rate of erosion could exceed the expected rate and therefore there is risk that some of the facilities would need relocation within the 20-year planning horizon and that the buffer may be completely eroded. As insurance for the protection of the park, a backstop revetment is suggested that would prevent further erosion beyond the buffer. This is indicated as a dashed line in the figures. Such a revetment need only be constructed when the beach had eroded through to the buffer. Beach nourishment would then be required to maintain the beach in front of the revetment.

At the western end of the beach, much of the existing parking area would need to be reconfigured to accommodate Parking Area A. Several existing buildings would need to be removed or relocated within Parking Area B. Parking Area C and D in the proposed design currently exist, but may need to be reconfigured to compensate for the loss of spaces elsewhere.

4.3 LONG-TERM VISION OF MANAGED RETREAT ALTERNATIVE

The longer-term (post 20-year) managed retreat alternative would allow the East Spit area to evolve naturally into a sand spit. The existing rock and parking lot would need to be removed to make space for the restored sand spit area. To the east of the restaurant and storage area is a roundabout that provides a turn around point and drop off area. The design also allows for views of the shore and limited parking for disabled persons in the vicinity of the roundabout. Some of the lost parking spaces may be relocated to other parking areas within the park. Existing rock could be reused to protect the eastern end of the park at the slough.

5. COMPARATIVE COSTS

These comparative costs are engineer's estimates of likely construction costs. The 20-year cost of alternatives has been projected in terms of present value assuming an annual rate of 6%. The Beach Nourishment and Structural Alternatives are based upon the Long-Term Beach Restoration and Shoreline Erosion Management Plan (Moffatt and Nichol, 2002).

5.1 BEACH NOURISHMENT

This alternative calls for the placement of 160,000 yd^3 of sand to be placed on Goleta Beach. The beach fill would extend from the west bluff to the pier, approximately 2200 ft long. The fill would increase the beach width to 100 ft. The cost estimate for obtaining, transporting and spreading upland sand on the beach is $25/$yd^3$ (Moffatt and Nichol, 2002). The approximate cost of the 2005 recharge is $4.0M.

The observed loss rates during the BEACON trial was in the order of 60,000 yd^3/yr. This is slightly less than the original estimate of 80,000 yd^3/yr (Moffatt and Nichol, 2002). At this rate, holding a beach in this position (without managed retreat) would require beach nourishment every two years. Years 1 to 20 cost of the nourishment would be $24.0M. Total 20-year cost would therefore be $28.0M.

An alternative using 260,000 yd^3 of dredged material to create an offshore sand berm was also suggested. The submerged berm would be placed 700 ft offshore and would be approximately 250 ft wide and 3000 ft long. It was assumed that the offshore sand berm would be reduced in size by approximately 40%, which is equivalent to placing 160,000 yd^3 of sand on the beach. The cost of placed sand was estimated to be $10/$yd^3$ (Moffatt and Nichol, 2002). The approximate cost of the 2005 recharge is $1.6M.

Assuming the same loss rate of 80,000 yd^3/yr, beach nourishment would be required every two years. Years 1 to 20 cost of the nourishment would be $10.0M. Total 20-year cost would therefore be $11.6M.

5.2 BEACH STABILIZATION

This alternative includes the construction of two groins, an attached rubble mound breakwater and beach nourishment on the beach (Figure 4). One rubble mound groin would be placed at the east end of the beach at the eastern edge of the parking lot and a sheet pile groin would be placed under the pier . Each groin would be 400 ft long. The cost of constructing the two groins is approximately $1.4M. The attached rubble mound breakwater would be at the west bluff and essentially act as an extension of the bluff. The attached breakwater would be 200 ft long and cost approximately $0.6M. In addition to the structures at the west and east ends of the beach, an initial nourishment of 160,000 yd^3 of sand would need to be placed on the beach at a cost of $4.0M, similar to the first alternative. The total initial cost of this alternative is $6.0M.

Even with structures in place it is expected that sand would be lost from the system. The rate of loss depends upon the trapping efficiency of the groins, which in turn is dependent upon their crest elevation and length. It is assumed that the groins are 80% efficient, cutting the loss rate to about 16,000 yd^3/yr. At this rate, maintaining a beach in this position (without managed retreat) would require beach nourishment every ten years. Years 1 to 20 cost of the nourishment would be $4.0M. Total 20-year cost would therefore be $10.0M.

The offshore sand placement approach cannot be relied on to pre-fill this alternative before downdrift erosion would occur and is not appropriate for the stabilization alternative due to the time taken for the sand to move onshore.

The Beach Stabilization alternative over the long term would cause downdrift erosion of the slough and the beach to the east of the slough. These unmitigated adverse effects could be a performance problem. Mitigation costs are not included in this estimate. In addition, there are potential safety issues associated with rock structures such as groins and breakwaters on beaches.

5.3 MANAGED RETREAT

The managed retreat alternative involves low initial costs of replacing fill from the back beach with sand, removing the western revetment and extending the eastern revetment. . The width and location of the buffer have been set to accommodate the likely shoreline evolution over the next 20 years and nourishment of the beach is expected only on a contingency basis. Erosion into the buffer is not anticipated to occur before 2025.

Removal of 1000 feet of rock forming the western revetment is estimated at $20k ($20/ft, Moffatt and Nichol, 2002). The extension of the eastern revetment, in front of parking lot C, by 150 feet is estimated at $0.25M ($1700/ft, Moffatt and Nichol, 2002).

It is suggested that the fill above MHHW is removed to the seaward edge of the buffer and replaced with sand. Removal cost of the fill would be $6-10/yd^3 if it could be reused on site and it is assumed upland sand would be used to replace it. Total volume of fill to be removed is about 20,000 yd^3 at a cost of $0.2M and replaced with about 30,000 yd^3 of sand at a cost of about $0.75M. Costs would be minimized if the beach fill was left in place, the erosion scarp was regraded each summer and allowed to erode the following winter. Total estimated initial costs would be about $1.2M.

The beach would then be allowed to retreat over the next 20 years. At predicted rates of future retreat the buffer will not be eroded until after 2025. The utilities and restrooms lie within the buffer zone and would not have to be moved until the back beach reached the buffer. The relocation of these facilities could be planned in advance and timed with the availability of funds. Cost for relocating the restrooms is approximately $0.2M for each restroom and the cost of new parking lots and lawn is estimated to be $0.8M (figures estimated by Santa Barbara County Parks).

A portion of the pressure sewer line has recently been relocated landward out of the buffer; the cost for relocating the remaining portion of the sewer line is estimated to be $50k (figure estimated by Santa Barbara County Parks). A larger undertaking is the relocation of 500 feet of the reclaimed water line that lies in the buffer zone between the West Bluff and the western restroom. The cost for relocating this portion of the reclaimed water line is estimated to be $0.5M ($100/ft, figure estimated by Santa Barbara County Parks).

If the beach is allowed to retreat to the edge of the buffer then it is estimated that longshore losses will be reduced from 80,000 yd^3/yr to about 10,000 yd^3/yr on average. This lower rate of loss will be more easily matched by natural updrift supply from the west, reducing the requirement for nourishment. Nourishment of the managed retreat alternative is not anticipated in the next 20 years. It may be required in subsequent years if the buffer zone is reached and utilities have not been removed. Smaller nourishments, carried out more often, may allow the reuse of suitable material captured in the debris basins of the Goleta Slough watershed. A backstop revetment may have to be constructed to protect the park if the beach does retreat more rapidly than anticipated. This would be constructed only where needed at an estimated cost of $1700/ft (Moffatt and Nichol, 2002).

With removal of the western revetment, extension of the eastern revetment, relocation of the restrooms, new parking lots and lawn, relocation of portions of the reclaimed water line, and replacement of the fill, the cost is estimated to be $2.9M. In the worst case, if the backstop revetment had to be constructed along the entire length of the beach, this would add an additional $3.7M. The total 20-year cost of the Managed Retreat Alternative would therefore range between $2.9 and $6.6M

5.4 SUMMARY OF ALTERNATIVES AND COSTS

The alternatives and their estimated costs described above are summarized in the table below.

Table 1 Summary of alternatives

	Existing Conditions	Beach Nourishment	Beach Stabilization	Managed Retreat
Lawn area	4.0	4.0	4.0	3.2 acres
Buffer area (sand or lawn)	-	-	-	1.3 acres
Beach area	3.0	4.5	4.5	4.5 acres
Parking spaces	550	550	550	550
Initial cost	-	$4.0M	$6.0M	$2.9M
Annual cost	-	$1.2M	$0.2M	-
20 year cost	-	$28.0M	$10.0M	$2.9-6.6M

6. REFERENCES

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7. LIST OF PREPARERS

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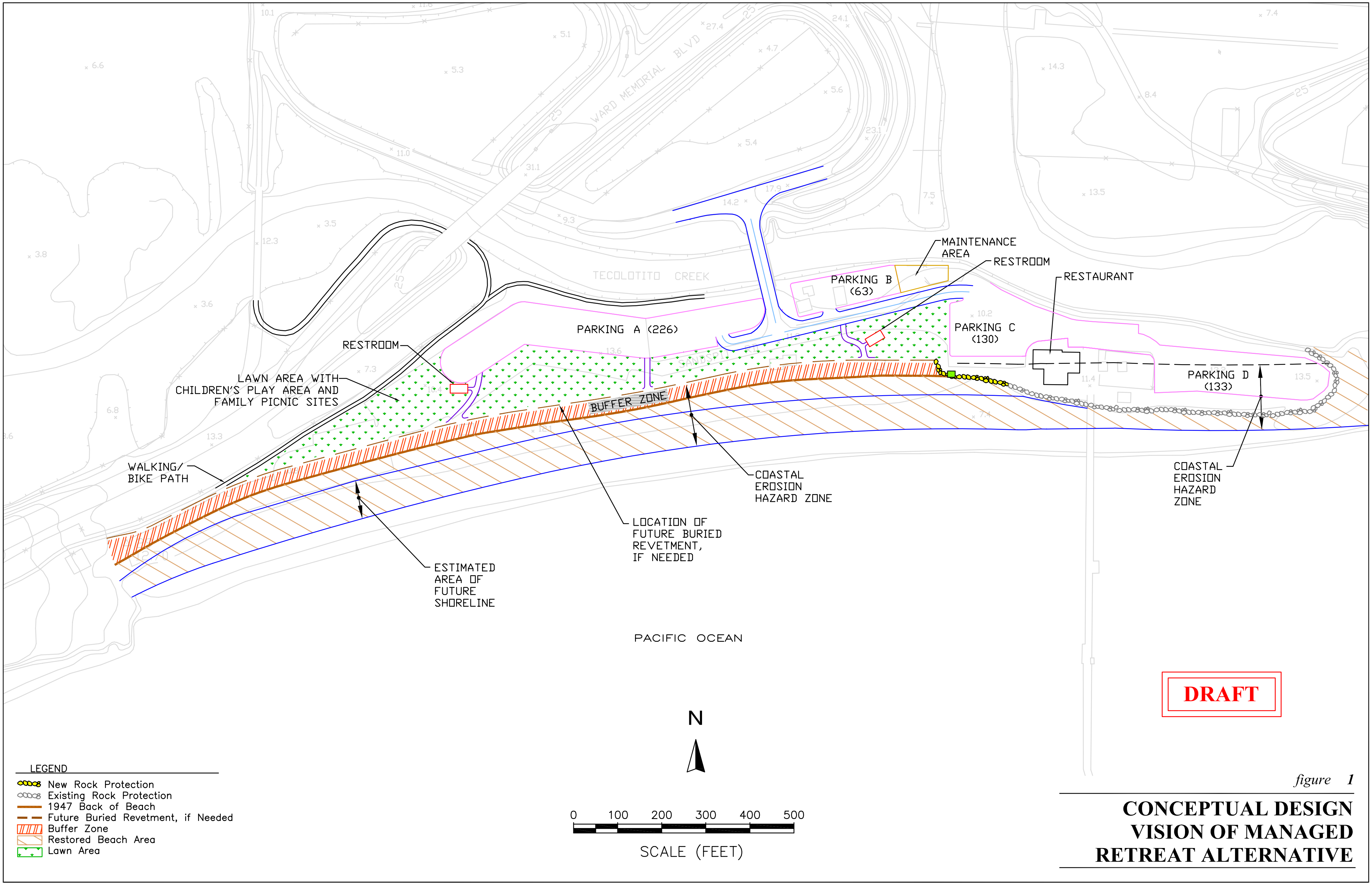

figure 1

CONCEPTUAL DESIGN VISION OF MANAGED RETREAT ALTERNATIVE

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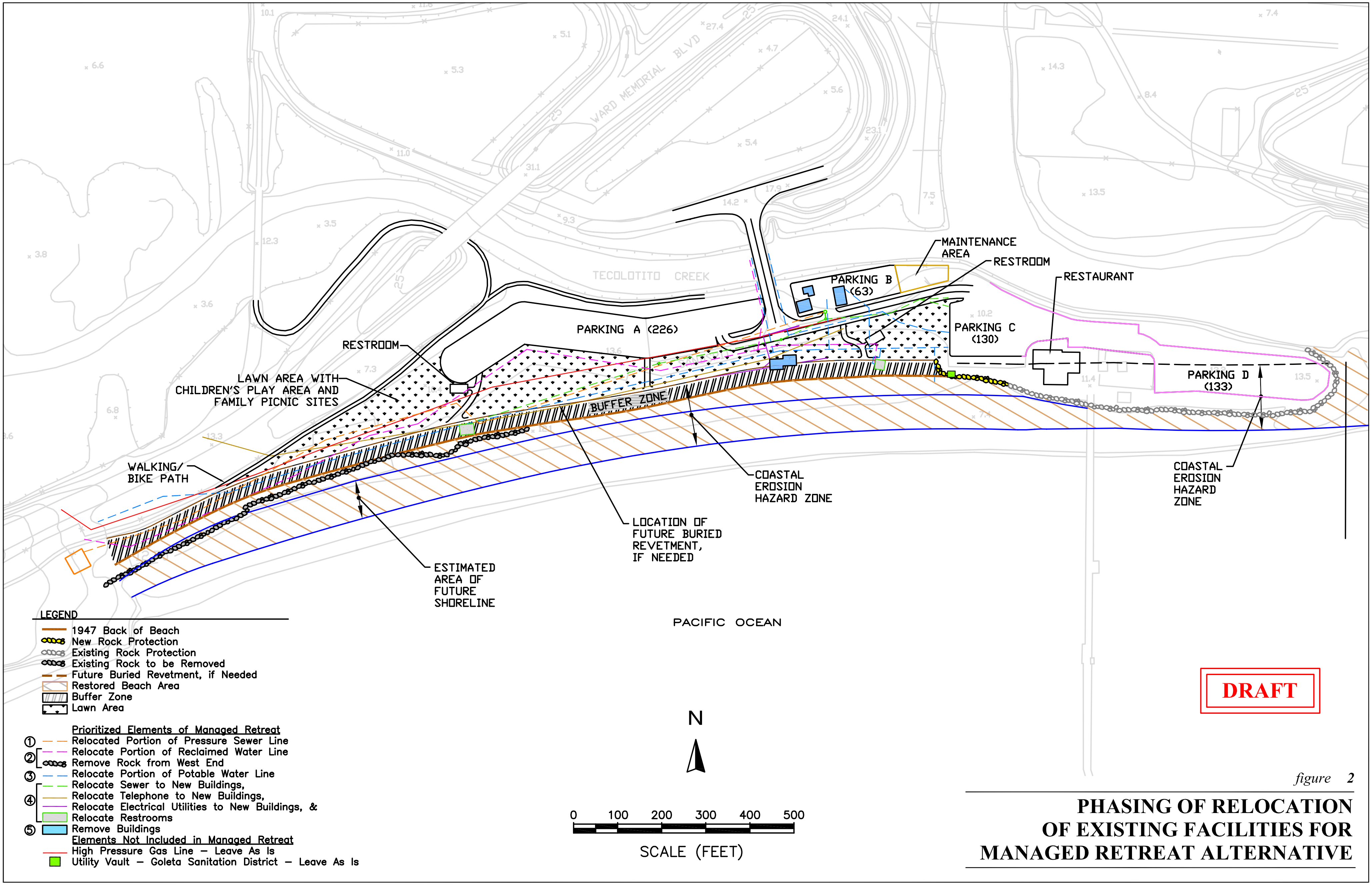

figure 2

PHASING OF RELOCATION OF EXISTING FACILITIES FOR MANAGED RETREAT ALTERNATIVE

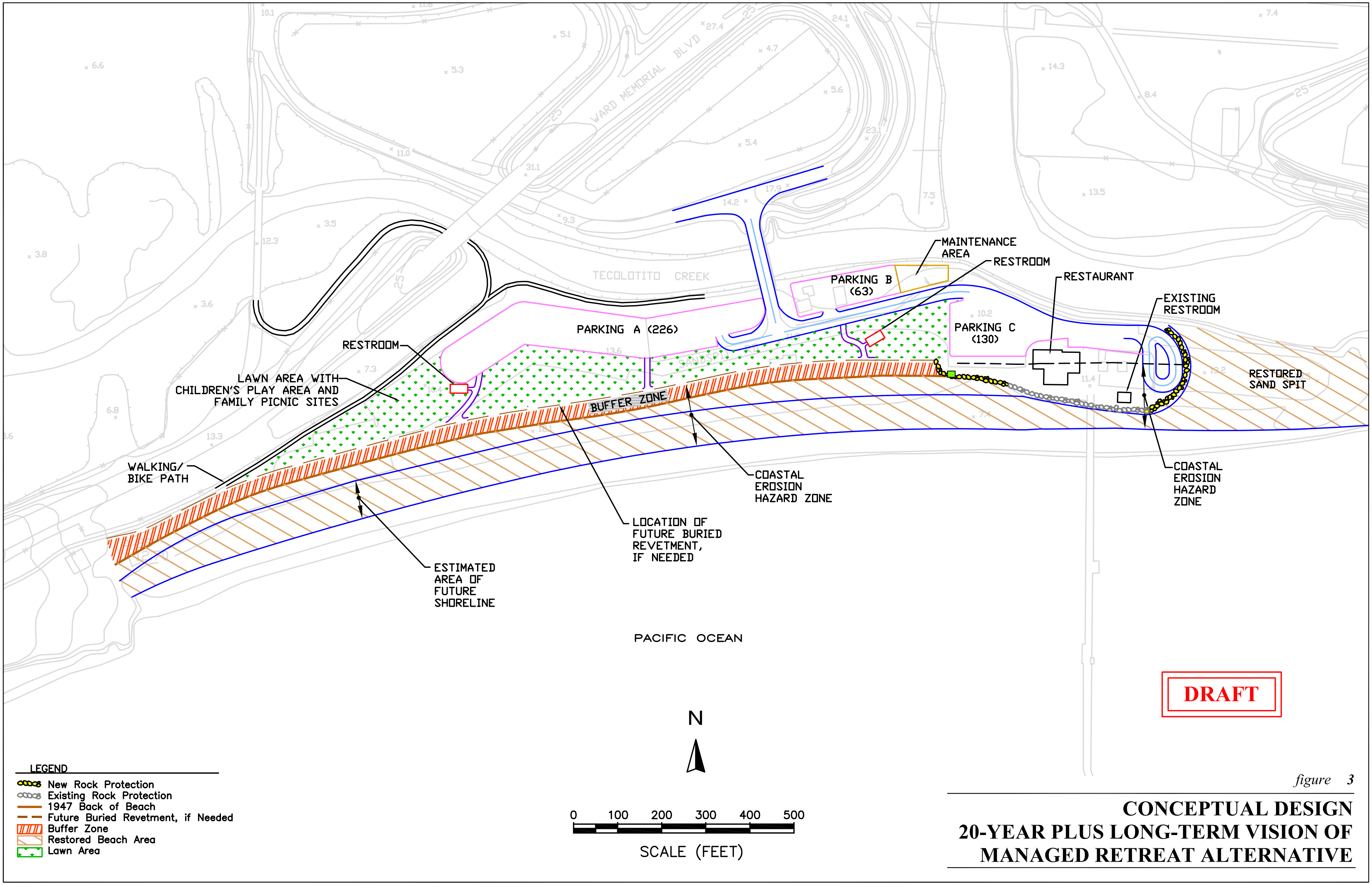

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figure 3

CONCEPTUAL DESIGN
20-YEAR PLUS LONG-TERM VISION OF MANAGED RETREAT ALTERNATIVE

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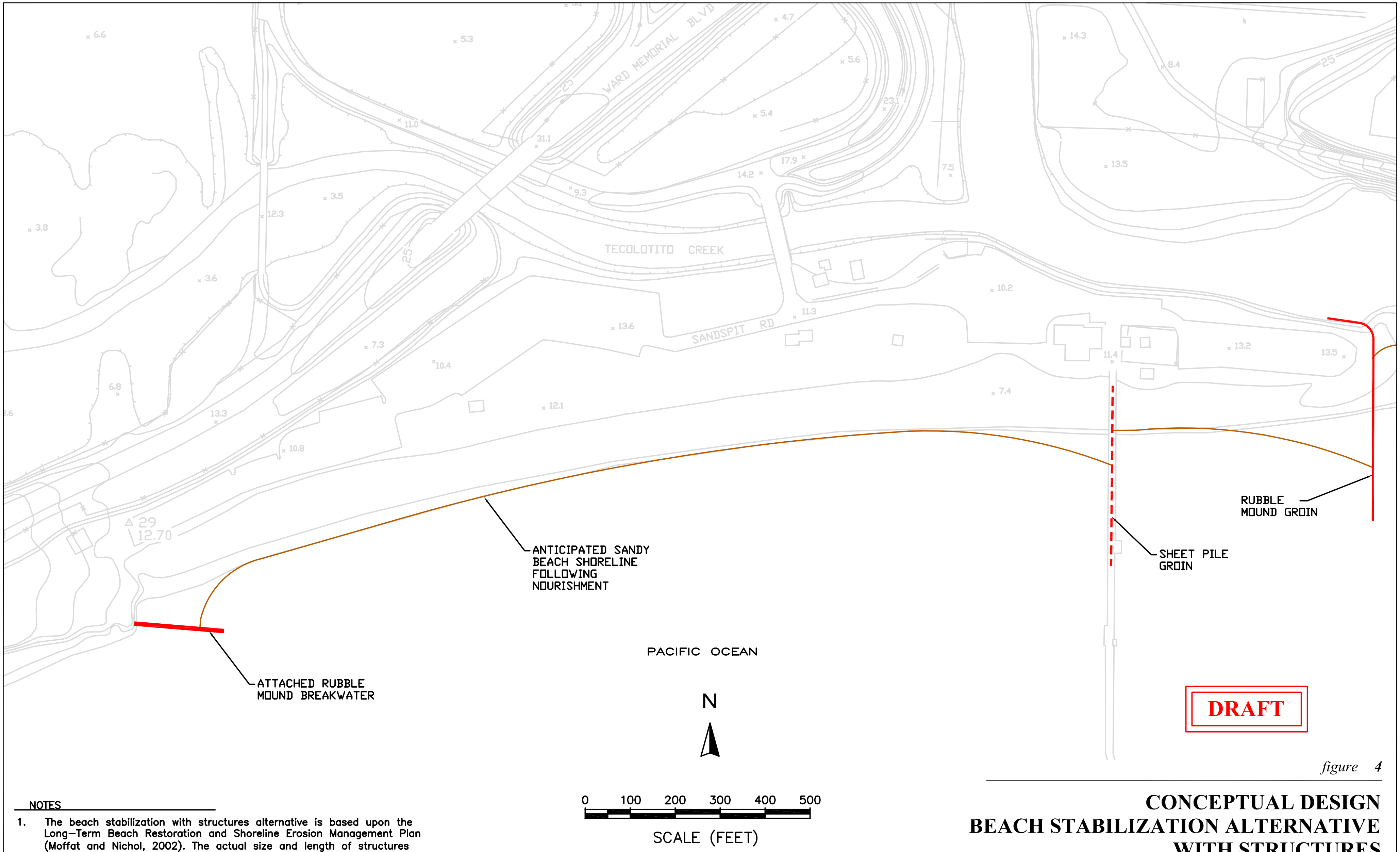

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figure 4

CONCEPTUAL DESIGN
BEACH STABILIZATION ALTERNATIVE WITH STRUCTURES

NOTES

1. The beach stabilization with structures alternative is based upon the Long-Term Beach Restoration and Shoreline Erosion Management Plan (Moffat and Nichol, 2002). The actual size and length of structures would need to be further analyzed to correspond to the nourished beach area. It is anticipated that the existing revetment would be removed along the length of the beach.

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Attachment 2

Exhibit 2: 2008 Study

Goleta Beach County Park
Park Reconfiguration Alternative

Prepared for
The Coastal Fund at UCSB
Surfrider Foundation – Santa Barbara Chapter
Environmental Defense Center

Prepared by

Philip Williams & Associates, Ltd.

