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Carmel River Lagoon

Natural Breach Alignment and Location

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Glossary

cfs	Cubic feet per second
CRL	Carmel River Lagoon
CRSB	Carmel River State Beach
CSUMB	California State University, Monterey Bay.
DD&A	Denise Duffy & Associates
lat	Latitude
lon	Longitude
MN	Moffatt & Nichol
MPWMD	Monterey Peninsula Water Management District
NDBC	National Data Buoy Center
nm	Nautical miles
NPS	Naval Postgraduate School

Executive Summary

This report provides an assessment of the natural stream alignment and breach location of the Carmel River Lagoon.

The analysis finds that lagoon morphology is primarily driven by discharge from the Carmel River, i.e. the planar extent of the lagoon grows as the water level within the lagoon increases. The analysis demonstrates that the morphological evolution of the lagoon is affected by water-level driven breaching and wave-driven breach migration north or south of its initial location. The ability of wave action to affect migration of the lagoon breach increases the closer the lagoon shoreline is to the ocean beach shoreline and dominates once a breach has formed. In this case, the direction of littoral sand transport, either north or south along the beach, strongly affects migration of the breach channel, which follows the littoral transport direction.

The analysis finds that there is no preordained seasonal pattern with respect to whether the breach migrates north, south or remains close to its initial location in a given year. Depending on the incident wave direction and their period, wave-driven littoral transport processes can induce northward or southward migration. The analysis finds that there are certain swell wave conditions that have a tendency to temporarily stabilize the breach channel at the north or at the central portion of the beach, while wind-wave events tend to cause a southward migration. This is likely the explanation behind why many of the breach channels are observed in approximately the same areas of the beach, whether at the northern, central, or southern portions.

However, it should be noted that these observations are after a breach has occurred and a channel formed. The analysis has not found any indication that there is a preferred location where a breach would naturally tend to occur.

While wave-driven processes are found to significantly influence the migration of the breach, it is primarily the inflow to the lagoon from the Carmel River that controls breaching and closure of the lagoon. Field observations have established that following the seasonal initial breach event, the lagoon will close temporarily and breach intermittently until its seasonal closure. Closure has been found to occur when discharge from the Carmel River decreases to around 10 cfs or lower. At flows of 20-200 cfs the lagoon may close and breach intermittently. During inflows higher than 200 cfs, a breach will remain open for as long as the discharge persists.

Because of the random nature of the wind and wave climate and significant variation in precipitation from year to year, lagoon breaching is highly dynamic and episodic. Irrespective of the ability of waves to close off a breach channel, it is still the discharge from the river that governs when a breach will occur, and when an open breach channel might close and subsequently re-form.

1. Introduction

The Carmel River Lagoon (CRL) undergoes an annual cycle of lagoon progression approximately as follows (per Figure 1-1):

1. Initial breaching, often in November through January. Initial breaching may be done mechanically (typically November to January), or occur naturally (typically December to January).