November 24, 2008

PWA REF. #1940.00

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For planning purposes we have provided estimates of construction costs to allow cost comparison of alternatives. These cost estimates are intended to provide an approximation of total project costs appropriate for the preliminary level of design. These cost estimates are considered to be approximately -15% to +30% accurate, and include a 25% contingency to account for project uncertainties (such as final design, permitting restrictions and bidding climate). These estimates are subject to refinement and revisions as the design is developed in future stages of the project.

TABLE OF CONTENTS

1. PROJECT SUMMARY

This project provides a conceptual design of a park reconfiguration alternative at Goleta Beach County Park in Santa Barbara, California. The premise behind this project alternative is to reconfigure the infrastructure and park facilities to allow for natural shoreline processes and realignment. Recent scientific research has shown that the coastal processes operating at Goleta Beach are highly variable and have resulted in fluctuations in beach width over the last 75 years. These changes appear to be caused by cyclic climate phenomena that regulate the direction of waves and storms. Recent research findings also provide insight into an erosion wave that propagated along coast causing the recent erosion at Goleta Beach before migrating down coast affecting Arroyo Burro, Shoreline Park, and currently Ledbetter Beach. This alternative attempts to provide a new vision of Goleta Beach that functions more naturally in light of these recent scientific findings.

The proposed alternative is based upon:

1. Goleta beach has historically fluctuated and has experienced a state of dynamic equilibrium with the most landward extent of erosion being the 1943 back beach.
2. A "coastal processes zone" which is proposed to encompass the likely most landward limit of future erosion corresponding to the 1943 back beach,
3. Park infrastructure within the "coastal processes zone" is proposed to be relocated to the extent practical except for the restaurant and associated buildings which will remain protected by the existing revetment.
4. This alternative reasonably minimizes potential future erosion damage, allows natural beach fluctuations, optimizes the natural beach width, and avoids downcoast impacts associated with the pile groin currently proposed by the County.

This proposed alternative is estimated to cost approximately $4.7 million to construct as opposed to the pile groin alternative which is estimate to initially cost about $8.4 million.

The benefits of this Park Reconfiguration alternative are to reduce the hazards associated with episodic coastal processes while enhancing public recreational opportunities and beach access. This alternative is the lowest cost alternative as well as a long term investment in the park which upgrades facilities and recreational amenities while reducing long term costs. Another important benefit to this alternative is to reduce the potential for downcoast impacts. This contrasts markedly with the likely increases in disruption of longshore sediment transport associated with the County's current proposal which includes a pile groin. By removing potentially threatened infrastructure away from the ocean's edge, this alternative provides a long term vision for Goleta Beach as a unique place to recreate and enjoy a special experience along California's coastline.

2. INTRODUCTION

PWA was commissioned by Environmental Defense Center on behalf of the Surfrider Foundation- Santa Barbara Chapter to provide a conceptual design of a park reconfiguration alternative at Goleta Beach County Park. This task included updating information on recent scientific advances on the historic evolution of the Santa Barbara shoreline and providing visual representations of the alternative. This park reconfiguration alternative provides a contrast with the proposed Santa Barbara County Beach Stabilization / Permeable Pile Groin project submitted to the California Coastal Commission (CDP-4-08-006).

A primary driver for these project alternatives has been erosion at Goleta Beach initiated during the 1997-98 El Niño. During the Goleta Beach Master Planning process, PWA was contracted by Santa Barbara County to examine managed retreat and realignment alternatives (PWA 2005). At the end of this process, another consultant for the county proposed a pile groin as the preferred alternative to undergo environmental review by the county. Although this environmental review was not completed, the pile groin project was submitted to the California Coastal Commission (CDP-4-08-006) prior to certification of the project's Environmental Impact Report.

Accommodation for the beach under this park reconfiguration alternative creates more space for the natural coastal processes to occur. This is the fundamental difference between the reconfiguration alternative proposed here and the proposed pile groin. The pile groin alternative attempts to manipulate the environmental conditions to move the shoreline zone to a new location. Unlike the pile groin proposal, the Park Reconfiguration Alternative works with natural processes to create a stable shoreline and protect down-coast beaches and natural resources.

3. FACTORS AFFECTING THE SHORELINE

The major issue to consider is where the shoreline is located in relation to the rest of the park. Some functions of the park (e.g., the restaurant, parking lots) have to be located landward of the shoreline. Other functions, such as wave dissipation and some ecological and recreational functions have to be located seaward of the line. The long-term management of the park depends on understanding the interaction of the shoreline with the various functions of the park and how these functions will change in the future. Historic changes at the park including the introduction of artificial fill and placement of rock revetments have altered the natural shoreline location and reduced naturally occurring beach widths.

We usually think of the shoreline as a line drawn on a map but this is an artificial line drawn by man. In reality, the shoreline is not static, it is continually moving, and so over time it describes not a single line but a zone. In general, the shoreline represents some time-averaged high water mark and is used to represent an area of wave activity and of the dynamic beach. If set back enough, structures and assets landward of the shoreline zone would not normally be in danger from erosion and flooding.

The shoreline zone responds at a variety of time scales:

- In the short term (days to months), during a storm the shoreline may move landward as sand is dragged offshore to form bars. In calmer weather, sand moves onshore and builds up the beach so the shoreline moves seaward. This rhythmic movement of the shoreline can be clearly seen when comparing summer and winter profiles at Goleta Beach.

- In the medium term (seasons to years), the shoreline may be influenced by particular events. A large amount of sand arriving at that part of the coast due to erosion in the watersheds or elsewhere along the coast may deposit sand widening the beach and moving the shoreline seaward. Changes in wave energy and water levels associated with El Niño and seasonal fluctuations (e.g. winter storms) also cause the shoreline to move.

- In the long term (decades), trends in sea level and tectonic earth movements may cause the shoreline to migrate. In the case of sea level rise, the shoreline will tend to migrate landward, which has been the general history for the last ten thousand years. Tectonic earth movements can result in episodic uplift which tends to move the shoreline seaward. In addition, climatic patterns such as the Pacific Decadal Oscillation a 50-60 year climate cycle which changes phase roughly every 25-30 years affects the location of storm tracks focusing wave energy into and out of the narrow swell window of the Santa Barbara Channel. Finally, reductions in sediment supply from dam, debris basins, and shoreline armoring also influence the shoreline position.

The natural position of the shoreline is not random – it is a response to a number of environmental variables and the beach is continually adjusting itself to accommodate changes in these variables:

- Wave energy – a beach dissipates wave energy in a number of ways by providing a long rough surface over which wave energy is transformed, into breaking waves and converted into sound, heat, sediment transport, and currents. Goleta Beach is relatively sheltered from large northwest wave events by the narrow swell window between Point Conception and the Channel Islands. At a more local scale, wave refraction around Campus Point further reduces wave energy. However, during large wave events, often associated with El Niños, when swell direction is more west, the response of the beach profile is to flatten and erode inland. These profile changes increase the ability of the beach to dissipate wave energy and are part of the natural beach response to storms. The narrowing or truncating of the beach area (e.g. as due to the existing revetment) available for wave energy dissipation can lead to an increase in scour on the fronting beach, and lower the sand levels.

- Sand supply– sand to Goleta Beach comes predominantly from the creeks and rivers to the north and west. Local geologic formations forming the nearby bluffs along Isla Vista only contribute small amounts of sand (Runyan and Griggs 2004) to the beach although the contribution of cobbles is not well understood. Sand arrives along Santa Barbara beaches often during episodic storm events when stream and river discharge pulse sediment into the ocean as deltas. Over time these deltas erode as sand is transported onshore during low wave energy conditions. Proliferation of dams and debris basins have impounded sand and reduced the amount of sand contributed to the beaches of Santa Barbara and Ventura County by about 40% (Willis and Griggs 2003). A reduction or interruption in upland or updrift sand supply is a primary cause of shoreline erosion.

- Sand transport - Sand along the Santa Barbara coast does not just move onshore and offshore, it also moves east along the coast (alongshore). Waves approaching a beach at an angle will tend to move sand along the coast. In general, the larger the incident wave angle and the larger the waves, the greater the transport of sand. The angle the waves approach is governed by the direction of storms and ocean swell waves, the shape of the seabed for several miles offshore and the shelter provided by headlands and islands. The shoreline may be relatively stable even though a large quantity of sand is being transported provided an equal quantity of sand is arriving from further up the coast. Along Goleta Beach to the Santa Barbara Harbor, estimates of the long term average annual alongshore transport is around ~300,000 yds^3(Patsch and Griggs 2007). However given the episodic nature of sediment supply and storm events in this region, the actual transport in a particular year typical differs from the long term average, and can vary with location along the shoreline (described further below).

- Sea level rise – the position of the shoreline is defined where the beach profile and the surface of the sea intersect. With rising sea levels, associated with climate change, the point of intersection will tend to move landward, moving gradually over decades. Relative sea level rise is the difference between global sea level rise rates and vertical land motions affected by local tectonic conditions. Episodic tectonic movements cause the land levels to rise faster than sea level with the result to move the shoreline seaward. Geological dating of the West Bluff at Goleta Beach places the age at ~45,000 years BP and provides some indication that this section of coast is uplifting at about the same rate of sea level rise ~2mm/yr (Keller and Gurrola 2000).

The key is to understand the width and location of the dynamic coastal processes zone in which the shoreline will fluctuate in the future in response to large wave events, changes in sediment supply, and sea level rise, and to accommodate this dynamic coastal processes zone with the other functions of the park.

4. RECENT SCIENTIFIC STUDIES RELATED TO GOLETA BEACH

Substantial research on Goleta Beach has been completed by several authors since the publishing of the PWA report (2005). The most pertinent articles are Revell and Griggs, Revell, Dugan, and Hubbard (in press), and Hapke et al. (2006, in press, 2006). In addition, there are ongoing efforts of the USGS combining long term shoreline and beach change research by Revell with ongoing seasonal monitoring funded in cooperation with BEACON.

In Revell and Griggs (2006), the authors found that the beaches along Goleta have not exhibited a high long term erosion trend, but rather beach widths oscillate apparently in phase with the Pacific Decadal Oscillation. During positive "cool" phases ("El Niño like"), storms come from a more westerly direction (Adams, Inman, and Graham 2008), resulting in a reduced sheltering of Goleta Beach from waves.

During the opposite phase, storms tend to be shifted northward increasing the wave sheltering and reducing wave energy resulting in wider beaches.

These authors also identified significant reductions to beach widths in front of shoreline armoring structures as a result of placement loss and passive erosion. The placement of rock revetments onto the beach reduces the overall beach area available for recreation and habitat while negatively impacting public beach access both vertically and laterally. Another significant impact to Goleta Beach has occurred at the ebb delta to Goleta Slough. The ebb delta was largest in 1938 prior to the development of the Santa Barbara Airport. The decline of this delta has been linked to the reduction in tidal prism as a result of filling of the Goleta Slough to construct the Santa Barbara airport.

The research by Revell, Dugan, and Hubbard (in press) grew directly out of a question that arose during the Goleta Beach Master Planning stakeholder process, “What is the impact of a large El Niño on Goleta Beach?” By combining topographic LIDAR data, historic shoreline change information, and measurements of ecological indicators, the authors examined the physical changes caused by the 1997-98 El Niño and the ecological response including identifying some timelines to beach and ecosystem recovery. The research found that the beaches narrowed by more than 50%, lost more than 60% of sand volumes, and also rotated in response to the El Niño storms. Beach rotation is a natural response of beaches during large storm events (often associated with El Niños) to reduce longshore sand transport and maintain sand on the beach. In this study, the authors identified the causative mechanism for the recent erosion at Goleta Beach - propagation of an erosion wave. After the El Niño, updrift Ellwood Beach remained in a rotated position for at least two years after the event. During this period, sand was naturally impounded at Ellwood, which initiated an erosion wave that migrated downdrift starving Goleta Beach. Historic profiles collected by Coastal Frontiers during monitoring of the Goleta Beach nourishment project, and subsequent seasonal surveys by the USGS, show a pulse of sand arriving at Goleta Beach in 2005. By 2005, the beach at Goleta had largely recovered its ability to buffer erosion. Currently, the erosion wave has continued to propagate downdrift affecting Arroyo Burro, Shoreline Park and is currently located at Ledbetter Beach on its way to the Santa Barbara harbor.

The last pertinent studies to Goleta Beach include examination of long term shoreline changes (1870s to recent) by the USGS and Revell. Both studies, using slightly different techniques, found that average annual long term shoreline change rates for Goleta Beach are less than -7in/yr (Hapke et al 2006, Revell and Griggs 2007). However, the average annual changes detected using a linear trend must be questioned given the oscillations observed in beach widths, and the large variability associated with the episodic nature of large storms and wave events. During this study, Revell identified that the 1943 shoreline was the most landward extent at Goleta Beach observed in the historic air photo record. In 1945, following the 1943 most eroded conditions, human changes resulted in the filling of much of the parkland artificially pushing the park seaward.

4.1 CONCEPTUAL MODEL FOR GOLETA BEACH

The recent measurement and observation of beach oscillations, stable sandy beaches (beaches that always have some sand and hence wider minimum beach widths), the measurement of storm event beach rotations and the historic and current documentation of erosion and accretion waves provide the basis for a revised conceptual model of beach behavior along the Santa Barbara coastline (Revell and Griggs 2006, Revell, Dugan and Hubbard in press, Revell and Griggs 2007). This conceptual model also builds on the discussion of the hook shaped bay presented in PWA 2005.

Along the Santa Barbara coastline, the stable beaches such as Goleta Beach and Ellwood form different sized sand boxes or sand deposits (hereafter referred to as boxes). These boxes are connected by the movement of sand between the boxes as driven by waves. Areas without much sand, such as Isla Vista, are typically stretches of shoreline where transport is more rapid and sand does not remain for long; these are not considered boxes. The sand boxes tend to extend from the base of the cliffs to a moderate depth offshore (~2m). In dune backed boxes, (e.g Ellwood and historically Goleta) these boxes extended well inland to encompass the entire dune system.

During calm wave energy periods, these sand boxes tend to be wide such as those beaches seen during the calm PDO phase in the 1970s (Revell and Griggs 2006) when wave energy was reduced. As each box fills, it must reach a certain level before it cascades sand downdrift making it available to the next box. When this cascading transport of sand is interrupted, (e.g shoreline rotations, or human alterations such as the construction of the Santa Barbara Harbor breakwater) or reduced (e.g. the proposed permeable pile groin), then the downdrift box closest to the impoundment begins to erode. Once that first downdrift box is reduced below the bypass level, then the next box downdrift begins to erode. Conversely as sand is moved around the impoundment, the downdrift boxes fill up again in the order that sand is received. In this example, as Ellwood filled up to the bypass level, sand cascaded downdrift to fill the next box, Goleta Beach.

During a major erosion event such as an El Niño, the boxes lose most of the sand AND the beach changes shape by rotating into the dominant wave direction - generally clockwise in response to large waves from the west. In dune backed boxes, the size of the box can get temporarily larger as sand is eroded from the dunes supplying even more sand to the overall system and thus reducing some of the erosion impacts. During these erosion events, much of the sand volume (>60%) is lost revealing a layer of cobbles that, without the sand on top, changes its behavior (due to increased porosity), and gains elevation providing a dynamic cobble revetment that becomes active during large erosion events. This change of shape and size of the boxes, and coarsening of grain size reduces some of the erosion impacts. It also affects the storage capacity of each box and can increase the recovery time for each box to reach bypass level. Only after a box reaches its unique bypass level will it begin to cascade and fill downdrift boxes. At Goleta Beach, the erosion wave initiated during the 1997-98 El Niño was a result of the lack of input from upcoast sediment sources during the time required to fill the sand box at Ellwood.

Generally most of the sand cascading between boxes occurs during the winter time in higher energy conditions. Since many of the boxes are located near inlets, if there is a flood event, many of these boxes gain sand. However, the sand that is gained is generally deposited offshore in deltas and not immediately used to fill the boxes. These deltas may however reduce rates of longshore sand transport which can result in wider beaches updrift. The deterioration of the ebb delta at Goleta Beach may be enhancing storm erosion impacts. Over time (seasons to years), the sand deposited in the deltas moves landward and fills in the boxes. Disruptions or alterations to the shape or storage capacity of these boxes such as that proposed under the pile groin alternative has the potential to impact downcoast beaches.

4.2 IMPLICATIONS FOR FUTURE MANAGEMENT

1. The oscillation of Goleta Beach appears to be a balance between occasional large pulses of sediment that widen the beaches and erosion periods when the sediment is transported eastward. Wave direction is especially important with most erosion occurring during energetic southerly El Niño conditions – which produces large waves from the west, and a reduction in wave energy during the negative phase of the Pacific Decadal Oscillation – associated with waves predominantly from the north. Recent indications from NASA suggest that we may be entering a negative phase of the PDO (2008).

2. In the event of future erosion waves such as the one that impacted Goleta following the 1997-98 El Niño, nourishment in the erosion wave of appropriate volumes could be conducted to reduce the recovery time and prevent further deterioration of beach buffering capabilities. Following the 1998 El Niño, about 510,000 yds^3 were removed from the beaches from Ellwood to Goleta with Goleta losing approximately 175,000 yds^3 of sand (Revell, Dugan and Hubbard in press). This erosion especially at updrift Ellwood catalyst the erosion wave. In order to offset a similar erosion wave an estimated 175,000 yds^3 of sand would be needed. This volume is of greater quantity than any single nourishment effort following the 1998 El Niño event despite an approximate ~270,000 yds^3 of sand nourished sporadically during the 9 years (~30,000 yds^3/yr) following the event (Moffat and Nichol 2008).

3. Infilling of Goleta Slough and the consequent reduction in the ebb delta has reduced the stability and possibly increased the longshore transport along Goleta Beach.

4. The park reconfiguration alternative will provide additional room for coastal processes to occur.

5. Another pulse of sand arrived at Goleta Beach in fall of 2005, with the corresponding beach widening providing additional erosion protection.

5. PARK RECONFIGURATION ALTERNATIVE

A conceptual design for a park reconfiguration alternative has been developed that considered the goals and outcomes from the Master Planning Working Group process, input from EDC and Surfrider

Foundation, and an understanding of historic and future shoreline evolution. The design consists of a park reconfiguration which allows for natural shoreline realignment along the west end of Goleta Beach and includes beach restoration, removal and refinement of coastal armoring, and the relocation of existing utilities and structures.

The constraints used to shape the alternative include:

- Same number of parking spots as 2008 (594)
- Same number of restrooms and facilities
- Same acreage of lawn as 2008 (4.0 acres)
- Similar acreage of beach as 2008 (3.0 acres)
- No new rock
- No backstop revetment landward of coastal process zone
- Removal of ranger housing and surrounding buildings as planned
- Maintain restaurant
- Maintain Pier

The philosophy behind the park reconfiguration alternative is to relocate threatened infrastructure from the seaward side of the park and put it on the landward side of the park. This will enable more room along the seaward side of the park for coastal processes to occur naturally, while enhancing the recreational and park amenities on the lawn area between the parking lots and the beach. (Figures 1, 2).

To determine the potential extent of shoreline realignment, a coastal processes zone is herein defined as an area in which storm induced erosion and flooding can cause either an erosion of the shoreline or damage to infrastructure that lies within the zone. The intention is to remove facilities, infrastructure and utilities from this zone (figure 3). Moving utilities and structures landward of this coastal processes zone would provide a setback from the existing shoreline and provide an increase in the area over which natural coastal processes could operate.

The coastal processes zone was defined landward using the 1943 back beach shoreline. The 1943 shoreline is the most landward observed in the past 80 years and pre-dates significant human alterations. The area between the landward edge of the buffer zone and the maximum seaward shoreline measured in 1975 provides the seaward limit of the coastal processes zone (Figure 4).

5.1 20-YEAR VISION OF PARK RECONFIGURATION ALTERNATIVE

Within 20 years, realignment to a stable shoreline position would be allowed to the west of the restaurant as shown in Figures 1 and 2. The restaurant and the parking lot on the spit to the east would remain in place protected by the existing rock revetment[1]. The area from the west bluff to the restaurant

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[1] The County may consider re-engineering this revetment given its current condition. While not included in this alternative, the potential exists to reduce the overall footprint of this structure while maintaining existing parking levels. A relocation of the pier restroom would upgrade the park facilities enhancing both public recreation and natural beach area while remaining consistent with the intent of this alternative – reconfigure the park to allow more room for natural processes to occur.

accommodates future coastal evolution within the coastal processes zone. The park reconfiguration alternative shows the coastal process zone as a restored beach area (Figure 1).

Landward of the coastal processes zone is a beach park area that includes the existing park amenities reconfigured for the future shore conditions: space for the same acreage of lawn that currently exists, a playground, barbecue pits, horseshoe pits, picnic tables and group picnic areas, public restrooms and paths that connect the beach to the parking areas. The approximate area of the lawn in the proposed Park Reconfiguration alternative is 4.2 acres with an initial .2 acre gain compared to existing conditions as a result of Parking Lot A relocation. This increase in lawn would be located in the coastal processes zone, so overtime this increase may be reduced to existing levels. This reconfiguration also extends the desirable beach/lawn interface and potential beach access by over 850 feet to a total of 1900 linear feet.

Landward of the beach park area are Parking Areas A and B and maintenance area. The maintenance area and ranger housing would be removed as already planned by the County. In the Park Reconfiguration alternative design, Parking Areas A and B are shown connected to the restored beach area with paths to focus beach access.

Approximately 1000 feet of existing rock revetment at the west end of the park would be removed; this section of revetment is not necessary under the proposed alternative. However, at this time, it is not practical to relocate the existing restaurant, adjacent restroom, and surrounding infrastructure given the economic value and lease arrangements with the restaurant. The existing rock revetment in front of the restaurant and restroom would be extended by 150 feet to the west to protect Parking Area C and the sewer outfall vault. The rock removed from the existing west end revetment would be used to protect the sewer outfall vault. The remaining rock will be stockpiled on site at the County maintenance yard or used to bolster the existing eastern rock revetment.

As the west end and mid park revetments are removed, the underlying fill will be regraded to provide safe public access then covered with sand and vegetated (Figure 5). This area within the coastal processes zone may be subject to episodic erosion which would likely oversteepen or create a scarp in the fill material. Ongoing maintenance in the spring would be required to regard this scarp and renourish with opportunistic sediments.

Ideally, the relocation of utilities and park amenities occurs initially, but it is not required that all the proposed changes in the conceptual design occur at once. Proposed changes could be implemented in a phased manner to accommodate the evolution of the beach and budgetary constraints, and to time work to avoid highest park use periods. It is recommended that relocation of existing utilities and restrooms within the coastal processes zone be completed early in the project, but it is possible to relocate facilities within the coastal processes zone on an as needed basis. This may affect the cost at the actual time of implementation.

5.2 PHASING OF 20-YEAR VISION

For the park reconfiguration alternative, existing utility lines, buildings, and parking lots would need to be reconfigured or removed to accommodate the design. It is anticipated that the coastal processes zone would be eroded at least once in the next 20 years given the trends in long term shoreline changes and the episodic pulses of sediment moving along the coast. While the beach would likely recover from such an erosion event, facilities in the zone may be damaged or lost. Structures and utilities within this zone, such as the restrooms, need not be relocated immediately but as erosion threats warrant and budgets allow. It is recommended a triggering threshold of 20 feet be used to identify when a utility or structure needs to be relocated. Figure 3 shows the elements in which either portions of utility lines or existing structures need to be relocated or removed as part of the park reconfiguration.

The utilities to be relocated include:

- Goleta Water District reclaimed water line
- Goleta Sanitation District pressure sewer line
- Potable water line
- Southern California Gas Line[2] (which lies outside the coastal processes zone)
- Small sewer lines to existing restrooms
- Park irrigation lines

Relocated facilities include:

- Parking Lot A
- Two restrooms
- Ranger housing (planned to be removed by County already)

The initial work includes removing the west end revetment and relocating Parking Area A landward. The next step is to regrade the scarp in the fill material at a 5:1 slope (H:V) and add lawn and sand at the landward extent of the beach (Figure 5). The vertical scarp in the fill that that forms following an erosion event could be a safety issue and also presents a negative image of the park. It is suggested if the scarp is exposed during the spring that the scarp be regraded (at 5:1 slope; H:V) and covered in sand e.g. from the sediment debris basins, and flood control projects located within the Goleta Slough watershed. This sand is already permitted for placement under BEACON's South Central Coast Beach Enhancement Program for opportunistic sediment use permit (SCCBEP). This sand would act as supplemental nourishment of the back beach.

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[2] We assume that responsibility for this infrastructure lies with the Utility District since it is a private entity utilizing public lands and is not the responsibility of the County of Santa Barbara. However, we have included this relocation cost for reference only and envision a cooperative approach between the county and utility districts to obtain funding e.g. grants and/or state funds and generate support from various stakeholder groups. This is not included in any of the cost estimating associated with any of the alternatives.

At the western end of the beach, much of the existing parking area would be reconfigured to accommodate Parking Area A. Several existing buildings would be removed or relocated as currently planned - within Parking Area B, including several maintenance sheds and onsite ranger housing. Parking Areas C and D in the proposed design currently exist, but will need to be reconfigured and restriped to compensate for the loss of spaces elsewhere. The total number of parking spaces in the park reconfiguration alternative is based on a uniform parking space dimension of 8 feet wide by 15 feet long as measured in air photos. A rigorous analysis to optimize the parking spaces, including spaces for varied sizes for compact cars and disabled parking, was not conducted as part of this analysis. There are a total of 594 parking spaces based on this estimate which is reported to be the current level of parking. The intent behind the parking analyses is to ensure that there will be equivalent number of parking spaces for the park reconfiguration alternative.

Given the likelihood that there could be another energetic El Niño in the next 20 years, the park reconfiguration alternative includes a one time erosion wave response nourishment of 175,000 yds^3 at some unknown date in the future. Annual maintenance costs for all alternatives would include seasonal monitoring as well as routine maintenance which should be similar for all alternatives. The park reconfiguration alternative would likely have slightly reduced operating costs due to the upgrading of new restroom and parking facilities and thus not require as many repairs.

5.3 ADDITIONAL OPTIONS

Several other options for the park reconfiguration alternative could also be included although these have NOT been cost estimated or incorporated into the proposed park reconfiguration alternative.

One option would be to replace the bathroom on the south side of the pier with a new restroom set inland on the opposite side of the restaurant buildings. This option would create space to enable a realignment of the armoring on the south side of the pier and increase the area available for the natural coastal processes at the most narrow point along Goleta Beach.

Another option to be considered would be the use of impervious pavement for all of the new parking lots. This would serve the purpose of improving local water quality conditions, and providing an educational showcase on one method of low impact development. These additional options could be included in any preliminary design stage if the county decides to move forward with this reconfiguration alternative.

6. COMPARATIVE COSTS

The Park Reconfiguration alternative's costs are PWA's preliminary engineers' estimates of likely construction and operation/maintenance costs. The County EIR's managed retreat and pile groin projects' costs are based upon the recent cost estimates by Moffatt and Nichol Engineers Long-Term Beach Restoration and Shoreline Erosion Management Plan (Moffatt and Nichol, 2002). For comparative purposes all of the cost alternatives are present in 2007 dollars.

For planning purposes we have provided order of magnitude estimates to allow cost comparison of alternatives. These cost estimates are intended to provide an approximation of total project costs appropriate for the preliminary level of design. These cost estimates are considered to be approximately -15% to +30% accurate. These estimates are subject to refinement and revisions as the design is developed in future stages of the project.

6.1 PARK RECONFIGURATION

The Park Reconfiguration alternative: removes and regrades fill from the back beach, replaces fill with sand, provides for major reconfiguration of existing parking lots that currently require reconstruction, removes the western segment of revetment, extends the eastern revetment and relocates restrooms and utilities farther inland. All park improvements (except the lawn) are proposed to be moved inland of a “coastal processes zone” consistent with contemporary research. The width and location of the coastal processes zone have been established to accommodate the likely shoreline fluctuations over the next 20 years and nourishment of the beach is expected only on a contingency basis with a one time nourishment cost estimated in response to a major erosion event. However, based on historic data, erosion into this zone is not anticipated to occur before approximately 2028.

The reconfiguration presented herein is one possible layout that maintains all uses and elements (in terms of function, not existing location) previously identified by County Parks, and included in other alternatives. The precise park configuration is subject to further design and community input.

Removal of 950 feet of rock forming the western revetment is estimated at $209k ($220/ft, modified from Moffatt and Nichol, 2008). The extension of the eastern revetment, in front of parking lot C, by 150 feet is estimated at $0.33M ($2200/ft, updated from Moffat and Nichol, 2002).It is assumed that the removal of rock from the western revetment will be used directly to extend the eastern revetment with the remaining material stockpiled at the County maintenance yard or placed on the existing eastern revetment.

The fill above MHHW would be removed to the seaward edge of the buffer and replaced with sand. Removal cost of the fill would be approximately \$11/yd^3 and include excavation and reuse on site during construction of the new parking lots. Sand backfill and fill will be accomplished using upland or opportunistic sand (already permitted under SCCBEP) or offshore sources. The total volume of fill to be removed is approximately 20,000 yd^3 at a cost of \$0.22M and replaced with approximately 30,000 yd^3 of sand at a cost of approximately $0.44M. Initial costs would be minimized if the beach fill was left in place; the erosion scarp regraded each spring and then allowed to erode the following winter (Figure 5) This phased approach would then increase the ongoing operations and maintenance cost. Total estimated initial costs considering the total removal of the fill as part of the initial construction is $0.96M.

The beach would then be allowed to fluctuate over the next 20 years in a state of dynamic equilibrium. At measured rates of historic retreat the coastal processes zone will not be eroded until after 2028. Although these rates do not account for the pulses of sediment through the system, the coastal processes zone will enable these natural processes to occur without jeopardizing infrastructure and park facilities. There are also some indications that we may be entering a different phase of the Pacific Decadal Oscillation which would be more conducive to beach accretion (NASA 2008). The utilities and restrooms lie within the coastal processes zone and would not have to be moved until the back beach reached within 20 feet of these facilities zone. The relocation of these facilities should be planned in advance and timed with the availability of funds. Cost for relocating two restrooms including necessary infrastructure is approximately $0.44M (figure estimated by Santa Barbara County Parks and updated to 2007 dollars). The cost of new parking lots is approximately $0.6M using unit costs of $3.60/sf from Moffatt & Nichol Engineers. The new lawn is estimated to be $136K.

A portion of the pressure sewer line has recently been relocated landward out of the coastal processes zone; the cost for relocating the remaining portion of the sewer line inland is estimated to be $58K (figure estimated by Santa Barbara County Parks and updated to 2007 dollars). A larger undertaking is the relocation of 500 feet of the reclaimed water line that lies in the processes zone between the West Bluff and the western restroom. The cost for relocating this portion of the reclaimed water line inland is estimated to be $0.57M ($1000/ft, figure estimated by Goleta Water District and updated to 2007 dollars) Additional utility relocations include 900 ft of electrical and telephone lines at a cost of $57K, 1100 ft of potable water line at a cost of $45K (figures provided by Santa Barbara County and updated to 2007 dollars). A high pressure gas line exists at the site and is assumed to remain in its current location and thus is NOT included as part of the Park Reconfiguration Alternative.

To be thorough, the construction cost for the new high pressure gas line was estimated at $500,000 to $800,000. This estimate is from the presentation by utility companies to the Goleta Beach Park Working Group on March 4, 2004. This was summarized in a letter to Steve Hudson and Jenn Feinberg from Dave Ward, dated 2-15-2008. These costs were updated to 2007 dollars (to match all other dollars in the memo and cost estimate) to arrive at a range of $570,000 to $910,000.

A one time beach nourishment is included as a contingency element estimated to occur within the 20-years following project construction. A volume of 175,000 cy is included in the Park Configuration Alternative at a unit cost of $14.5/cy (estimate from Moffatt & Nichol Engineers, 2007). This volume of sand would widen the entire Park beach about 40 to 50 feet (following redistribution to the entire shoreface). It is anticipated that this level of beach nourishment would be desired following a severe winter such as that associated with a strong El Nino. This may or may not occur within the 20 year planning horizon. This item could also be considered a necessary addition to the other alternatives as well, which are also susceptible to storm impacts and erosion waves.

With removal of the western revetment, extension of the eastern revetment, relocation of the restrooms, new parking lots and lawn, relocation of portions of the sewer line, water line, electric and telephone lines, and the reclaimed water line, replacement of the fill, the initial project cost is estimated to be $4.7M, and with the ongoing beach nourishment as needed on a contingency basis the 20-year project cost is estimated to be $8.4M.

6.2 SUMMARY OF ALTERNATIVES AND COSTS

The alternatives and their estimated costs described above are summarized in the Table 1 below. A detailed cost summary and comparison of the alternatives is presented in Table 2.

Table 1. Summary of Alternatives (2007 dollars)

	Existing Conditions	**Managed Retreat**	**Permeable Pier/ Pile Groin**	**Park Reconfiguration**
Lawn area	4.0	2.87	4.0	4.2 acres
Buffer area (sand or lawn)	-	1.3	-	1.3 acres
Beach area	3.0	4.0	8.6	4.5 acres
Total area for recreation	7.0	8.5	12.6	10.0 acres
Alongshore length of lawn/beach	1,035	1,900	1,300	1,900 ft.
Parking spaces	594	594	594	594
Sand Pre-fill	-	100,000 yds^3	550,000 yds^3	30,000 yds^3
Initial cost	-	$7.5M	$8.7M	$4.7M
20 year cost	-	$11.1 M	$9.6M*	$8.4M

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* This cost does not include future nourishment which could increase the cost an estimated $10.5M (see text p. 17)

Table 2. Detailed Summary and Comparison of Alternatives.

Construction Element	Managed Retreat Alternative	Beach Stabilization (Groin) Alternative	Park Reconfiguration Alternative
Estimate Prepared by:	Moffat & Nichol	Moffat & Nichol	PWA
Initial Construction Phase	**Estimated Cost[1]**	**Estimated Cost[1]**	**Estimated Cost[1]**
Mobilization & Demobilization	$200,000	$100,000	$100,000
Temporary Protective Fence	$12,600	$18,600	$9,000
Detour Traffic	$15,000	$15,000	$15,000
Utility Relocations	$275,500	$0	$728,000
Demolition	$687,500	$0	$288,000
New Restrooms	$229,250	$0	$444,000
West. & Mid. Revetments Removal	$220,000	$96,000	$209,000
New East Revetment	$89,750	$0	$90,000
East Revetment Repair	$483,800	$0	$0
West-End Backstop Revetment	$211,121	$216,108	$0
New Parking Lots	$325,500	$0	$612,000
New Lawn	$985,000	$0	$136,000
Removal of Fill Material	$0	$0	$222,000
Beach Nourishment	$1,547,128	$0	$0
Groin, Deck Construction	$0	$759,000	$0
Beach Pre-Fill	$0	$4,924,500	$435,000
Subtotal	$5,282,149	$6,129,208	$3,288,000
Contingency (25%)	$1,320,537	$1,532,302	$822,000
Eng, Design, Super, Admin (15%)	$792,322	$919,381	$493,200
Permitting (2.5%)	$132,054	$153,230	$82,200
TOTAL - Initial Phase	**$7,527,062**	**$8,734,121**	**$4,685,400**
Secondary Construction Phase[2]			
Mobilization & Demobilization	$100,000	$0	$100,000
Temporary Protective Fence	$12,600	$0	$9,000
Detour Traffic	$15,000	$0	$15,000
Beach Nourishment	$1,660,979	$0[3]	$2,500,000
New Lawn	$704,000	$0	$0
West-End Backstop Revetment	$0	$0	$0
Groin, Deck Construction	$0	$588,000	$0
Subtotal	$2,492,579	$588,000	$2,624,000
Contingency (25%)	$623,145	$147,000	$656,000
Eng, Design, Super, Admin (15%)	$373,887	$88,200	$393,600
Permitting (2.5%)	$62,314	$14,700	$65,600

TOTAL - Secondary Phase	**$3,551,925**	**$837,900**	**$3,739,200**
TOTAL	**$11,078,987**	**$9,572,021**	**$8,424,600**
Operating and Monitoring Costs			
Annual	$130,000	$130,000	$130,000
20-year Total	$3,500,000	$3,500,000	$3,500,000

Notes:

1. All costs are presented in 2007 dollars.
2. The secondary construction is anticipated to occur in 2013, but costs are presented in 2007 dollars under the assumption that net escalation of construction costs relative to monetary inflation is small and accounted for in the contingency.
3. This cost does not include future nourishment which could increase the cost an estimated $10.5M (text p. 17)

The operating and monitoring costs are based on estimates for ongoing costs prepared by Santa Barbara County using annual costs with and escalation of 3% annually over the 20-year project period. PWA changed the annual costs for the Groin Alternative from $120k to $130k. It is also likely that the managed retreat alternative and the park reconfiguration alternatives would have reduced annual maintenance costs due to the replacement of aging facilities.

The Park Reconfiguration alternative is the lowest cost, while maintaining / replacing aging facilities (utilities, restrooms, shore protection for restaurant), in addition to enhancing and maintaining the lawn and beach areas and interface. The Park Reconfiguration Alternative does not include the potentially large, adverse effects to the downcoast beaches and tidal inlet associated with the Permeable Groin Alternative.

In contrast, the Permeable Pile Groin project costs approximately 45% more than the Park Reconfiguration Alternative, without providing new parking areas or new restrooms. The pile groin is unlikely to prevent the beach fluctuations associated with sand supply changes and episodic storm events. Given the alteration to the storage capacity of Goleta Beach, and the potential for larger volume losses following erosion events, there is a much higher risk that the permeable pile groin will have downcoast impacts. Initial pre-fill of 550,000 yds^3 may initially mitigate downcoast impacts. However, the increased storage capacity would result in greater sand impoundment following erosion events and increase the time for Goleta to fill up before cascading sand down drift. Downcoast impacts similar to those observed following the 1997-98 El Niño as the causative erosion wave passed through Goleta, could be expected to worsen as a result of the pile groin alternative. It is likely that any contingency nourishment required with the Pile Groin would include the eroded fillet volume (550,000 yds^3) and the volume necessary to infill another erosion wave (~175,000 yds^3). The cost of such a contingency is not included in cost estimating for the groin alternative and would may add an additional $10.5M in nourishment costs to the 20 year total.

It is also important to note that PWA reviewed a hard groin alternative with a similar placement as the proposed pile groin (PWA 2005), and found that the salient created by the groin did not extend updrift (west) enough to protect the west end of the park. Given the proposed groin's permeability of 33%, the groin would be less successful than a solid structure in retaining sand. The greater the permeability designed to mitigate downcoast impacts, the less effective the sand trapping and the smaller the salient. Given the variable coastal process and sediment supply conditions the tuning of the groin would likely require ongoing maintenance increasing operations and maintenance as well as recreational opportunity costs.

PWA's initial assessment of the Permeable Groin alternative is that it is too risky to recommend. In general, the Permeable Groin Alternative is dubious in terms of effects and effectiveness, although more technical work is needed to evaluate the supporting modeling results and assumptions.

As a result of the Park Reconfiguration Alternative's lower cost, the alternative's effectiveness, avoidance of downcoast impacts, and the ability to retain and improve park facilities as well as the uncertainties associated with the proposed groins, the Park Reconfiguration alternative is the preferred alternative.

7. LIST OF FIGURES

8. REFERENCES

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9. LIST OF PREPARERS

This report was prepared by the following PWA staff:

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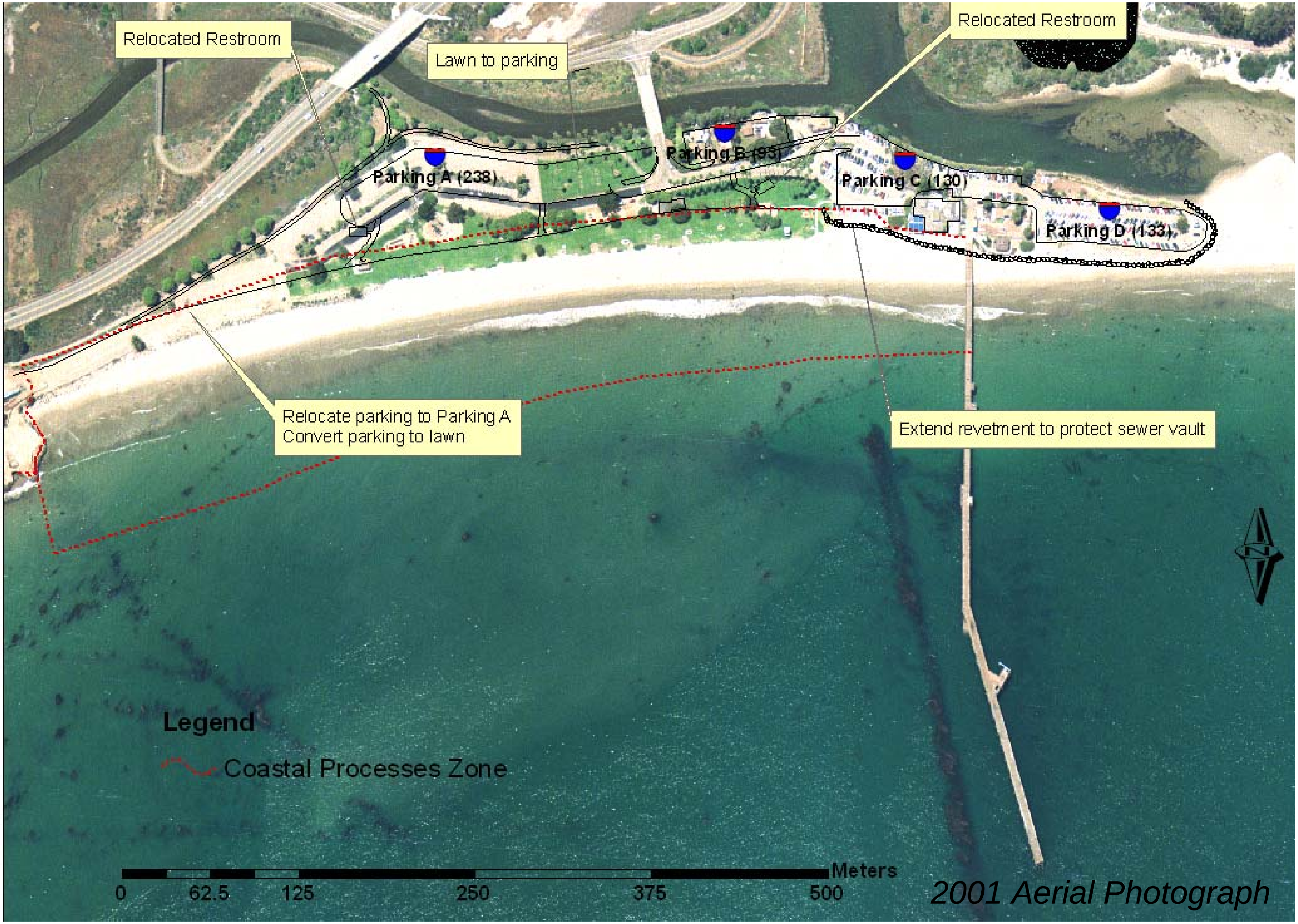
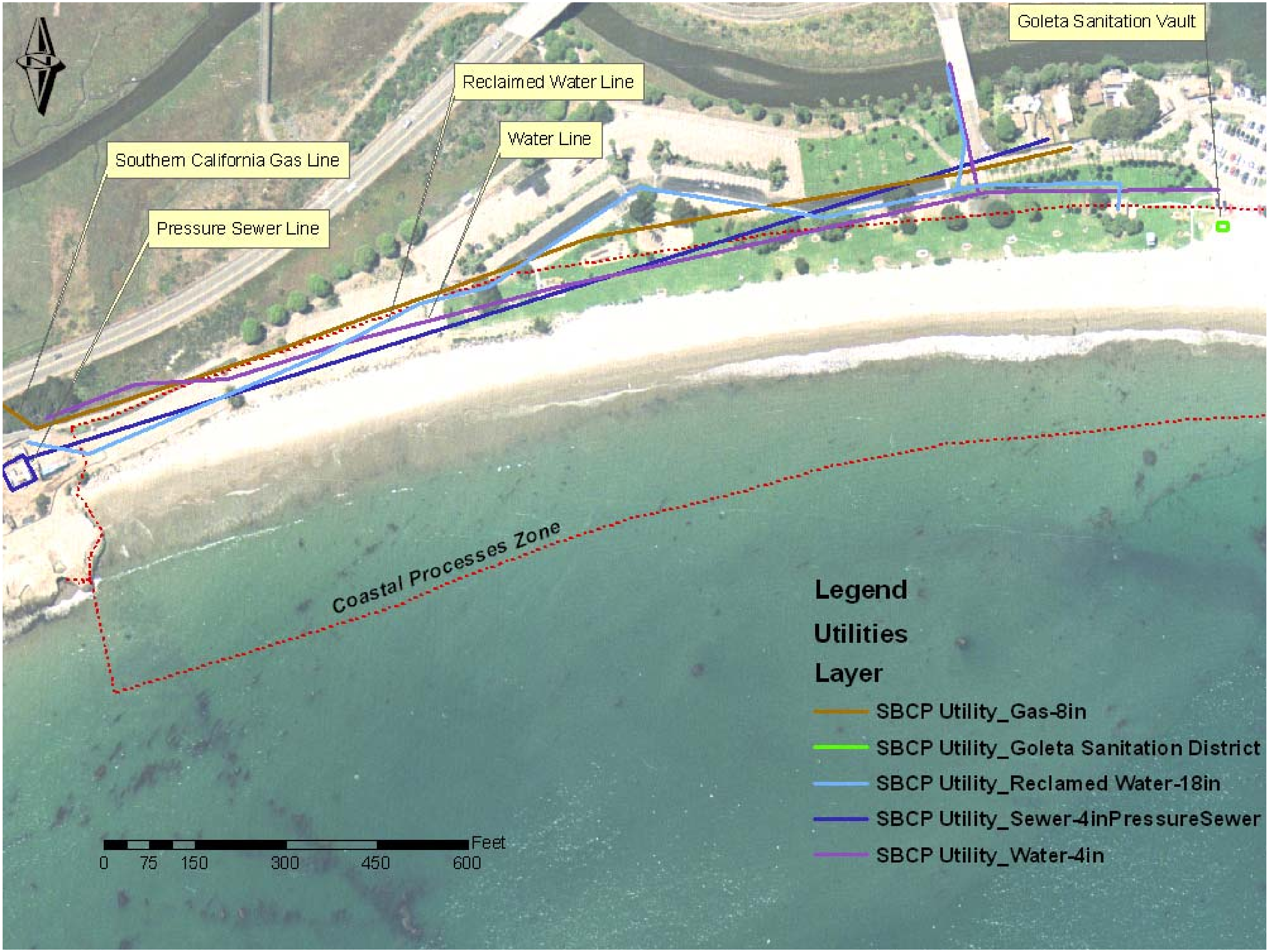
Philip Luecking, P.E.
Jeremy Lowe

With technical review by:

Michael Walther, P.E.


Relocated Restroom
Lawn to parking
Relocated Restroom
Parking A (238)
Parking B (93)
Parking C (130)
Parking D (133)
Relocate parking to Parking A
Convert parking to lawn
Extend revetment to protect sewer vault
N
Legend
Coastal Processes Zone
0
62.5
125
250
375
500
Meters
2001 Aerial Photograph


N
Goleta Sanitation Vault
Reclaimed Water Line
Water Line
Southern California Gas Line
Pressure Sewer Line
Coastal Processes Zone
Legend
Utilities
Layer
SBCP Utility_Gas-8in
SBCP Utility_Goleta Sanitation District
SBCP Utility_Reclamed Water-18in
SBCP Utility_Sewer-4inPressureSewer
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75
150
300
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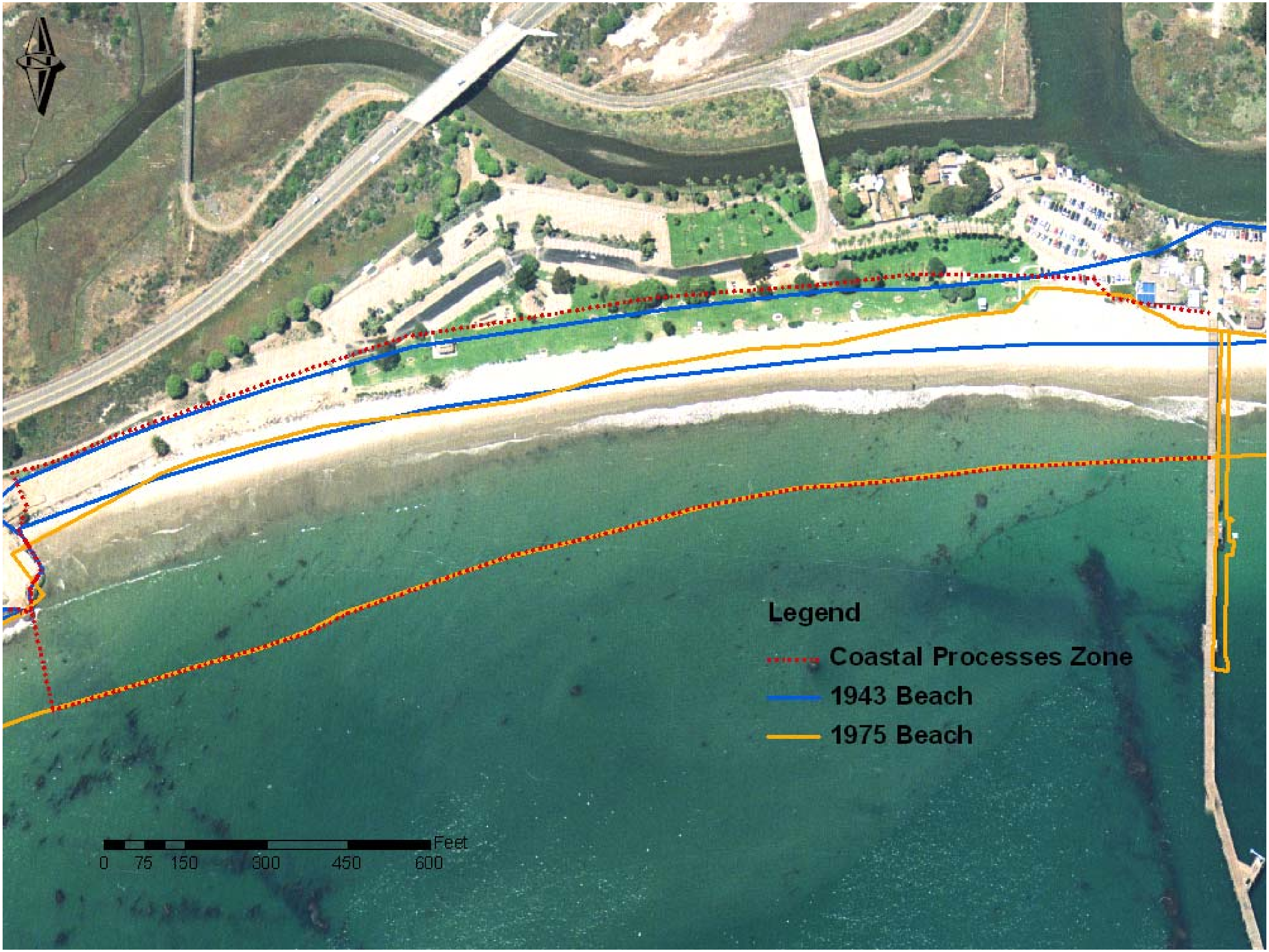
600
Feet


N
Legend
Coastal Processes Zone
1943 Beach
1975 Beach
Feet
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75
150
300
450
600

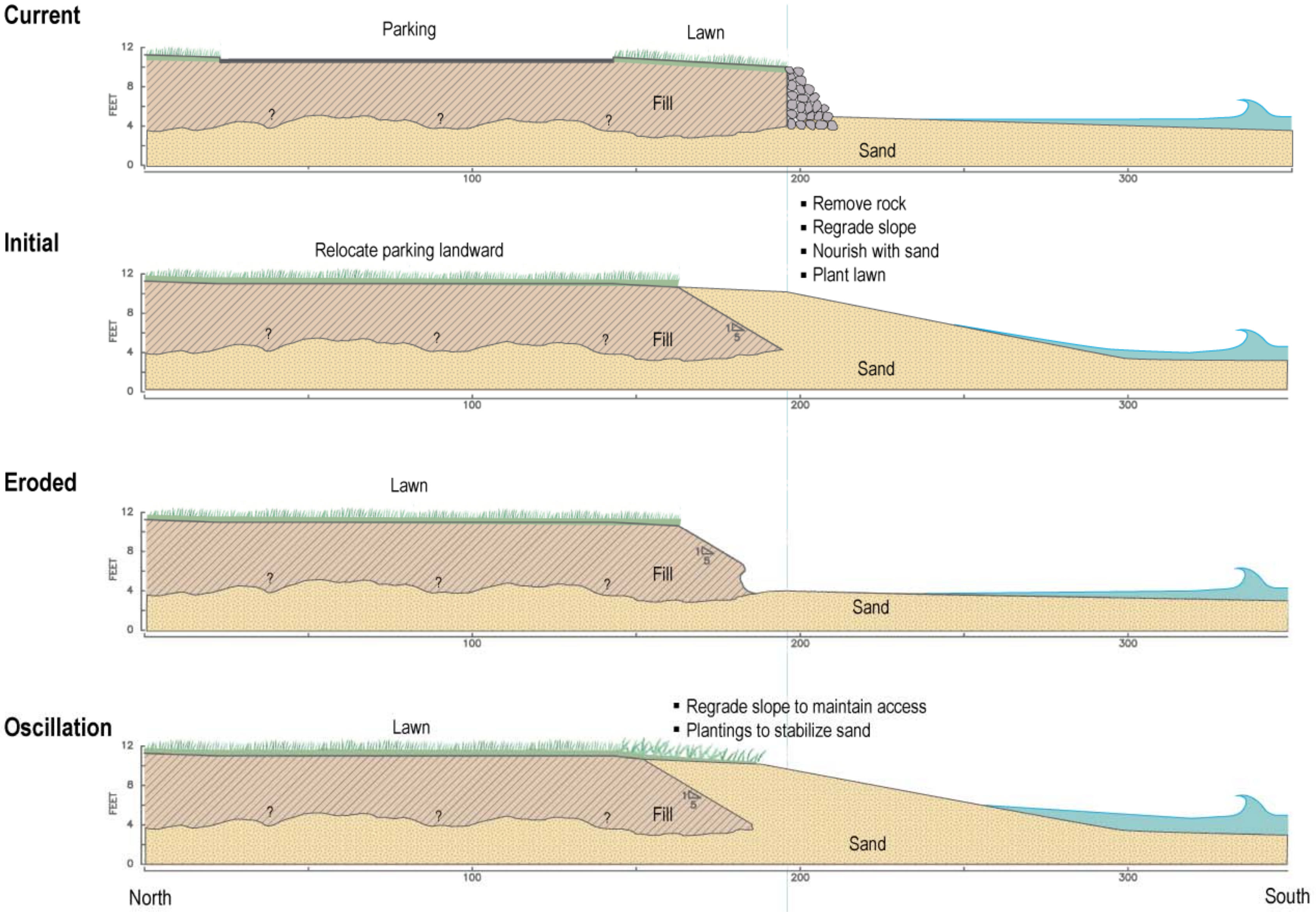

figure 1

Goleta Beach

Evolution of Park Reconfiguration Alternatives

#1940

PWA

Attachment 3

ESA PWA

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Exhibit 3: 2011 Study

memorandum

date	February 28, 2011
to	Chris Gabriel, Michael Osborn, Penfield and Smith
from	David Revell, PhD., Bob Battalio, P.E. with contribution from Louis White, P.E. Barry Tanaka and Scott Stoller P.E.
subject	Goleta Beach Technical Memo on Erosion Mitigation Alternatives, Project Number 2051

Introduction

This technical memorandum provides the coastal geomorphology and engineering services as requested by Penfield and Smith (P&S) to assist in the preliminary design for Goleta Beach 2.0.

The Goleta Beach 2.0 plan (County of Santa Barbara, Parks Department) is similar to the managed retreat plans developed previously by Santa Barbara County Parks and a Working Group (PWA, 2004; 2008). The plan entails relocating utilities farther landward within a corridor adjacent to a new bike and pedestrian path on the northern side of the park, to reduce the risk of damages and the need for armoring, while allowing for a wide beach. Facilities not planned for relocation at this time include a restroom building seaward of the proposed utility corridor on the west end of the park, and a sewer vault located farther east near the restaurant. At the request of P&S and the County, we have formulated and described several alternatives for protection of these facilities. These Coastal Erosion Mitigation Alternatives are presented here as part of the preliminary design for Goleta Beach 2.0.

The utilities at most risk and being considered for relocation include:
- Sempra Energy/ So Cal Gas 8” High Pressure Gas Main
- Verizon Telephone/ Shared Electrical Conduit
- Goleta Water District 18” Reclaimed Water Line
- County of Santa Barbara 2.5” Domestic Water Line
- County of Santa Barbara 4” Sanitary Sewer Force Main

Coastal Geomorphology

This study provides some conceptual design alternatives at Goleta Beach County Park in Santa Barbara, California. The premise is to relocate infrastructure and park facilities to allow for natural shoreline processes while providing reasonable assurances that utilities and other improvements will not be damaged by a design-level storm. These alternatives are based on recent scientific research which has shown that the coastal processes operating at Goleta Beach are highly variable and have resulted in fluctuations in beach width over the last 75 years (Revell and Griggs

2006, Revell and Griggs 2007, Revell 2007). These changes appear to be caused by cyclic climate phenomena that regulate the direction of waves and storms.

The oscillation of Goleta Beach appears to be a balance between occasional large pulses of sediment that widen the beaches and erosion periods when the sediment is transported eastward. Wave direction is especially important with most erosion occurring during energetic southerly El Niño conditions – which produces large waves from the west, and a reduction in wave energy during the negative phase of the Pacific Decadal Oscillation – associated with waves predominantly from the north. Recent indications from NASA suggest that we may be entering a negative phase of the PDO.

Recent research findings also provide insight into an erosion wave catalyst by the 1997-98 El Niño that propagated along coast causing the 1999 erosion at Goleta Beach before migrating down coast affecting Arroyo Burro, Shoreline Park, and currently Ledbetter Beach (Revell, Dugan and Hubbard in press). This alternative suggests a new means to reduce erosion hazards at Goleta Beach while maintaining more natural functions in light of these recent scientific findings.

Figure 1 and Figure 2 depict a “coastal processes zone” within which the shore can be expected to oscillate, based on historic shoreline positions. Map 1 shows the location of historic shoreline positions which delineate the most eroded (1943) and widest extents (1970s) of Goleta Beach using a high precision geodetic control network to rectify historic imagery and digitize back beach and wet/dry shoreline position. The widest shore was digitized from a 1975 air photo, although 1979 was likely a bit wider. The wet/dry shoreline position was adjusted to a mean sea level position using the tide level at the time of the photos. Goleta beach has historically fluctuated and has experienced a state of dynamic equilibrium with the most landward extent of erosion being the 1943 back beach. The accuracy of the rectification procedure for determining the horizontal location of the 1943 backbeach is +/- 26 feet (Figure 1). A “coastal processes zone” which is proposed to encompass the likely most landward limit of future erosion corresponds to the 1943 back beach delineated in Figure 1 and Figure 3. Park infrastructure currently within the “coastal processes zone” should be relocated outside of this zone to minimize potential future erosion damage, enable natural beach fluctuations, optimizing the natural beach width, and avoiding downcoast impacts.

Base Flood Elevations or 100 year Total water levels

This summary of current 100 year total water level storm events is based upon review of FEMA flood insurance studies (FIS) and wave transformation modeling. FEMA FIS maps estimate a 100 year Base Flood Elevation (BFE) of 9 feet. However, using a more sophisticated wave run up total water level approach (PWA 2009, Revell et al in press) including wave transformation method developed by the Coastal Data Information Program at Scripps, we calculated a wave runup elevation of 13.5 feet NAVD for a 100 year event. These BFE and coastal processes zone are shown in Figure 3.

Given the State of California guidance on sea level rise in Executive order S-13-08, and the California Adaptation Plan we incorporate the 16 inch rise in sea level by 2050. This equates to a 100 year BFE by 2050 of ~15' NAVD.

Coastal Erosion Mitigation Alternatives

A range of erosion protection alternatives have been developed for each of the two locations identified by the County and P&S. Descriptions and preliminary engineers' estimates of construction costs follow.

The geotextile core dune and cobble berm (also called a dynamic cobble revetment) was based partly on a similar design constructed at Cape Lookout State Park in Oregon (Komar, Revell, and Good, 1999; Allan and Komar 2004). This was built and later adopted by the US Army Corps of Engineers as part of their Section 227: Innovative Shore Protection Program (http://chl.erdc.usace.army.mil/Media/5/1/4/FSCapeLookout_May05.pdf). The 3cy geotextile bags were stacked, then capped with sand, erosion control fabric and vegetated with native dune grasses. A cobble berm was built in front of the geotextiles to bolster natural shoreline protection and reduce scour. This has been successful for the 10 years since construction including the significant El Niño wave event of 2009-10.

West End – Utility Corridor and Path (Figure 4):

- Earth Berm: Excess earth from the removal of park features will be used to construct a compacted earth cover over the utilities, thereby armoring them from extreme wave runup and erosion. The earth berm will erode slowly enough to prevent exposure of the utilities for the duration of a cluster of erosive events, after which the berm geometry could be restored. A sloped face would deflect wave runup and limit the extent of vertical scour and erosion, while allowing water to pass over the top.

- Low Wall: A low wall above ground extending down to the elevation of the buried utilities to impede erosion during extreme events. The wall would be extended upward to form a curb for the pathway.

- Passive Dewatering: This is an experimental alternative that has potential to accelerate natural accretion processes by reducing the saturation of the beach face during falling tides. The theory is based on the proven scientific principle that when sediment entrained in the wave swash runs up a dry sand beach face, it infiltrates thus depositing sand and increasing sediment deposition. In reality, this has been applied at several locations around the world with varying levels of success. This alternative should be considered experimental and best combined with the current opportunistic sand placements along the entire beach from the pier westward (Figure 5).

Sewer Vault (Figure 6)

- Rock Revetment: A rock revetment would be constructed seaward of the sewer vault and extended eastward to join the existing revetment protecting the restaurant. We expect that rock removed from the west end would be used.

- Geotextile Core Dune and Cobble Berm: Geotextile bags will be filled with sand and arrayed to form an embankment. The embankment will be covered with sand and additional loosely woven geotextile fabric, and planted with native dune species. During extreme events, the sand bags would be exposed and the berm could be reconstructed and planted. A scour apron or berm of cobble would be placed at the toe of the reinforced-dune to mitigate undermining by erosion. Cobble tends to segregate from sand and move landward during erosive conditions, and can dissipate wave runup , providing protection for landward areas. This alternative is an engineered version of naturally occurring dunes and shorelines (Figure 7).

- Passive Dewatering: This is an experimental alternative that has potential to accelerate natural accretion processes by reducing the saturation of the beach face during falling tides. The theory is based on the proven scientific principle that when sediment entrained in the wave swash runs up a dry sand beach face, it infiltrates thus depositing sand and increasing sediment deposition. In reality, this has been applied at several locations around the world with varying levels of success. This alternative should be considered experimental and best combined with the current opportunistic sand placements along the entire beach from the pier westward (Figure 5).

Engineers' Estimates

For planning purposes we have provided order of magnitude estimates to allow cost comparison of alternatives. These cost estimates are intended to provide an approximation of total project costs appropriate for the preliminary design. These cost estimates are considered to be approximately -30% to +50% accurate. Contingencies should be added to account for project uncertainties (such as final design, permitting restrictions and bidding climate). These estimates are subject to refinement and revisions as the design is developed in future stages of the project.

Location	Alternative	Length (Feet)	Unit Cost ($/LF)	Cost
West End – Utilities Corridor and Path	Earth Berm[1]	500[2]	$100	$50,000
	Low Wall	500	$500	$250,000
	Passive Dewatering	2000[3]		$500,000
Sewer Vault	Rock Revetment	250[4]	$1,000[5]	$250,000
	Geotextile-core Dune and Cobble Berm	250	$3,000	$750,000
	Passive Dewatering	2000[3]		$500,000

---

[1] Does not include cost to relocate utilities farther landward, this cost is for a compacted earth berm

[2] Only western segment near high erosion zone

[3] The estimate is for one treatment along the entire shore, from the western end to the pier,

[4] From revetment at restaurant to 50' west of vault

[5] Assumes use of rock salvaged from unpermitted emergency revetment.

The estimate for passive dewatering is very approximate. This is an innovative approach to mitigating erosion and is considered experimental. The estimated cost is based on the existing cost structure of a system implemented in Hillsboro Beach, FL. The estimate allows for a $50,000 installation cost which includes an initial site investigation, an initial lease rate of $100,000 per year for 3 years, and a purchase cost of $150,000, for a total of $500,000.

Recommended future work

A more detailed analysis of future coastal flood and erosion hazards should be considered as part of future design. Such improvements could involve a review of profile data that could provide a better design beach profile. Also, analyses of storm-induced changes including a sensitivity analysis of predicted erosion based on a range of geomorphic variables would provide a more refined assessment of erosion risk. Computations of wave parameters including runup and rock sizing or wave loads would typically be performed for design of coastal structures.

Opportunistic nourishment of the beach with sand from inland sources is an existing program permitted through BEACON that can be used to help mitigate erosion risks, especially in conjunction with other actions such as retreat. More traditional nourishment which has been conducted previously could also be used, however the complications and environmental impacts associated with obtaining and placing sediments from offshore sources, or for sediment obtained at the Santa Barbara Harbor, the potential downcoast impacts to beaches south of Santa Barbara Harbor need to be considered and the long term sustainability of such a practice may prove cost prohibitive in the long term.

The County could also investigate use of cobble nourishment especially in the hotspot west end to provide higher levels of natural beach protection. This is currently being used at Surfer’s Point in Ventura. Subsurface mapping would be beneficial to understand the structure of the fill material as well as identify any cobble subsurface.

Specific guidance from the Coastal Commission during the pile groin alternative hearing suggested that a more detailed look at managed retreat be considered. A comparison of the Coastal Processes Zone and the proposed locations for the utilities and path indicate that these facilities may not be at risk of damage due to erosion. However, given that there are uncertainties associated with future erosion and rates of sea level rise, one alternative to further reduce risk is to locate the utilities elsewhere.

Some additional work with Caltrans and other large infrastructure stakeholders could examine the potential to move the utilities even farther landward perhaps on the other side of 217 to reduce the need for some of these alternative shore protection strategies. However the two County of SB utilities run to the pump station on the oceanside (south) of the highway and it may be more difficult and expensive to have two crossings under Highway 217. The earth berm alternative also provides some flood and erosion protection for a low lying section of Highway 217 which Caltrans would likely support.

Engineering and geomorphic design of the restored beach geometry is required along with the other components of Goleta Beach 2.0, prior to construction.

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List of Figures

2001 Air Photo courtesy Calfiornia Coastal Commission

figure 1

Goleta Beach 2.0 – Infrastructure Protection Alternatives

Coastal Processes Zone

PWA Ref# 2051.00

ESA PWA

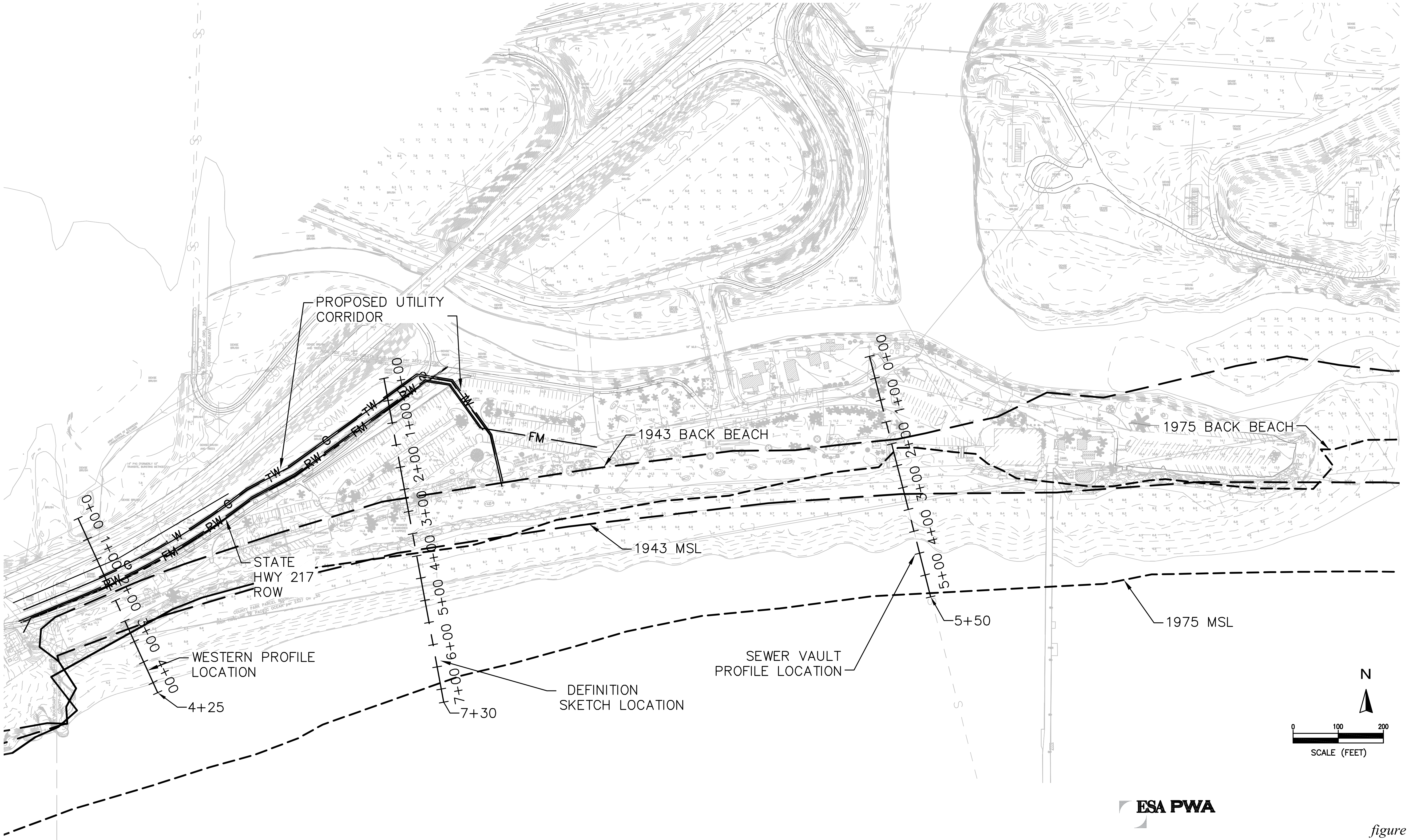

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figure 2

Goleta Beach 2.0 - Infrastructure Protection Alternatives

SITE PLAN

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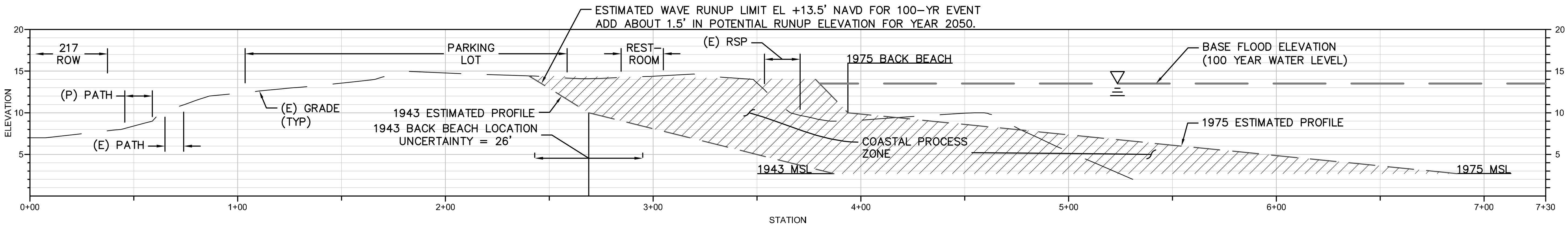


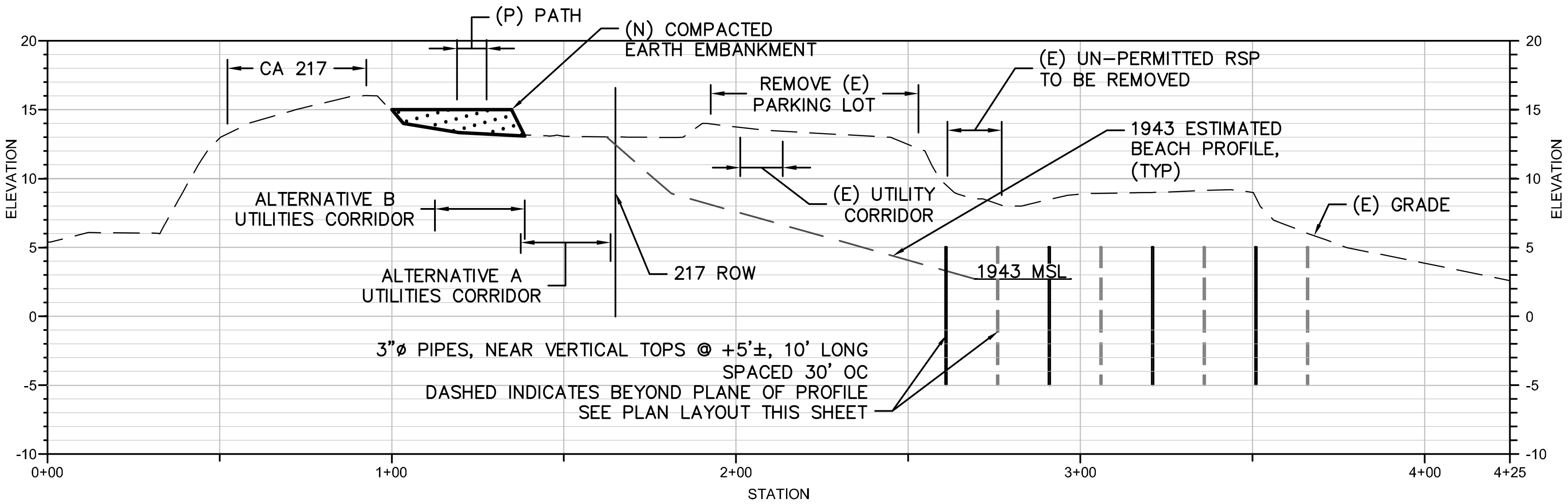
NOTES
1. SCALE IS 1" = 50', 4X VERTICAL EXAGGERATION
2. VERTICAL DATUM IS NAVD 88
3. MSL = 2.69' NAVD. (ASSUMED CONSTANT OVER TIME)

ESA PWA

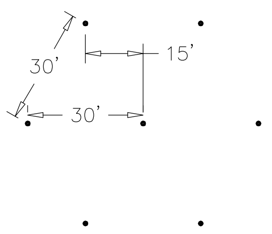
figure 3

Goleta Beach 2.0 - Infrastructure Protection Alternatives

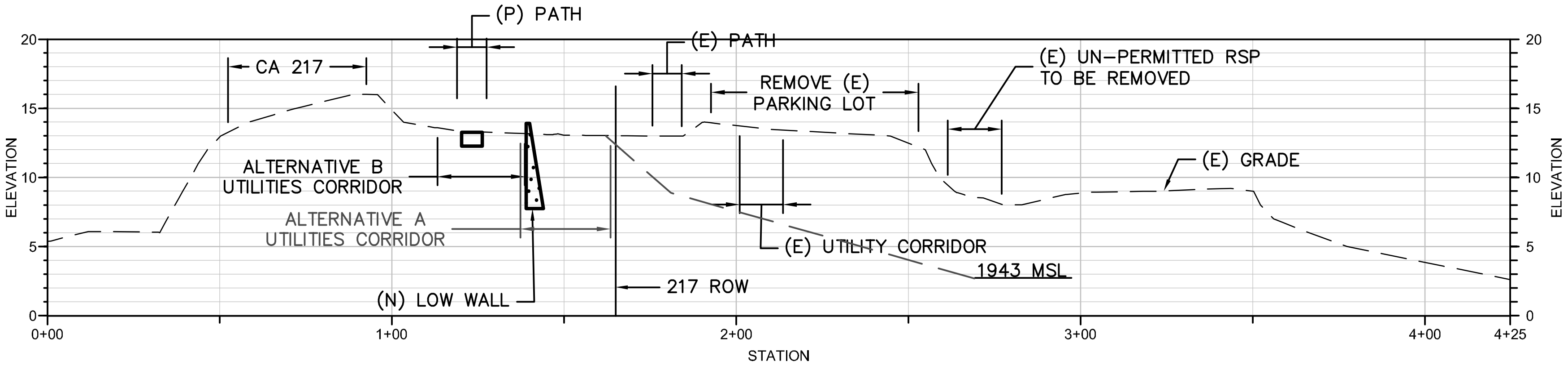
PROFILE DEFINITON SKETCH



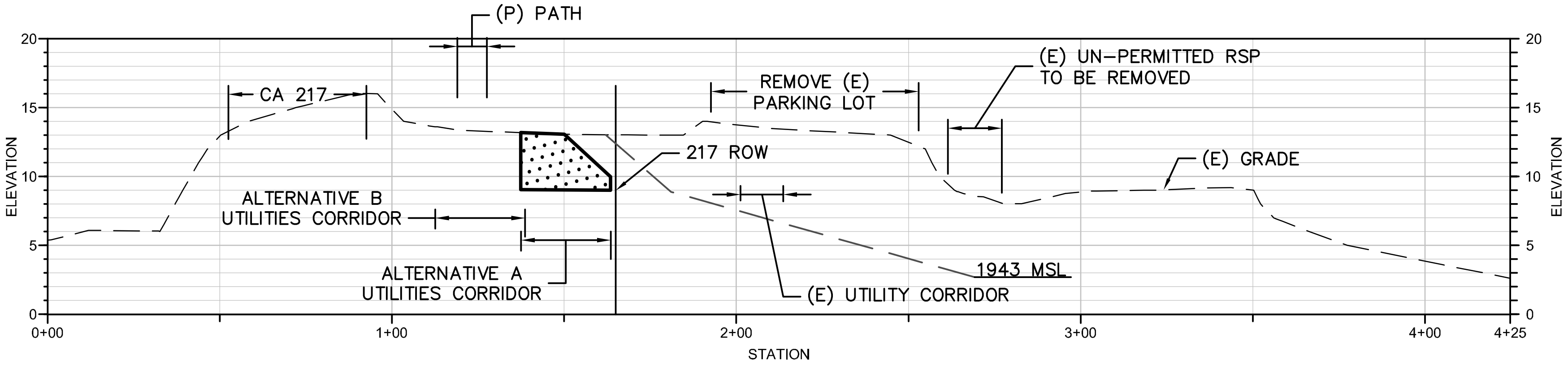
EXPERIMENTAL PASSIVE DEWATERING ALTERNATIVE



PLAN VIEW LAYOUT OF "PEMS"



WALL ALTERNATIVE



EARTH BERM ALTERNATIVE

NOTES

1. SCALE IS 1" = 50', 4X VERTICAL EXAGGERATION
2. VERTICAL DATUM IS NAVD 88
3. MSL = 2.69' NAVD. (ASSUMED CONSTANT OVER TIME)

ESA PWA

figure 4

Goleta Beach 2.0 - Infrastructure Protection Alternatives

WESTERN PROFILE

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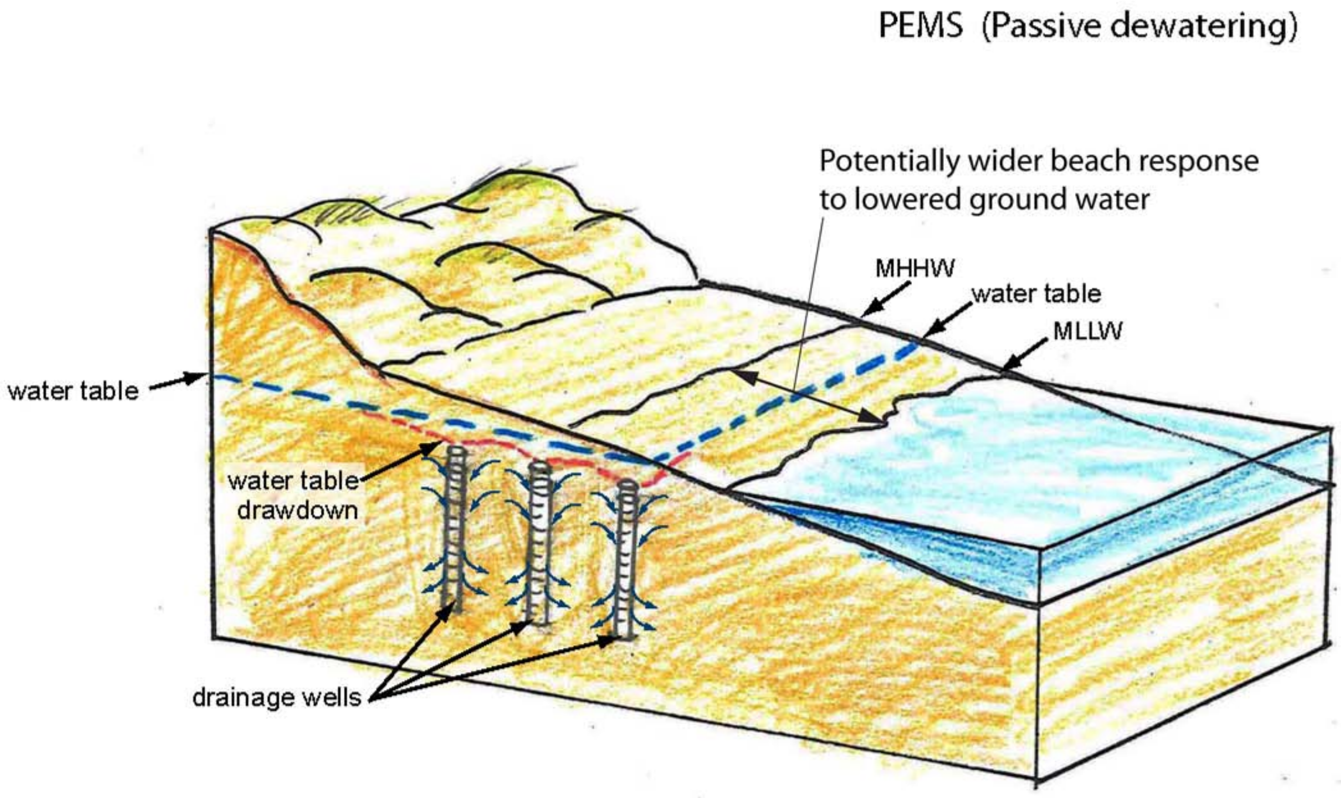
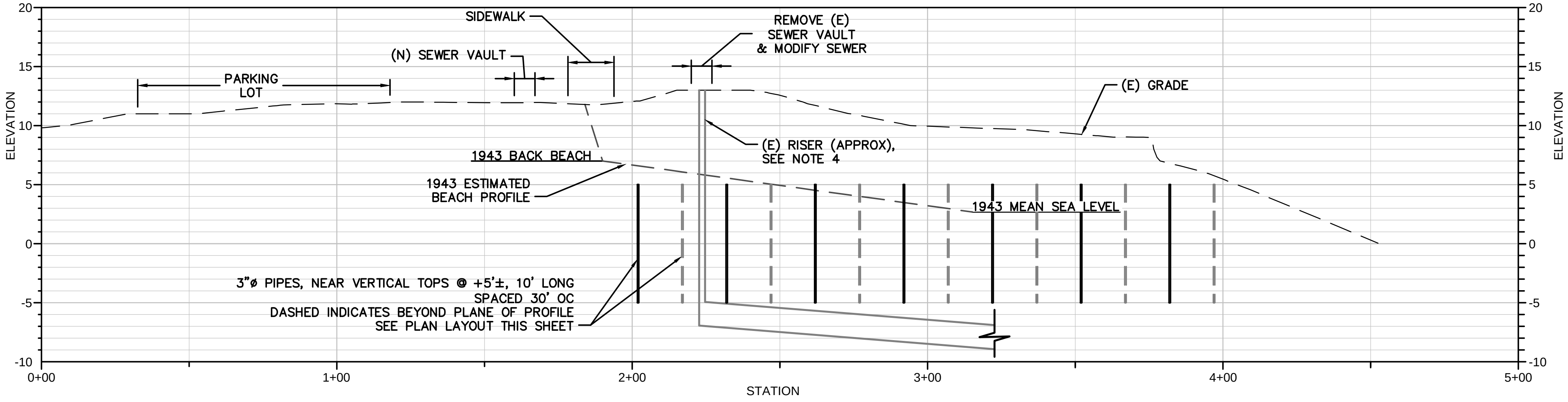


figure 5

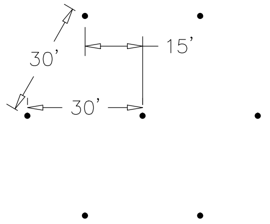
Goleta Beach 2.0 – Infrastructure Protection Alternatives

Conceptual Drawing of Passive Dewatering Alternative

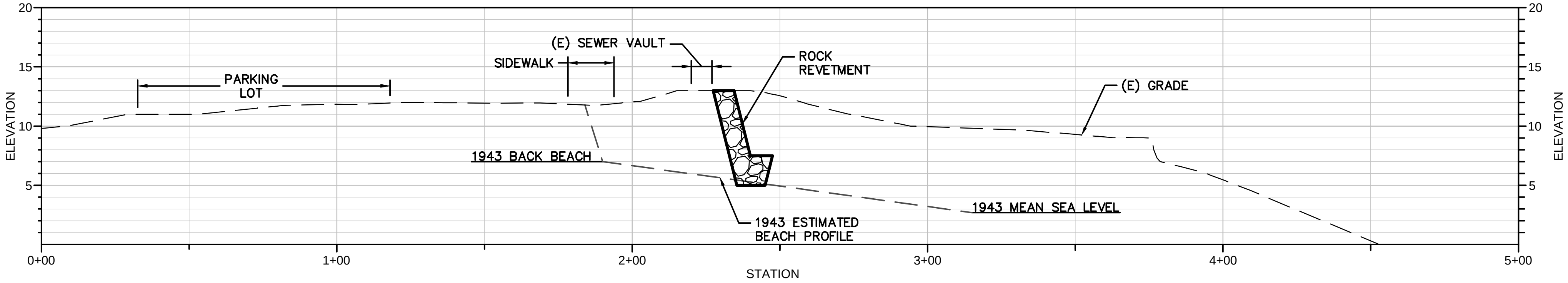
PWA Ref# 2051.00



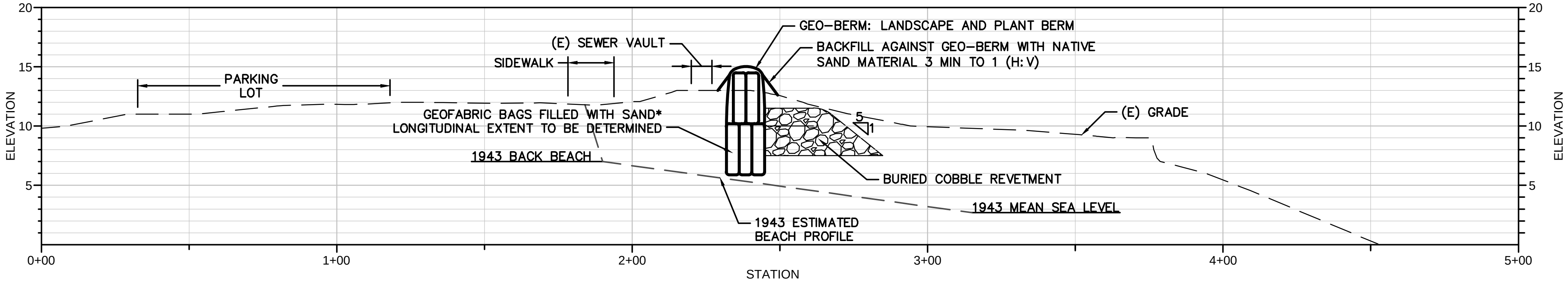
EXPERIMENTAL PASSIVE DEWATERING ALTERNATIVE



PLAN VIEW LAYOUT OF "PEMS"



REVETMENT ALTERNATIVE



GEO-BERM ALTERNATIVE

* EACH GEO BERM 3'X10'. DURING SEVERE STORM EROSION, BERMS WILL SETTLE. PLACE MORE ON TOP.

NOTES
1. SCALE IS 1" = 50', 4X VERTICAL EXAGGERATION
2. VERTICAL DATUM IS NAVD 88
3. MSL = 2.69' NAVD. (ASSUMED CONSTANT OVER TIME)
4. SEWER DIMENSIONS APPROXIMATE OUTFALL AT -6' EL ESTIMATED, TO BE VERIFIED

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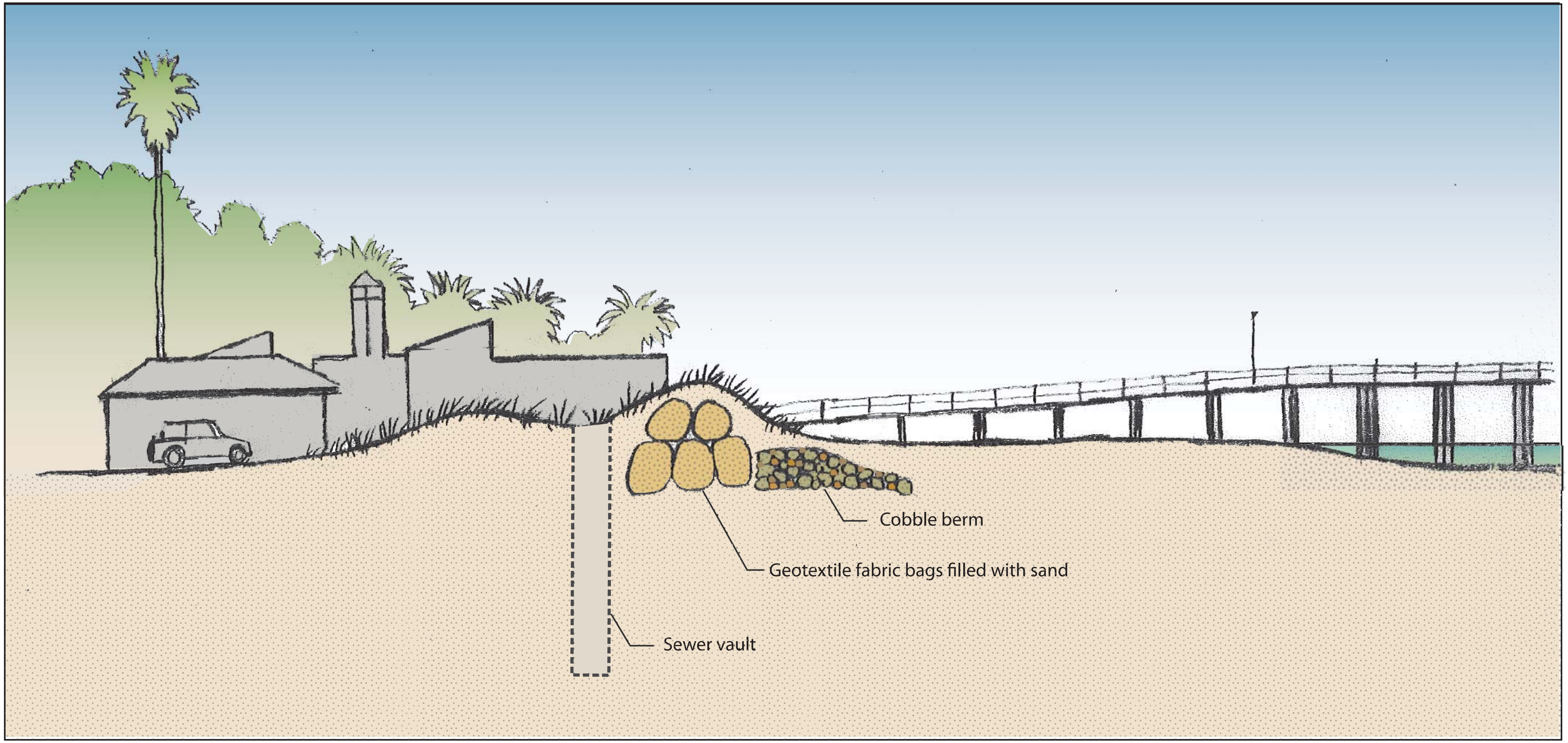
ESA PWA

figure 6

Goleta Beach 2.0 - Infrastructure Protection Alternatives

SEWER VAULT PROFILE



Goleta Beach (existing)

figure 7

Goleta Beach 2.0

Conceptual Drawing of Geotextile Core Sand Dune

PWA

Attachment 4

Exhibit 4: Cobble Berms Summary, Battalio, 2012

Cobble Berms: A Brief Summary in Support of the Ocean Beach Master Plan

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ESA PWA
January 20, 2012

The Ocean Beach Master Plan has identified an array of actions to mitigate coastal hazards and improve the public space. One of the elements in the Master Plan is a cobble berm to be installed in South Ocean Beach, from the vicinity of Sloat Boulevard southward to the limit of development at Fort Funston. The cobble berm is an innovative approach to allow erosion while protecting a sewer tunnel and providing public access. The report provides background information on cobble berms in support of the Master Plan report and other documents.

This report is not exhaustive in terms of identifying and considering all available knowledge. Nor is this work adequate to conclude the appropriateness of construction of a cobble berm at Ocean Beach. Additional work is needed prior to implementation.

Background:

The purpose of the cobble berm (dynamic revetment) at Ocean Beach is to “soften” the protrusion of the Lake Merced Transport Pipe that will result from shore recession. Under the Hybrid Scenario, the Lake Merced Pipe will be protected in place until it is replaced or no longer needed. Since the pipe crown is about even with the back beach elevation, it is likely that erosion will remove most of the overburden covering the pipe. The San Francisco PUC and DPW have indicated that this could allow vertical or lateral movement of the pipe, or otherwise change the loadings such that the pipe could rupture. Hence, the Hybrid plan includes a Taraval-type seawall (Figure 1) or a structural modification of the pipe itself (e.g. reinforcing the pipe internally or reducing its section and elevation).

Figure 1: Taraval Seawall. The picture shows the north end, near Santiago Street, during an extreme, eroded condition during the 1998 El Nino. Photograph © Bob Battalio, taken 1998.

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Since the feasibility of these "protect-in-place" approaches have not been fully evaluated, the most intrusive to beach use is assumed, which is the Taraval-type Seawall, as depicted in the Master Plan graphics for South Ocean Beach (Figure 2).

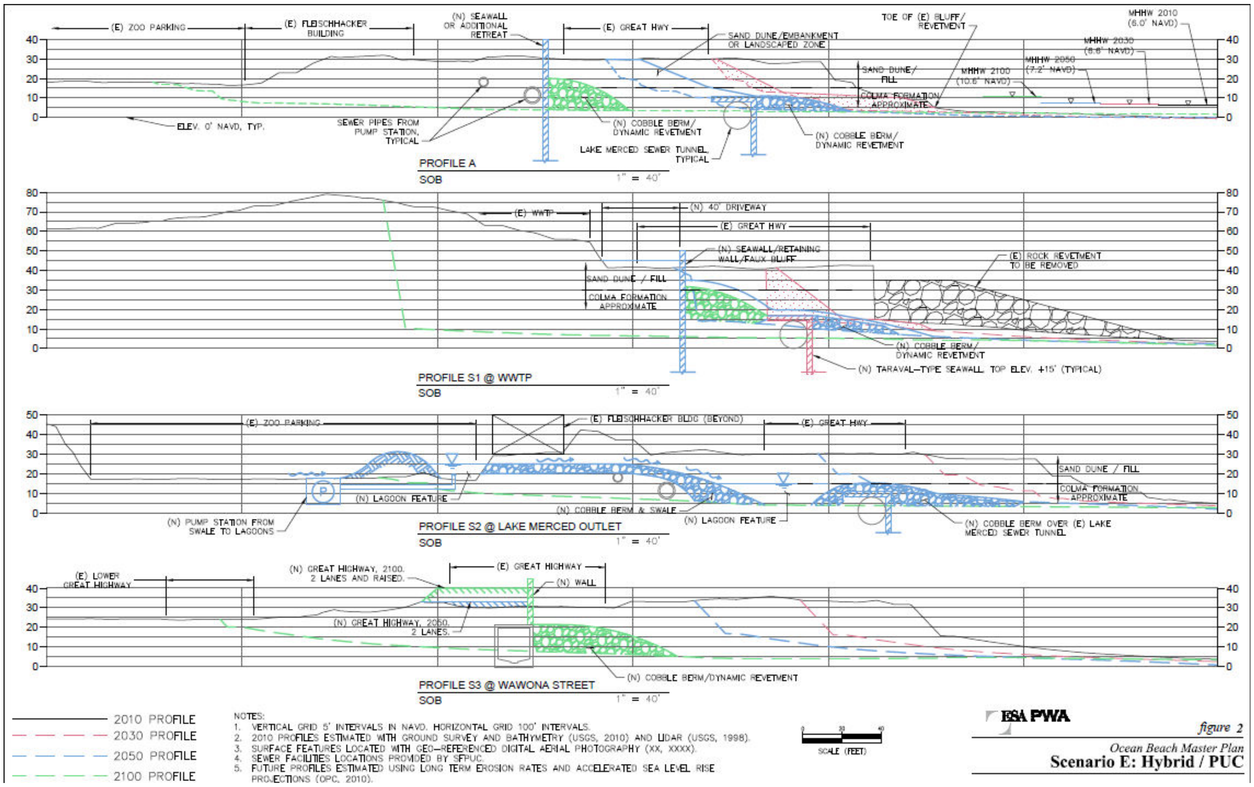

Figure 2: SOB Sections of Hybrid Scenario, Ocean Beach Master Plan.

The Lake Merced Pipe and protective structure(s) are likely to be exposed, and result in a vertical offset with the beach (similar to the condition shown in Figure 1). To mitigate this impact somewhat, a cobble berm is proposed in front of the wall. It is intended that the cobble berm would mitigate wave reflection and scour, provide a more accessible surface for people, and have a tolerable appearance. Also, the cobble berm is intended to provide a stable sill for a new outlet from Lake Merced to the beach (Figure 2, Profile S2).

In this application, the cobble berm is therefore a shore protection and hydraulic structure that is intended to provide a better balance with recreational and ecological objectives than more traditional quarry stone revetments and reinforced concrete seawalls. The cobble berm is not required to protect facilities, however, as the proposed Taraval-type seawall or structural modification of the pipe would be "stand-alone." Therefore, the proposed cobble berm could also be considered a landscaping element.

Finally, the cobble would replace the existing rubble and revetments at the site (Figure 3). The proposed extent of the cobble berm is in South Ocean Beach, generally from Sloat Boulevard southward to Fort Funston (Figure 4).

Figure 3: Picture(s) of existing rubble, SOB. Photograph © Bob Battalio, taken February 1, 2010.

Figure 4: Plan extents of the proposed cobble berm are generally from Sloat Boulevard to the south end of the Southwest Sewer Treatment Plant, in the Master Plan region called South Ocean Beach (SOB).

Definition of a Cobble Berm, aka Dynamic Revetment

Cobble berms are mounds of rounded rock sorted and shaped by waves (Allen et al, 2005; Everts et al, 2002; Lorang, 1997; Bauer, 1974). These features are naturally occurring at locations where rock exists, such as the toe of coastal cliffs and at the mouths of creeks and rivers, and are often covered by sand some or most of the time. These features have been installed by man as a component of restoring beach morphology and ecology, and also for erosion and flood mitigation. When installed as a erosion control structure where they wouldn't otherwise exist, cobble berms are often called dynamic revetments. The term "dynamic revetment" is intended to hearken to a traditional revetment of rough, angular quarry stone that has the appearance of an engineered rock slope, like a breakwater. The term "dynamic" is intended to contrast with traditional quarry stone revetments and convey that the smaller, rounded rock (cobble) is expected to move in response to wave action. At Ocean Beach, San Francisco, the term dynamic revetment is probably more applicable. This is because the cobble berm would be introduced – cobble deposits are not known to exist at Ocean Beach.

Examples

Cobble berms and dynamic revetments have been constructed in several locations.

- Cape Lookout Oregon: A dynamic revetment was installed at Cape Lookout State Park (CLSP), Oregon, in 2000 (Allan and Komar, 2004; Allan et al., 2005; Allan et al., 2006; Allan and Hart, 2007). Allen and Komar (2004) described the design of the cobble berm, backed by artificial sand dunes, and report success in accomplishing the goal to minimize overtopping events and erosion problems at the park. The cobble berm was placed in the back of the beach with a seaward slope of 5:1 (H:V) with artificial dunes located directly behind the berm (Figure 5). Monitoring efforts have demonstrated that seasonal variations in the level of sand significantly affect the activity and transport of cobble and gravel. In the summer, when moderately gentle surf deposits sand on the beach face, the gravel-sand intercept increases and covers the larger size sediment, inhibiting the movement of cobble and gravel. In contrast, during winter months when large waves remove sand from the beach and expose underlying cobble and gravel, significant cross-shore and along-shore transport of gravel and cobble is evident. We have heard but not verified that some damage may have occurred recently (winter 2011-12).

Figure 5: Cape Lookout Cobble Berm. Source: Allan et al, 2005.

- Pacifica state beach: Pacifica State Beach is located in Pacifica, CA, just south of San Francisco. The project is an often-referenced example of managed shore retreat and realignment (NOAA, 2007a). Cobble berm and beach nourishment (cobble and sand placement) were proposed as part of a design for the Pacifica State Beach Enhancement (PWA, 2005). Funding was not sufficient to import cobble to “recharge” the degraded cobble berm (Figure 6). There was some grading of cobble after removal of fill and structures, in particular at the mouth of the restored San Pedro Creek. Figure 7 shows the cobble sill at the restored mouth of San Pedro Creek.

Figure 6: Pacifica State Beach. Photograph April 15, 2005, Courtesy, City of Pacifica.

Figure 7: Picture of Cobble berms at Pacifica State Beach before the restoration project. Note the “double berm” which implies landward motion of the lower cobble berm. The house in the background was purchased by the State and demolished. San Pedro Creek mouth is on the far side of the next house, which was also demolished. Photograph © Bob Battalio, taken March 9 2002.

Figure 8: Picture of San Pedro Creek Mouth with cobble sill. Photograph © Bob Battalio, taken December 20, 2011.

- Surfers point: Surfers Point is project with erosion mitigation and managed retreat objectives at the mouth of the Ventura River, California (NOAA, 2007b). The project entails removal of fill and pavement, and placement of cobble and sand to restore the back beach for public recreation, ecology, and storm damage reduction. Cobble underlays the entire area owing to its location at the mouth of the Ventura River. Therefore, cobble placement was considered restoration of the disturbed backshore. The project was designed using a reference site from a less disturbed shore on the other side of the river mouth at Emma Wood State Beach, as well as consideration of the available design guidance and analysis of water levels, waves and runup (PWA, 2005). Figure 9 is a picture of the reference site, showing the cobble berm and the dunes and wetlands behind it. The water side (beach restoration, cobble and sand placement) was designed by PWA and Phase 1 was constructed in 2010-2011. PWA is presently monitoring the project. Figure 10 is a picture of the constructed portion (Phase 1).

Figure 9 Emma Wood reference site for Surfers Point. This reference site is on the west side of the Ventura River Mouth, and the Surfers Point site is on the east side. The dead trees are casualties of coastal erosion, as the shore, with cobble berm, migrates landward. Source: PWA, 2005.

Figure 10 Surfer s Beach post construction phase 1. The new cobble berm is buried beneath the sand. Cobble is exposed along the shore. Phase 2 will include the renovation of the shore in the forefront of the photograph. Photograph courtesy of the City of San Buenaventura and Rasmussen (construction contractor), taken fall, 2011.

- Puget Sound: There are many gravel and some cobble beaches along the shore of Puget Sound. Several projects have been pursued, resulting in several documents addressing the overall concept and design of shore form enhancements (ESA, 2010), and cobble – gravel berms in particular (ESA PWA, 2010). An example of a constructed gravel-cobble system is at Birch Bay, Whatcom County (CGS, 2004). This project entailed a shore section as a demonstration project, to test the concept developed by Bauer (1974) for the remainder of the shore. The project was constructed in 1986 and has been re-nourished with sediments ten times since then. Figure 11 shows the site from a monitoring report (CGS, 2004). Figure 12 shows a proposed enhancement for the adjacent shore (PWA, 2002; 2007)

Figure 1. Oblique aerial photo mosaic of the study site, located immediately left (north) of the mouth of Terrill Creek (at right). Photos taken May 24, 2001 for WA Dept. of Ecology.

Figure 11: Birch Bay Demonstration Project: Source: CGS, 2004.

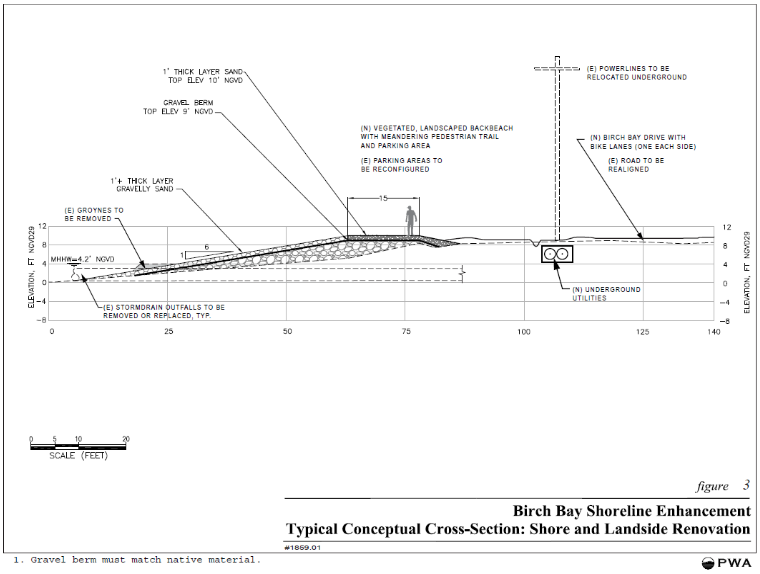

figure 3

Birch Bay Shoreline Enhancement

Typical Conceptual Cross-Section: Shore and Landside Renovation

#1659.01

1. Gravel berm must match native material.

PWA

Figure 12: Birch Bay Typical Section, showing conceptual design cross-section of new gravel-cobble berm with sand cover. Source: PWA, 2007.

Description of Behavior and Design Considerations:

Cobble berms (aka Dynamic Revetments) respond differently to waves than shores comprised of smaller sediments and engineering structures composed of large quarry stone boulders.

Function – Berm morphology and processes

Cobble berms exist because of the natural sorting of wave runup processes. The momentum of breaking waves results in wave runup and rundown on a beach. The runup will entrain and transport sediment landward and the following rundown carries sediment seaward. The extent that sediment is moved depends also on the sediment size, density and distribution of sediment, among other factors. Sand tends to have a net movement landward during gentle surge induced by low-steepness waves (typical of summer conditions in California), and move offshore in storm waves which are steep and very energetic. Large sediments such as gravels and cobbles react differently than sand because of their size. Larger particles settle more rapidly and can stand on a steeper slope, but also respond disproportionately to acceleration versus drag. Hence, cobble tends to move onshore under the abrupt wave runup but tends to not move as far offshore under the longer duration but slower wave rundown. Therefore, relative to sand, cobble tends to move onshore during large wave events while sand tends to move offshore more often. This results in a typical winter-time sorting and exposure of cobble and gravel underlying beaches that are sandy in the summer time.

Cobble and gravel berms tend to have a larger voids and hence dissipate the extent of wave runup and rundown. However, the morphology of coarse sediment beaches results in overtopping that can be extensive during extreme conditions. Hence, cobble berms in their natural configuration are not complete barriers to wave runup and erosion. In fact, most natural cobble shores include driftwood and other wrack on the crest of the berm.

Gravel and cobble also move along shore under oblique wave action but the transport is also different than sand. In generally, the along shore transport is less rapid than sand and not as uniform.

Cobble and gravel berms processes are not manifested unless the deposits are large enough to interact and respond to wave runup as a mass. Therefore, designs typically include a minimum thickness, extent and volume. Also, if the voids are filled with sand, the cobble will tend to react to storm wave similar to sand until the sand is sorted out and the high porosity of a cobble deposit can interact with the waves and affect cobble movement.

Function – public access

A dynamic revetment / gravel -cobble berm can be traversed on foot more easily than a quarry stone revetment or a vertical seawall. The mass of rock will also reduce and adjust to scour that occurs when wave action reaches a wall or cliff.

Function – Lake Merced Outlet and Lagoon Sill

Cobble deposits are often found at river and creek mouths. The discharge from the rivers and creeks degrades the elevation of the cobble berm that forms under wave action alone, resulting in a lowering of the berm elevation in the vicinity of the mouth and specifically in the channel(s). However, the cobble tends to reduce down-cutting, thereby acting as a weir or sill. Therefore, the low point in the channel and the elevation of the water upstream are typically higher where a cobble deposit exists in comparison to a stream mouths on sandy shores without cobble. This function of a cobble sill will be beneficial for a restored mouth of Lake Merced, in order to inhibit wave overtopping and salt water intrusion, and provide a hydraulic control for a lagoon-like feature. This feature would be ephemeral, and filled with sand during low rainfall conditions. Profile 2 in Figure 2 is a schematic of the Lake Merced discharge and coastal lagoon feature. This type of managed system will not provide full ecological benefits and is not sustainable over the long term without intervention. Future restoration, if it occurs, that removes development from the flood plain and allows higher water levels in Lake Merced would not require a cobble sill to inhibit salt water intrusion and pumping would not be needed.

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Attachment 5

Estuaries and Coasts
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Exhibit 5: Dugan et al, 2017

Generalizing Ecological Effects of Shoreline Armoring Across Soft Sediment Environments

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Abstract Despite its widespread use, the ecological effects of shoreline armoring are poorly synthesized and difficult to generalize across soft sediment environments and structure types. We developed a conceptual model that scales predicted ecological effects of shore-parallel armoring based on two axes: engineering purpose of structure (reduce/slow velocities or prevent/stop flow of waves and currents) and hydrodynamic energy (e.g., tides, currents, waves) of soft sediment environments. We predicted greater ecological impacts for structures intended to stop as opposed to slow water flow and with increasing hydrodynamic energy of the environment. We evaluated our predictions with a literature review of effects of shoreline armoring for six possible ecological responses (habitat distribution, species assemblages, trophic structure, nutrient cycling, productivity, and connectivity). The majority of studies were in low-energy environments (51 of 88), and a preponderance addressed changes in two ecological responses associated with armoring: habitat distribution and species assemblages. Across the 207 armoring effects studied, 71% were significantly negative, 22% were significantly positive, and 7% reported no significant difference. Ecological responses varied with engineering purpose of structures, with a higher frequency of negative responses for structures designed to stop water flow within a given hydrodynamic energy level. Comparisons across the hydrodynamic energy axis were less clear-cut, but negative responses prevailed (>78%) in high-energy environments. These results suggest that generalizations of ecological responses to armoring across a range of environmental contexts are possible and that the proposed conceptual model is useful for generating predictions of the direction and relative ecological impacts of shoreline armoring in soft sediment ecosystems.

Keywords Coastal armoring · Shore protection structures · Salt marsh · Mangrove · Estuary · Beach · Ecosystem function

Introduction

Soft sedimentary shores composed of mud, sand, and gravel make up the majority (two thirds) of the world's coastlines (Reise 2001). Soft sediments are associated with a variety of ecosystems including beaches, dunes, coastal bluffs, marshes, estuaries, bays, and inlets (Nordstrom 2000). These areas provide a range of ecosystem functions and services, ranging from storm protection to wildlife habitat to carbon sequestration (e.g., Snelgrove 1999; Piersma 2009). Human use of the shore is intense, with most of the world's megacities and more than 600 million people living in the coastal zone (Neumann et al. 2015). The coasts are the sites of major cities, ports, and residential development, and many areas have been altered to

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accommodate human activities such as agriculture and commerce.

Soft sedimentary shores are inherently dynamic, and this has led to the installation of coastal armoring structures built for the purpose of protecting upland areas and slowing or halting erosion and migration of the shoreline (Nordstrom 2000; Rippon 2001; Charlier et al 2005; Griggs2005a, b). Shoreline armoring is widely used on all types of open and sheltered coasts and is being increasingly applied to soft sediment shores to protect human infrastructure and reduce shoreline retreat (Bulleri and Chapman 2010; Gittman et al. 2015). The resulting proliferation of shoreline armoring in the second half of the twentieth century has led to extensive hardening of coastlines in many regions (Nordstrom 2000; Airoldi et al. 2005). Thousands of kilometers of armoring are present on the coasts of Europe and Japan, and up to 60% of the shoreline has been armored along some urban coasts (Airoldi et al. 2005). In the USA, armoring is also widespread, occupying 12–30% of the total shorelines of individual states and reaching proportions of 50–70% or more along urban coasts (Gittman et al. 2015). Furthermore, the extent of armoring is expected to increase as a result of expanding coastal populations and cities interacting with growing threats from climate change, storm surges, and sea level rise.

Armoring of shorelines results in a suite of geomorphic and physical effects on soft sediment coastal ecosystems (e.g., Nordstrom 2014). By fixing shoreline position, armoring constrains possible responses and evolution of soft shores to changes in sea level and other dynamic coastal processes (Griggs 2010). The most immediate effect of an armoring structure is placement loss, which is the direct loss of shoreline habitat resulting from the footprint of the structure itself (e.g., Kraus and McDougal 1996). Placement loss can be substantial in high-energy environments where larger dimensions are necessary to ensure that the armoring structure is stable. The presence of armoring along a coast also alters hydrodynamics, modifying the flow of water and affecting sediment dynamics of soft shore environments (e.g., Fletcher et al. 1997; Miles et al. 2001; Runyan and Griggs 2003; Martin et al. 2005). The hardened faces of alongshore structures, such as seawalls and revetments placed on beaches, reflect wave energy and constrain natural landward migration of the shoreline, generally leading to the loss of beach area and width as well as flanking erosion of adjacent shorelines (e.g., Hall and Pilkey 1991; Griggs 2005a, b, 2010). The geomorphic and erosive processes involved in these shoreline changes have been well described through numerical, laboratory, and field studies (e.g.,Kraus and McDougal 1996; Ruggiero 2010), and coastal engineers have a fairly good understanding of which aspects of the physical environment must be considered when installing shoreline armoring in different coastal settings. For example, the US Army Corps of Engineers has developed guidance that can be used to calculate stable sizes for armoring structures intended for different shorelines (USACE 2002, Coastal Engineering Manual).

In contrast, the ecological responses to shoreline armoring have received far less attention and are difficult to generalize across ecosystems and structure types. Although recent reviews on ecological responses to armoring are valuable and are beginning to address this important gap (e.g., Bulleri and Chapman 2010; Dugan et al. 2012; Nordstrom 2014; Perkins et al. 2015; Gittman et al. 2016b), the majority of available studies have been conducted in a specific ecosystem, precluding a critically needed broader synthesis across soft sediment ecosystems. For example, there is evidence that the presence of armoring affects water quality (i.e., Bolduc and Afton 2004), habitat connectivity (i.e., Dugan and Hubbard 2006), and species distributions (i.e., Morley et al. 2012). However, these studies were conducted in a tidal marsh, an open coast beach, and an estuarine beach, respectively, so they cannot be evaluated across a common framework. Moreover, one would expect that ecological responses to armoring would vary depending on the type of structure installed (e.g., seawalls vs. breakwaters vs. constructed oyster reefs) and its relative location on the shore profile. In other words, the ecological effects of armoring are expected to be context dependent based on both the characteristics of the environment and those of the armoring structure itself.

To address the need for a common synthetic framework on ecological effects of armoring, we developed and evaluated a conceptual model that allows more general comparisons of ecological responses of soft sediment coastal ecosystems to armoring across the spectrum of open to sheltered shores and a range of different types of armoring structures. We predicted that ecological effects would intensify as (1) a function of increasing energy at the armoring structure and (2) with increasing influence of the structure in modifying the velocities and flow of water from waves and currents. These formed the two axes of our conceptual model. To critically evaluate the predictive power of our conceptual model, we identified a suite of six general categories of ecological responses that we expected would be affected by the presence of armoring. We then conducted a literature review of studies on the ecological effects of a diversity of shore-parallel armoring structures ranging from living shorelines to seawalls across a spectrum of soft sediment environments. We categorized our literature review results according to the hydrodynamic energy of the environment and the intended effects of each armoring structure on water velocities and flow. We quantified the number and direction of significant ecological responses reported, which enabled us to assess the predictive power of our conceptual model. We also used our results to identify key data gaps and develop further hypotheses.

Conceptual Model

Our analysis focused on shore-parallel structures placed in either the intertidal or the nearshore subtidal zones of the coast. We included numerous types of shoreline armoring and coastal defense structures, such as seawalls, revetments, bulkheads, and breakwaters, as well as sills, constructed oyster reefs, and living shorelines. Living shorelines are highly variable in structure and purpose and sometimes incorporate sills, revetments, plantings, and oyster reefs (see Gittman et al. 2016a). In some manifestations, living shorelines can be indistinguishable from traditional armoring (Pilkey et al. 2012). For our analysis, as long as they were parallel to shore, living shoreline studies were included, regardless of the range of ways in which they were designed and constructed. Although also widespread in a variety of soft sediment environments, our analysis excluded studies of groins, jetties, and other armoring structures built perpendicular to shore.

In order to place this wide variety of armoring structures into a common framework, we asked two key questions: (1) Is the engineering purpose of the structure to slow the velocity of water flow from waves and tides impinging on a shoreline or to completely prevent or stop the flow of water to the shoreline? (2) What is the hydrodynamic energy at the structure? We reasoned that if the purpose of the structure is to stop water flow and the hydrodynamic energy is high, that would require a very different type of armoring and cause more pronounced ecological effects than if the purpose was to slow water flow in a low-hydrodynamic energy setting. Our conceptual model is therefore organized along the axes of the intended effect of the structure on water flow and the hydrodynamic energy at the structure, which allows us to broadly categorize armoring structures as they are applied to different shoreline situations, elevations, and soft sediment environments.

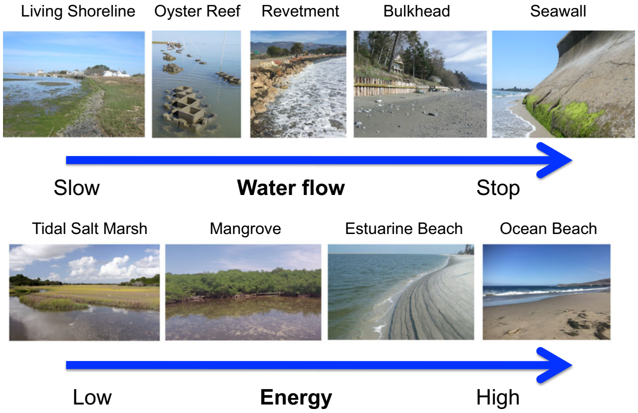

Fig. 1 Illustration of gradients in the two axes of influence for the conceptual model of shoreline armoring effects. *Top row* Engineering purpose with respect to intended effect of structure on water flow (slow vs. stop). *Bottom row* Hydrodynamic energy (low to high) at the structure as determined by the environment

The axis of water flow in the conceptual model can be thought of as a measure of the extent to which water generated by waves and tides is prevented from moving through or over the structure to the shoreline. Impermeable structures generally stop or prevent water flow through or over the structure whereas permeable or low height structures serve to slow water velocity and allow flow through or over the structure to reach the shoreline (Fig. 1, top). The size of the structure is also a consideration, as taller and longer structures will be more effective at stopping water flow to the shoreline. At one end of the spectrum, a seawall or revetment installed to prevent wave and storm surge intrusion is intended to stop water from reaching upland areas. In more sheltered areas, such as harbors and estuaries, a much smaller bulkhead can often provide a similar function. Revetments placed on open coasts designed to stop waves from reaching coastal cliffs, highways, or buildings tend to be tall and wide but are generally considered less reflective of wave energy than a seawall in the same setting. Smaller revetments that are more typical of sheltered shorelines, however, can often be somewhat more permeable and also tend to be less reflective of hydrodynamic energy than a bulkhead. Shorter structures, such as sills, are generally designed to retain sediments and still allow water to flow across or through the structure, serving to reduce water flow and velocity (Gittman et al. 2014). Again, living shorelines can span a broad range of permeability, size, and purpose with regard to their intended effects on water flow (i.e., Bilkovic et al. 2016; Gittman et al. 2016a).

A second important consideration that determines the type of armoring structure installed in a particular area is the amount of hydrodynamic energy that reaches and interacts with the structure. Hydrodynamic energy, broadly defined, encapsulates several important contributing aspects that affect armoring structure decisions, including the relative influence of waves and tides in the environment and the tidal elevation of the structure. In general, marshes and mangroves are lower-energy environments with tides dominating the hydrodynamic conditions (tide range/wave height > 3) (Hayes 1979), whereas open coast beaches are high-energy, wave-dominated environments (tide range/wave height = 0.5 to 1) that occupy the opposite end of the hydrodynamic energy spectrum (Fig. 1, bottom). In the middle are medium- or mixed-energy shores influenced by both tides and waves (tide range/wave height = 1 to 3). Hydrodynamic energy also varies within an environment, based on factors such as the tidal height in the profile at which the structure is placed and the role of local influences such as boat wakes and fetch. For example, the average hydrodynamic energy at a seawall placed well above mean high water on an open coast beach will be lower than that of a seawall located below mean sea level on the same shore profile (e.g., Weggel 1988). Although the conceptual model could theoretically be applied within a single soft sediment habitat (e.g., low vs. high elevation on an estuarine beach), in this study we focused on differences in hydrodynamic energy across environments so that we could encompass a broad range of ecosystem types (from beaches to marshes) in our evaluation of the conceptual model.

For our analyses, we used the two axes (effects on water flow and hydrodynamic energy setting) to divide our conceptual model into two categories of intended effects of the structure on water flow to the shoreline (slow or stop water flow) and three levels of hydrodynamic energy of the environment (low, medium, and high). The resulting six boxes (Fig. 2, labeled 1–3 for the hydrodynamic energy level and a or b for the engineering purpose of slowing or stopping water flow) allowed us to scale the effects of shore-parallel armoring structures across a range of soft sediment environments and structure types. One result of this categorization is that the range of possible combinations of coastal armoring structure and ecosystem is bounded, with some types of structures tending to occur more prevalently in certain ecosystems. For example, salt marshes are low in energy, and structures placed there to stop water flow, such as bulkheads (box 1b), are generally lower in height and require a smaller cross-shore footprint to maintain structural stability than in an open coast environment (e.g., USACE 2002). Large, detached breakwaters that slow water flow are found along open coasts (box 3a) or in bays (box 2a) whereas smaller sills are more prevalent in marsh and estuarine settings (box 1a). Revetments that stop or prevent water flow to the shoreline, albeit with less direct reflection of energy than seawalls or bulkheads, can be found on open coast beaches (box 3b) as well as lining the shores of estuaries, harbors, and bays (box 2b).

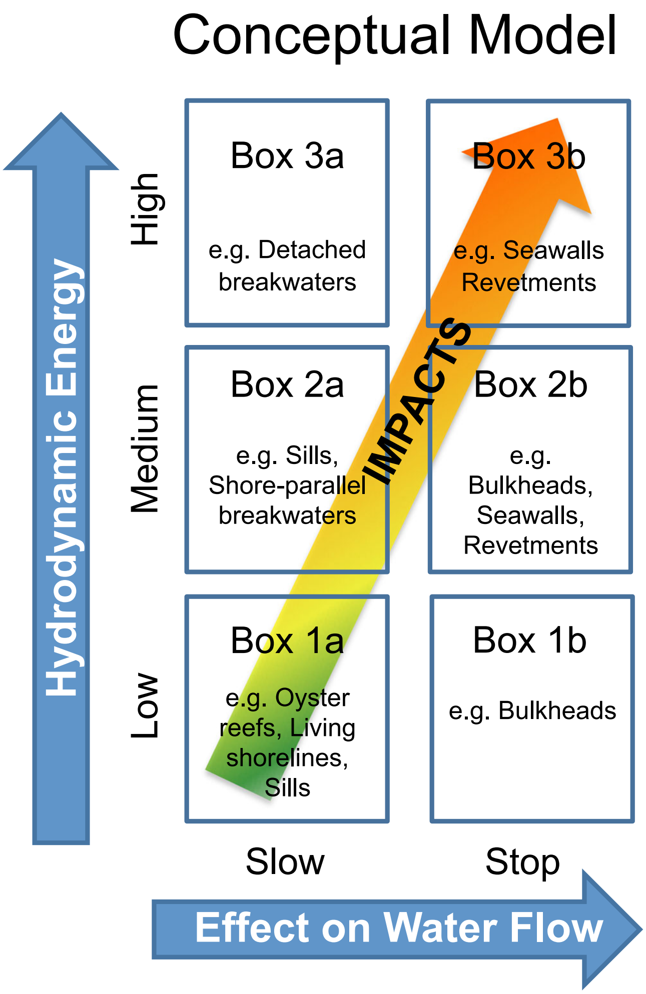

Fig. 2 Conceptual model showing predicted ecological impacts in soft sediment environments across the array of shoreline armoring types used to either slow or stop water flow (*x*-axis) and with different hydrodynamic energy levels at the armoring structure (*y*-axis). Ecological impacts are predicted to increase as one moves *up* and to the *right* within the parameter space

We used the conceptual model to predict the relative ecological impact of armoring structures given different combinations along the two axes (diagonal arrow in Fig. 2). Along the water flow axis, we predict that structures designed to slow rather than stop water flow will also allow more natural functioning and connectivity of aquatic and terrestrial habitats as opposed to those designed to stop water flow to the shoreline. Modeling studies have demonstrated that increased permeability of armoring structures could reduce wave reflection (e.g., Mallayachari and Sundar 1994; Zhu and Chwang 2001; Karim et al. 2009) and overtopping (e.g., Hieu and Vinh 2012), both of which could decrease sediment erosion and alter hydrology, affecting nutrient cycling and water quality. Impermeable barriers that completely prevent water flow to reach the shoreline will reflect more of the energy from waves and tides than those designed to slow velocity but still allow water flow through the structure to the shoreline. The hydrodynamic energy of the environment (the vertical axis) will also affect the design and impact of the armoring structure both across and within soft sediment environment types. Armoring structures in high-energy shoreline environments tend to be larger than those in low-energy environments (USACE 2002), leading to greater placement loss and, therefore, likely greater impacts to habitat and species distributions. Thus, a structure designed to slow water flow in an environment with low hydrodynamic energy (e.g., a low crested riprap sill in a marsh) would be expected to show the least amount of ecological impact, whereas one designed to stop water flow in a high-energy environment (e.g., a seawall on an open coast beach) would be expected to show the greatest impact. We did not have an *a priori* expectation as to which of these axes would be more important and so predicted a general upward increase in ecological impacts commensurate with intensification of both factors (Fig. 2).

To investigate these predictions for ecological impacts, we identified six categories of ecological responses that we expected could be altered by the presence of shoreline armoring in soft sediment ecosystems (see Fig. 3 for examples of negative responses). These categories are described below, along with the rationale for each category.

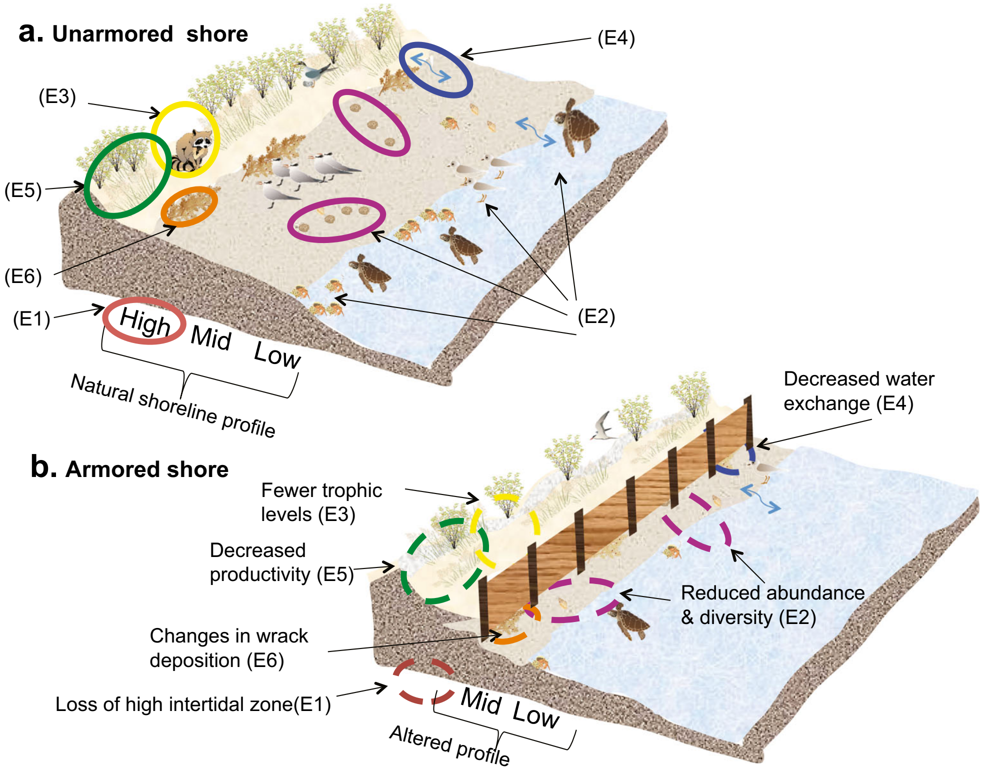

Fig. 3 Comparison between unarmored (**a**) and armored (**b**) shorelines, with examples of effects for the six ecological responses evaluated in this review (E1 habitat distribution, E2 species assemblage, E3 trophic structure, E4 nutrient cycling, E5 productivity, E6 connectivity). *Broken ellipses* in panel **b** signify negative impacts and correspond to the ellipse of the *same color* in panel **a**

(E1) Habitat Distribution: The loss or alteration of coastal habitats associated with armoring can directly impact many functions of soft sediment ecosystems including species distributions, biodiversity, connectivity, productivity, food webs, and wildlife support. In addition to the immediate placement loss that occurs when the footprint of an armoring structure covers a portion of the shore habitat, over time, the presence of a structure can result in the loss and alteration of intertidal habitat on its seaward side due to increased erosion and subsequent conversion to subtidal habitat (Fig. 3). This can result in a loss of habitat for intertidal biota and of nesting habitat for birds, fish, and sea turtles. Armoring structures can also result in the alteration of habitat characteristics, such as grain size, shore profile, and light regime, which can affect species distributions. By blocking seawater inundation and water flow, armoring can also result in the loss of intertidal habitat on the landward side of a structure and its conversion to upland. Armoring may also provide a novel hard substratum habitat in an area otherwise devoid of anything but soft sediment, and in some cases, this novel habitat may also include three-dimensional aspects, such as the nooks and crannies associated with rock revetments, that increase habitat complexity and provide refuges and microhabitat for some organisms.

(E2) Species Assemblage: The shifts in habitat noted above and other environmental characteristics of armoring structures can affect species assemblages, with consequent implications for biodiversity, abundance, size structure, and community composition (Fig. 3). Armoring structures can also potentially support both native and invasive species that require hard substrates and may provide stepping stones for their dispersal and spread to new areas.

(E3) Trophic Structure: Shifts in trophic and food web structure associated with armoring follow from shifts in habitat characteristics, species distribution, and productivity (Fig. 3). This can include changes in prey or predator abundance, shifts in diet, and altered complexity and functional redundancy of food webs. This category includes effects on animals that forage in coastal soft sediment ecosystems, including birds, fishes, reptiles, and mammals.

(E4) Nutrient Cycling: Changes in hydrology and sediment characteristics associated with armoring will likely affect microbial communities and biogeochemical cycling with impacts to nutrient cycling, rates (i.e., denitrification), organic matter dynamics, and oxygen levels (Fig. 3). The presence of the structure may also interfere with water exchange across the interface, potentially reducing surface water runoff and associated nutrients from the upland.

(E5) Productivity: Primary production may be affected by the presence of armoring, particularly if there are changes in light (through shading) or nutrient availability (Fig. 3). Primary production includes that of phytoplankton, macroalgae, vascular plants, and microphytobenthos. Secondary production may be affected as well, either as a consequence of changes in primary production or changes in habitat and species distribution.

(E6) Connectivity: Armoring can represent a physical barrier that interferes with the exchange and accumulation of organisms, wrack, litter, sediment, and propagules on the shoreline (Fig. 3). Depending on the location of the structure, this can prevent or deter the movement between upland, intertidal, and subtidal areas and affect vital shoreline ecotones at the boundary of land and sea. Loss of connectivity has implications for many of the other ecological effects described above, such as nutrient cycling, productivity, species assemblages, and trophic structure.

Methods: Literature Review and Evaluation of Conceptual Model

To evaluate the predictions of our conceptual model, we used the results of a literature review that focused on the six categories of ecological responses to shoreline armoring (E1–E6) we identified. We conducted a systematic search of Google Scholar and Web of Science using key words related to armoring (breakwater, bulkhead, coastal armoring, coastal hardening, living shoreline, oyster reef, riprap, revetment, seawall, shoreline armoring, shoreline hardening, sill, impoundment) and environment (beach, estuary, lagoon, mangrove, salt marsh, tidal creek, harbor, river mouth). This was augmented by papers that came to our attention through conferences and other means as we were conducting this effort. Papers were included in the literature review if they contained ecological results.

We classified each study in terms of environment and type of armoring structure to assign it into one of the six boxes in our conceptual model. Due to the limited scope of information available, we did not further classify studies or study results based on tidal elevation, size (height and length), submergence regime, or construction material of the armoring structures for our analysis.

We identified which of the six categories of ecological responses were evaluated in each study and whether the effects were significantly positive, significantly negative, or not significant according to the authors of each paper reviewed. Examples of negative responses are illustrated in Fig. 3, and additional examples of positive and negative responses are provided in Table S1.

In studies where more than one box in the conceptual model was studied or more than one ecological response category was evaluated, we assessed each box and/or response category result separately. However, if more than one variable was measured within a particular effect category, it was only counted once. For example, if a study measured the abundance of multiple species, it was only included once under species assemblage (E2). In most cases, multiple variables responded similarly (i.e., there were significant reductions in all species evaluated). In the few cases where there were mixed results, a paper was scored according to the majority of effects (i.e., if the abundance of four out of five species was significantly reduced, this was counted as a negative effect). Effects of armoring on habitat distribution (E1) and species assemblages (E2) were often reported together (i.e., a change in habitat was associated with a change in species distribution or abundance). We separated these effects for our analyses by assigning changes in habitat availability or quality, including nesting habitat, to E1 and changes in abundance or distribution of organisms to E2.

Results

We located a total of 88 studies that evaluated ecological effects of shore-parallel coastal armoring on soft sediment environments (Table S2). The majority of studies ($n = 51$) were conducted in low-energy environments: most of these were conducted in salt marshes and tidal creeks ($n = 47$) and only four in mangroves. A total of 24 studies were conducted in medium-energy systems, including studies in harbors, river mouths, and estuaries. We located only 13 ecological studies conducted in high-energy environments, the majority of which were conducted on open coast sandy beaches.

The majority of studies in low-energy environments investigated structures designed to slow water (Box 1a), such as sills, rather than stop water flow (e.g., bulkheads) (Box 1b) (Fig. 2, Table 1). Box 1a in our conceptual model included most of the living shoreline and oyster reef studies but also

Table 1 Distribution of studies of ecological effects of shoreline armoring across the axes of hydrodynamic energy and intended effect of armoring structure on water flow that define the six boxes in the conceptual model

Hydrodynamic energy of environment	Effect on water flow	
	Slow a	Stop b
High: 3	5	11
Medium: 2	13	19
Low: 1	36	24

Note that the total for this table ($n = 108$) exceeds the number of studies (88) because studies that examined more than one structure type were represented in multiple boxes of the conceptual model, as appropriate included sill, revetment, and riprap installations in low-energy environments, whereas Box 1b primarily included studies of bulkheads and impoundments designed to stop water flow. Studies in the medium-energy environments were split fairly evenly between structures designed to slow vs. stop water (Table 1). Those in Box 2a of the model included studies of detached breakwaters in harbors and bays, whereas those in Box 2b included studies of seawalls, bulkheads, and shoreline revetments. For high-energy environments, there were more studies of structures designed to stop water flow (Table 1). Box 3a of our model included studies of detached breakwaters that were mostly conducted along open sandy coastlines while Box 3b covered studies of seawalls and massive revetments on open coast sandy beaches.

We identified results that covered all of the six categories of ecological response variables (E1–E6), indicating a surprisingly wide range of investigations of the ecological impacts of armoring (Table 2). However, a preponderance of these was focused on alterations in E2 (species assemblage (94)), followed by E1 (habitat distribution (57)). There were far fewer studies that evaluated the responses to armoring in regard to E3 (trophic structure (18)), E4 (nutrient cycling (18)), E5 (productivity (13)), and E6 (connectivity (7)). Below, we summarize the results for each of the ecological responses and then compile the information into an overview of positive and negative effects across all categories. Mixed results were rare and only reported in three studies. A list of the individual papers included in this analysis along with their assigned boxes, ecological response variables, and significant effects can be found in Table S2.

E1: Habitat Distribution

The effects of coastal armoring on habitat distributions and availability were well represented in the literature review with a total of 57 observations, with studies measuring effects in terms of intertidal zone widths and distributions, habitat characteristics (e.g., depth, elevation, slope, and grain size), and nursery and nesting habitat for birds, fish, and sea turtles as well as the provision of novel hard substrate habitats for epifauna. The majority of these observations were reported for low-energy environments (33 in salt marsh and tidal creeks and 1 in mangroves), but results were available for medium-energy environments (14) and high-energy environments (9). Similar numbers of studies evaluated armoring structures placed to slow (30) as opposed to stop (27) water flow for this response (Fig. 4). Of the 57 observations related to effects on habitat associated with armoring, 38 were negative, 17 were positive, and 2 were detected to have no difference.

The large numbers of studies of armoring effects on habitat distribution was spread among all six boxes of our conceptual model (Fig. 4). Where structures were installed to slow water in low-energy environments, Box 1a, a mix of positive and negative responses was reported. Multiple studies concluded that adding constructed oyster reefs, living shorelines, or permeable riprap armoring structures provided significant new habitat area (e.g., Davis et al. 2002. Piazza et al. 2005, Swann 2008, Powers et al. 2009, Scyphers et al. 2014, Gittman et al. 2016a). However, a myriad of negative observations was also reported for Box 1a. Armoring, including riprap and marsh impoundments, eliminated habitat, reduced habitat quality, or provided habitat suitable for invasive species (Hendon et al. 2000; Peterson et al. 2000; Boys et al. 2012; Geraldi et al. 2014; Lowe and Peterson 2014; Patrick et al. 2014, 2016). For Box 1b of our model, where bulkheads and seawalls were put in place to stop the flow of water in low-energy environments, all observations were negative except for one where a bulkhead was reported to provide new habitat for epifaunal communities (Wong et al. 2011). In all other studies of salt marshes and tidal creeks in which the armoring structure was designed to stop water flow (Box 1b), studies reported that habitat was lost, habitat quality was reduced, or

Table 2 Distribution of study results from the literature review that were reported as significantly positive, negative, and not significant (NS) for each of the six ecological responses (E1–E6) in each of the six boxes of our conceptual model (1a, 2a, 3a, 1b, 2b, and 3b)

Direction of response	Box 1a			Box 1b			Box 2a			Box 2b			Box 3a			Box 3b		
	+	−	NS	+	−	NS	+	−	NS	+	−	NS	+	−	NS	+	−	ND
E1: Habitat Distribution	10	8	2	1	13	0	4	3	0	1	6	0	1	2	0	0	6	0
E2: Species Assemblage	12	15	4	1	18	0	3	8	1	2	14	0	1	5	0	0	9	1
E3: Trophic Structure	3	2	1	1	4	0	0	0	0	0	3	1	1	0	0	0	2	0
E4: Nutrient Cycling	1	8	1	1	4	0	0	1	0	0	1	1	0	0	0	0	0	0
E5: Productivity	1	5	1	1	2	1	0	0	0	0	0	0	0	0	0	0	2	0
E6: Connectivity	0	1	0	0	1	0	0	1	0	0	3	0	0	0	0	0	1	0
Total	27	39	9	5	42	1	7	13	1	3	27	2	3	7	0	0	20	1

Numerous studies reported multiple ecological effects which resulted in the total sample size ($n = 207$) presented here

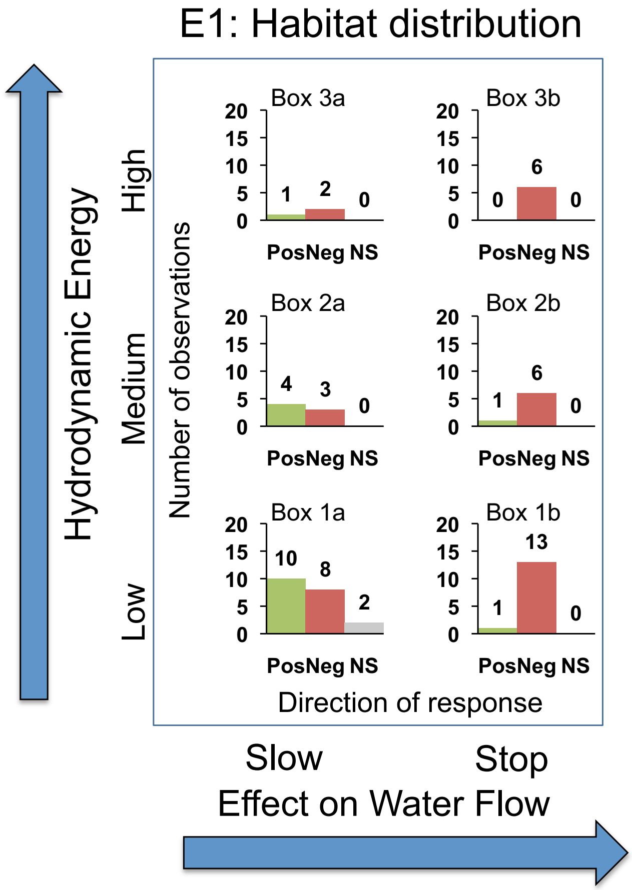

Fig. 4 Ecological effects on habitat distribution (E1) reported in studies included in our literature review. The histograms correspond to the six combinations of intended effects of an armoring structure on water flow and the hydrodynamic energy of the environment represented by the boxes in the conceptual model (Fig. 2). In the histogram for each box, the number of significantly positive (*green*), negative (*red*), and not significant (*NS*) (*gray*) observations is plotted

the armoring structures provided habitat for undesirable invasive species (e.g., Bozek and Burdick 2005; Baily and Pearson 2007; Freiss et al. 2008; McPherson 2009; Balouskus and Targett 2012; Gittman et al. 2016b). Similarly, seawalls in mangrove ecosystems resulted in reduced mangrove forest habitat area (Heatherington and Bishop 2012).

For Box 2a of our model, where structures were put in place to slow water in medium-energy environments, effects on habitat were again mixed. Permeable structures such as riprap structures, oyster reefs, and constructed habitat benches provided habitat, often by increasing the availability of structurally complex habitat (Toft et al. 2007, 2013; Pister 2009; Drexler et al. 2014). Other studies, however, found that riprap structures eliminated soft sediment intertidal and benthic habitat (Sobocinski et al. 2010; Heerhartz et al. 2014; Dethier et al. 2016). For Box 2b, where seawalls and bulkheads were used to stop water flow, all observations but one were negative. Although Drexler et al. (2014) found that seawalls provided habitat for oysters, many other studies found that these structures generally reduced habitat (Bilkovic and Roggero 2008; Sobocinski et al. 2010; Heerhartz et al. 2014; Dethier et al. 2016) unless remedial actions were undertaken to increase habitat complexity (Browne and Chapman 2011, 2014).

For structures installed to slow water in high-energy environments (Box 3a), Martin et al. (2005) concluded that a low-crested breakwater structure provided new habitat, but others reported that breakwaters, revetments, and low-crested structures reduced structural complexity and eliminated habitat (Moschella et al. 2005; Vaselli et al. 2008). For Box 3b of our model, several studies found that seawalls reduced or eliminated intertidal and upper shore and coastal dune habitats in sandy beach ecosystems (Dugan and Hubbard 2006; Dugan et al. 2008; Jaramillo et al. 2012; Rodil et al. 2015). Negative results were also reported where armoring reduced the quality of critical beach nesting habitats for sea turtles, a globally threatened group (Rizkalla and Savage 2011).

When taken together, the majority of the results for habitat distribution (72%) were negative, particularly for structures designed to stop the flow of water (92% overall), a result in agreement with predictions of our conceptual model. These negative results were most commonly associated with the loss of habitat area and reduced habitat quality. For structures intended to slow the flow of water, positive results made up 50% of the results in Box 1a, 57% for Box 2a, and 33% in Box 3a. Most of these were associated with constructed oyster reefs and living shorelines that provided new habitat for native species.

E2: Species Assemblages

Effects on species assemblages were the most commonly documented ecological response to shoreline armoring in our review, with a total of 94 observations. The majority of these were in low-energy habitats (47 in salt marsh and tidal creek ecosystems, 3 in mangroves), with 25 in medium-energy habitats and only 16 observations in high-energy open coast environments. Approximately equal numbers of studies evaluated structures placed to slow (49) as opposed to stop (45) water flow.

A majority of the significant responses of species assemblages to armoring were considered negative (69), with only 19 reports of positive responses and 6 reports of no significant differences detected (Fig. 5). When distributed across the boxes of our conceptual model, we found that most of the positive responses were observed for Box 1a (structures designed to slow water in low-energy environments). Positive results included increases in epiphyte and epifaunal abundance and diversity on the structures themselves (e.g., Wong et al. 2011; Peters et al. 2015), particularly for oysters (e.g., Piazza et al. 2005; Powers et al. 2009; Scyphers et al. 2011), as well as increases in other invertebrates and in fish on living

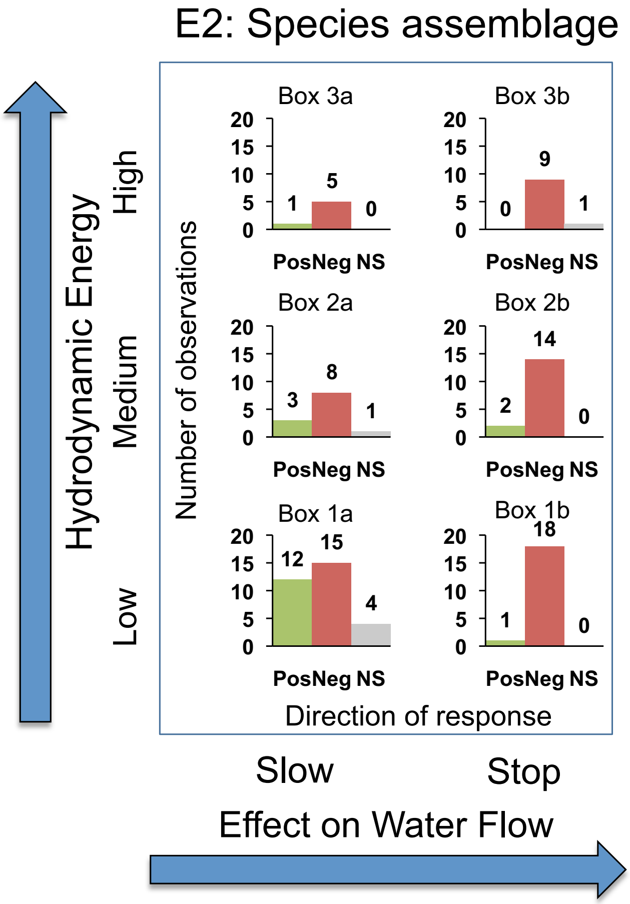

Fig. 5 Ecological effects on species assemblages (E2) reported in studies included in the literature review. The histograms correspond to the six combinations of intended effects on water flow and the hydrodynamic energy of the environment and represented by the boxes in the conceptual model (Fig. 2). In the histogram for each box, the number of significantly positive (*green*), negative (*red*), and not significant (*NS*) (*gray*) observations is plotted

shorelines (Gittman et al. 2016a). However, the majority of observations in Box 1a were negative and included decreased species diversity and/or abundance for a wide range of assemblages including microbial communities (Bernhard et al. 2012), primary producers (e.g., Sturdevant et al. 2002; O'Connor et al. 2011), infaunal invertebrates (e.g., Peterson et al. 2000; Seitz et al. 2006; Bilkovic and Mitchell 2013), nekton and fish (Bilkovic 2011; Boys et al. 2012; Lowe and Peterson 2014, 2015) and waterbirds (Bolduc and Afton 2003). In Box 1b, negative responses to armoring dominated the results with decreases in diversity and abundance reported for mangroves (Anthony and Gratiot 2012; Heatherington and Bishop 2012), salt marsh vegetation (Bozek and Burdick 2005), invertebrates (Seitz et al. 2006; Lawless and Seitz 2014; Swamy et al. 2002), and nekton and fish (e.g., Balouskus and Targett 2016; Lowe and Peterson 2014, 2015).

For medium-energy environments, studies of structures designed to slow water (Box 2a) had mixed results, but again, negative impacts made up the majority (75%) of the reports, including impacts on invertebrates (Morley et al. 2012; Dethier et al. 2016) and on nekton and fish (Scyphers et al. 2015; Torre and Targett 2016). The few positive results were primarily associated with epifauna on the armoring structures themselves (Toft et al. 2013; Drexler et al. 2014) or in one case fish (Toft et al. 2007). For Box 2b, observations were almost entirely negative, with bulkheads and seawalls, resulting in reductions in invertebrates (Sobocinski et al. 2010; Rolet et al. 2015; Dethier et al. 2016; Heerhartz et al. 2016), fish (e.g., Bilkovic and Roggero 2008; Munsch et al. 2014; Scyphers et al. 2015), and even terrapins (Isdell et al. 2015).

Effects on species distribution were again almost entirely negative for armoring structures in high-energy environments (Boxes 3a and 3b). Studies classified in Box 3a found that the presence of armoring depressed invertebrate diversity and abundance (e.g., Moschella et al. 2005; Martins et al. 2009; Bacchiocchi and Airoldi 2003) and also facilitated invasive species (Vaselli et al. 2008). The sole positive result for Box 3a was reported for benthic diversity and for fish associated with offshore breakwaters (Martin et al. 2005). For Box 3b, all results were negative including responses by coastal dune plants (Rodil et al. 2015), infaunal invertebrates (e.g., Lucrezi et al. 2010; Jaramillo et al. 2012), and birds (Dugan et al. 2008).

Armoring was associated with declines in both species diversity and species abundance across all soft sediment environments and structure types. The majority of observations in all six boxes of our conceptual model were negative, and positive results were most often associated with structures designed to slow water. Although our synthesis is limited by the literature available, this outcome is in general agreement with the predictions of our conceptual model, with negative results predominating (≥86%) in studies of armoring structures designed to stop water flow at all hydrodynamic energy levels (Boxes 1b, 2b, and 3b). For the structures designed to slow water flow, positive results made up 39% of the reports in Box 1a, 25% in Box 2a, and 17% in Box 3a.

E3: Trophic Structure

Trophic structure and food webs were among the least studied ecological response to armoring found in our review (Table 2). Studies included in this category evaluated variables such as the number of trophic categories, prey availability, shifts in diet, and predator abundance, including fish, birds, and marine mammals. A total of only 18 trophic structure effects were identified, with the majority of studies occurring in low-energy habitats (10 in salt marshes or tidal creeks and 1 in mangroves), 4 in medium-energy habitats and 3 in high-energy beaches. More of these studies evaluated structures placed to stop (11) as opposed to slow (7) water. A majority of the significant responses were considered negative (11), with only 5 reports of positive responses.

Across the boxes of the conceptual model (Table 2), we found mixed results for Box 1a: salt marsh habitats with riprap armoring and sills in the Chesapeake Bay were found to have fewer trophic levels (e.g., Bilkovic and Mitchell 2013). However, living shorelines (Gittman et al. 2016a) and sills in North Carolina (Wong et al. 2011) were reported to maintain higher trophic levels and oyster reefs were associated with increased prey for fishes (Grabowski et al. 2005). For Box 1b, the presence of bulkheads and levees were found to reduce prey availability and result in diet shifts for nekton in marshes (e.g., Lowe and Peterson 2015), although Wong et al. (2011) reported that bulkheads had a positive effect due to epifaunal colonization. For Box 2b, Munsch et al. (2015) documented different food availability and consumption by juvenile salmon adjacent to seawalls, and Jackson et al. (2015) found that shorebirds preferred to forage at unarmored sites. There was only one study in Box 3a: Martin et al. (2005) observed an increase in the number of trophic groups (fish) near a low-crested armoring structure. For Box 3b, significantly reduced diversity (50% lower) and abundance (66% lower) of shorebirds, key intertidal predators, as well as 75% fewer gulls and 86% fewer seabirds were reported on California beaches where seawalls were present (Dugan and Hubbard 2006; Dugan et al. 2008).

Although there are relatively few observations available for trophic structure and food web responses to shore-parallel armoring, the majority of results (≥75%) in studies of armoring structures designed to stop water flow (Boxes 1b, 2b, and 3b) were negative, whereas positive results comprised half of the results in Box 1a and 100% in Box 3a (Table 2), an outcome in general agreement with the predictions of our conceptual model.

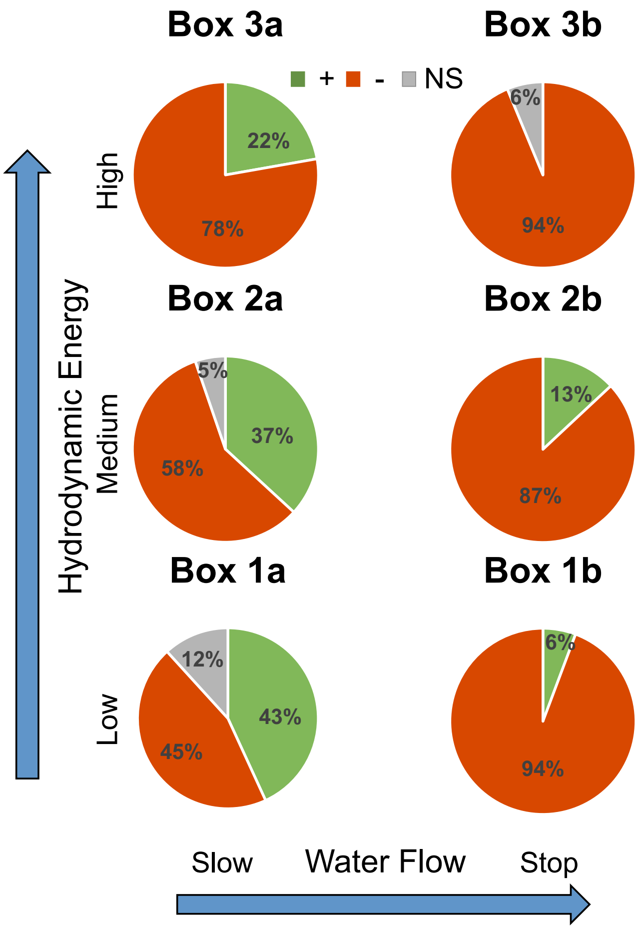

Fig. 6 Summary of the direction of ecological responses (+/−) of combined observations for habitat distribution (E1) and species assemblages (E2) reported in studies in the literature review. The pie charts correspond to the six combinations of intended effects on water flow and the hydrodynamic energy represented by the boxes in the conceptual model (Fig. 2). In the pie chart for each box, the percentage of significantly positive (*green*), negative (*red*), and not significant (*NS*) (*gray*) observations are plotted

E4: Nutrient Cycling

The effects of coastal armoring on nutrient cycling have not been widely documented, with a total of only 18 reports in our review (Table 2). The response variables considered in the studies included nutrient concentrations, rate measurements (i.e., denitrification), organic matter composition, and oxygen levels. The majority of these observations were studies of low-energy environments (15 in salt marshes and tidal creeks and 1 in mangroves) with only a few in medium-energy habitats (2) and none for higher-energy open coast environments. Most of these observations were for armoring structures placed to slow (11) as opposed to stop (7) water. A majority of the significant responses to armoring related to nutrient cycling were considered negative (14), with only 2 reports of positive responses.

Across the boxes of our conceptual model, we found the highest number of observations for Box 1a (Table 2). These were primarily negative. For example, salt marsh impoundments were associated with declines in dissolved oxygen levels and salinity (Bolduc and Afton 2004) and lower rates of nutrient accumulation (Sturdevant et al. 2002). Several studies documented reductions in sediment organic matter or total organic carbon and nitrogen in association with different armoring structures (sills, revetments, and impoundments) in salt marshes (e.g., Bryant and Chabreck 1998; Peterson et al. 2000; Currin et al. 2008; Bilkovic and Mitchell 2013). In Box 1b, lower organic carbon concentrations were again observed in association with structures (Peterson et al. 2000), and Windham-Myers et al. (2013) found that the reduction in tidal flushing created by the presence of an impoundment resulted in anoxia and the buildup of reduced sulfur. Working in a mangrove system, Dick and Osunkoya (2000) found reduced leaf litter decomposition and greater retention of carbon, nitrogen, and phosphorus on the landward side of tidal floodgate structures. Invasive algae growing on bulkheads and revetments in salt marshes were associated with increased N_2 production and represented the positive observations reported for Boxes 1a and 1b (Geraldi et al. 2014). There was only one study for Box 2a, wherein Morley et al. (2012) saw an increase in temperature at armored sites, and there was one study for Box 2b, wherein lower sediment organic carbon was observed in association with areas with more shoreline armoring in a developed river estuary (Partyka and Peterson 2008).

Although there are relatively few observations available for evaluating the response of nutrient cycling to armoring, the majority of results (>80%) were negative for studies of armoring structures designed to either stop or to slow water in medium-energy environments (Boxes 2a and 2b). The few positive results were reported only for low-energy environments (Boxes 1a and 1b) (Table 2).

E5: Productivity

The effects of coastal armoring on productivity were not well represented in the literature review, with a total of only 13 observations (Table 2). These studies measured effects including the primary production of macroalgae, plants, and microphytobenthos and the secondary production of higher organisms. The majority of these observations were reported for low-energy environments (10 in salt marsh and tidal creeks and 1 in mangroves) with none in medium-energy environments and only 2 in high-energy beach environments (Table 2). The dominance of primary producers in salt marshes compared to beaches and other shore types may explain some of this disparity. These studies were balanced between armoring structures placed to slow (7) as opposed to stop (6) water. For the limited number of studies (13) examining the effects of shoreline armoring on productivity, the majority of results (69%) were negative (9), 2 were positive, and 2 were found to have no change (Table 2). All the positive and no change results for this ecological response category were observed in low-energy environments (Boxes 1a and 1b).

Although there were relatively few observations of armoring effects on productivity, four of the six boxes from our conceptual model (Table 2) were represented in the literature review. For Box 1a, riprap, sill, and impoundment structures were associated with reduced productivity and biomass of plants and algae (O'Connor et al. 2011; Sturdevant et al. 2002) and reduced cover, growth, and biomass of marsh grass (*Spartina* spp.) (Currin et al. 2008; Bilkovic and Mitchell 2013). Reductions in productivity in salt marsh (Freiss et al. 2008) and mangrove (Heatherington and Bishop 2012) ecosystems were also associated with seawalls (Box 1b). However, Wong et al. (2011) observed positive responses to armoring in low-energy habitats, reporting that the presence of both sills (Box 1a) and bulkheads (Box 1b) led to greater secondary production in salt marshes in North Carolina than in habitats without the added structure. The single study for a sandy beach (Rodil et al. 2015) concluded that the presence of both revetments and seawalls (Box 3b) limited the growth and development of coastal strand and dune vegetation.

E6: Connectivity

Despite the importance of connectivity, this was the least documented ecological response in our literature review, with a total of only seven observations (Table 2). The studies included in this ecological response evaluated effects of armoring on the exchange of materials, mobile organisms, and propagules across shore zones and ecosystems. The majority of these observations were reported for low- and medium-energy environments, with one in salt marshes and tidal creeks and one in mangroves, four in medium-energy habitats, and one in a high-energy beach environment. Most of these studies evaluated armoring structures placed to stop (five) as opposed to slow (two) water (Table 2). All observations related to effects of shoreline armoring on connectivity were negative, including those for structures designed to stop or to slow water flow.

Although there were relatively few observations of armoring effects on connectivity, five of the six boxes from our conceptual model (Table 2) were represented. The addition of armoring structures in low-energy environments to limit the flow of water (Box 1a) restricted the passage of fish and crustaceans (Boys et al. 2012). In Box 1b, the addition of a seawall reduced availability and prevented movement of propagules in a mangrove ecosystem (Anthony and Gratiot 2012). In medium-energy soft sediment environments, Box 2a, the only study available found that riprap armoring significantly limited material transfer from adjacent marine and terrestrial habitats to the shoreline (Heerhartz et al. 2014). For Box 2b, results were again negative, indicating that bulkheads and seawalls limited material transfer and restricted the movement of fish species, including economically valuable salmon (Heerhartz et al. 2014; Munsch et al. 2014; Heerhartz and Toft 2015). In the one example for a high-energy environment (Box 3b), seawalls were found to eliminate the upper intertidal zones of sandy beaches, thereby reducing material transfer and retention in the form of marine macrophyte drift (Dugan and Hubbard 2006). These results indicate the presence of an armoring structure can prevent the passage of organisms, and in many cases it also reduces the deposition and retention of drift material and key subsidies, such as macrophyte wrack.

Although only a few studies examined the effects of shoreline armoring on connectivity, the negative effect of a loss of connectivity across zones and ecosystems and the associated habitat fragmentation and restriction of landward movement was reported in all soft sediment environments and in all of the boxes with results represented in our conceptual model.

Summary of Ecological Effects

A total of 207 effects were evaluated across the six boxes of the conceptual model. They were split fairly evenly between results of studies of structures designed to slow water (106) and those designed to stop it (101). Although the majority of studies were conducted in low-energy environments (75 in Box 1a and 48 in Box 1b), all boxes of the conceptual model were represented (Table 2). Across all 207 effects evaluated, 71% were reported to be significantly negative, 22% were significantly positive, and only 7% were not significant (Table 2).

Habitat distribution (E1) and species assemblage (E2) were the two ecological responses with sufficient results to allow comparison across all six boxes of the conceptual model (Figs. 4 and 5). These two ecological effects were also often closely related (i.e., when there is a shift in habitat that often has an effect on species assemblage) due to the important influence of habitat on species distributions. When we combined the results for these two responses to provide a broader summary (Fig. 6), the percentage of negative responses reported within each hydrodynamic energy category were greater for structures designed to stop water flow (Boxes 1b, 2b, and 3b) (16 to 49% greater) than for those designed to slow water flow (Boxes 1a, 2a, and 3a). The percentage of negative responses reported also increased with increasing hydrodynamic energy for structures designed to slow water flow (45% in Box 1a, 58% Box 2a, and 78% in Box 3a) but were more uniformly high for those designed to stop water flow across environments (94% in Box 1b, 87% in Box 2b, and 94% in Box 3b) (Fig. 6).

The percentage of positive ecological effects for the combined results for E1 and E2 were largely the converse of the negative results. Within a given hydrodynamic energy environment, the percentage of positive results were greater for structures built to slow as opposed to stop or prevent water flow (Fig. 6). For structures designed to slow water flow, the percentage of positive ecological effects clearly declined with increasing hydrodynamic energy, from 42% in low- to 22% in high-energy environments. This trend for positive effects was less clear for structures designed to stop water flow as all boxes had a very low percentage of positive effects, and no positive results were reported in high-energy environments. Many of the positive results reported were from studies of constructed oyster reef and living shoreline structures, although a number of positive effects we tallied were associated with the colonization of new and novel hard substrate habitats provided by armoring or shoreline protection structures.

Collectively, the combined results for E1 and E2 in Fig. 6 were consistent with our predictions that the ecological effects of shoreline armoring would be greater for structures designed to stop as opposed to slow water flow and provide some evidence that ecological effects may intensify with increasing hydrodynamic energy of the environment or setting. They also suggest that the purpose of the structure with respect to water flow has a greater effect on ecological responses than the hydrodynamic energy of the soft sediment environment.

Discussion

As indicated by the number of recent papers in our literature review (as well as the other papers included in this special issue), the ecological effects of shoreline hardening are receiving increased attention. Placing this information in the framework of our conceptual model enabled us to scale the ecological effects of shore-parallel armoring and allowed comparisons across a range of soft sediment ecosystems and armoring structures. However, our review revealed major gaps in knowledge and highlighted the fact that existing information on ecological responses to armoring is unevenly distributed across habitat types and does not necessarily cover the range of potential environmental and armoring contexts. We found the majority of studies have been conducted in low-energy systems, particularly salt marshes, with much less attention to beaches and open coast shores. There was also a notable dearth of studies in mangrove systems. The distribution of studies across the various ecological responses were largely focused on changes in habitat and species distribution, leaving crucial gaps in our understanding of how the presence of shoreline armoring affects key ecological responses of nutrient cycling, connectivity, productivity, and trophic structure. Filling these gaps will allow a far more complete evaluation and synthesis of the ecological responses to shoreline armoring than was possible here.

Despite the gaps in knowledge, the majority of studies in our literature review reported significantly negative effects of shoreline armoring in all six categories of ecological responses that we evaluated. Shoreline armoring of a wide array of structure types resulted in habitat loss, shifts in species assemblages and trophic structure, changes in nutrient cycling, reduced productivity, and the loss of connectivity in soft sediment environments across all boxes of our conceptual model. Negative effects of armoring on habitat and connectivity have the potential to trigger impacts in all the other ecological responses we evaluated.

Reported positive effects of armoring were far fewer and were less evenly distributed across our six ecological response categories and the boxes of the conceptual model. Although low, the proportion of positive effects reported was generally higher in the ecological response categories of habitat distribution (E1), species assemblages (E2), and trophic structure (E3) than in the other three categories (E4–E6) (Table 2). This pattern seems consistent with the colonization and use of the novel hard substrate habitats provided by armoring structures in otherwise soft-bottomed ecosystems by a variety of organisms that prefer hard substrates (e.g., Meyer et al. 1997; Davis et al. 2002; Swann 2008; Browne and Chapman 2011). However, facilitation of species distributions by armoring structures can be ecologically negative if non-native invasive species are involved because such species may preferentially use artificial structures as stepping stones, potentially increasing their spread to new areas (e.g. Airoldi et al. 2005, Bulleri and Airoldi 2005, Tyrell and Byers 2007).

Placing the results from our literature review in the framework of our conceptual model enabled us to coarsely scale the ecological effects of armoring and allowed comparisons across a range of soft sediment ecosystems and structures. The percentage of negative responses varied clearly with the intended purpose of armoring structures on water flow, increasing from those designed to slow water flow to those designed to stop water flow within a given hydrodynamic energy level. The distribution of results among the six boxes in our conceptual model was consistent with our prediction that the ecological effects of shoreline armoring would be greater for structures designed to stop as opposed to slow water. Although less clear-cut, there was also evidence that ecological effects may intensify with increasing hydrodynamic energy of the environment. Overall, our results suggest that the purpose of the structure with respect to water flow has a greater effect on ecological responses than the hydrodynamic energy of the soft sediment environment (Table 2, Fig. 6). This finding has potential implications for refining the design and permeability of armoring structures in ways that can reduce ecological impacts, particularly in low-energy environments.

One of the limitations of the results reported here is that our synthesis relies on the reported significance of responses in studies with a wide range of sample sizes. Using effect size, which takes sample size and variance into account, can provide a normalized measure that can be more quantitatively compared across studies. The recent paper by Gittman et al. (2016b), which compared effect sizes for ecological responses to three armoring structure types (breakwaters, riprap revetments, and seawalls), concluded that greater ecological impacts on biodiversity and abundance were associated with seawalls compared to revetments and breakwaters. This result is in agreement with that predicted by our conceptual model for structures designed to stop vs. slow water flow. However, their meta-analysis did not address any possible differences with respect to the different hydrodynamic energy levels of soft sediment environments affected by armoring. In our review, the ecological response of species assemblages (E2) was the only category with sufficient data to allow comparisons of effect sizes across most of our conceptual model (five of six boxes) (see Table S3 for complete results). We found the lowest effect sizes for armoring structures in low-energy environments (Boxes 1a and 1b) with two- to five-fold higher effect sizes in medium- and high-energy environments, a result that is broadly consistent with our predictions. These results, along with those of Gittman et al. (2016b), suggest that comparing effect sizes from studies designed to make common measurements across all six boxes of our conceptual model could advance synthesis and allow more general predictions of ecological responses to armoring across soft sediment ecosystems and structure types.

Another refinement of our conceptual model would be to incorporate quantitative information on permeability and hydrodynamic energy of armoring structures. We divided our conceptual model into six boxes for heuristic purposes but recognize that both axes are continuous variables that can be scaled in terms of water flow (i.e., $m^3 s^{-1}$) and energy (i.e., $kW m^{-1}$). This refinement would allow one to focus more precisely on the hydrodynamic energy at the structure and how impacts might be influenced by characteristics, such as tidal elevation of the structure. For example, the lower an armoring structure is located with respect to high water levels, the greater the associated physical impacts (Weggel 1988, Wiegel 2002a, b, c). Our conceptual model would predict ecological effects to scale similarly with decreasing intertidal elevation of the structure, which would move it up the hydrodynamic energy axis and consequently magnify the effects it exerts on the coastal ecosystem. This also implies that as existing armoring structures effectively move lower on the shore profile with rising sea level, their ecological impacts would be expected to increase. Considering additional attributes of armoring structures such as size, construction material (e.g., Nordstrom 2014) or the amount of surface area that is partially or completely submerged would provide fruitful ways to further refine and increase the specificity of the predictions of our conceptual model.

This effort provides a needed first step in generating discussion and motivating synthesis that can lead to a comprehensive framework for scaling the ecological effects of shoreline armoring across a range of coastal soft sediment ecosystems. The conceptual model allowed us to evaluate predictions regarding the direction and relative ecological impacts of shore-parallel armoring structures in different soft sediment environments based on relatively simple criteria. The results of our literature search were largely consistent with the predictions of our conceptual model and suggest that such cross-environment generalizations are possible and may have implications for balancing the protection of coastal infrastructure with the conservation of coastal ecosystems. However, our analysis also highlights substantial research gaps and the need for comprehensive studies designed to make systematic comparisons of the ecological effects of shoreline armoring across structure types and environments. The results from these types of comprehensive efforts could be useful for assessing the relative ecological costs of various approaches to shoreline armoring and for informing the development of strategies to minimize their impacts on coastal ecosystems (Nordstrom 2014, 2016). Increasing the ability to generalize ecological responses to shoreline armoring across soft sediment coastal ecosystems and structure types is especially important, given that the motivation to build additional armoring in soft sediment environments is expected to continue to increase in response to sea level rise, coastal development, and other pressures.

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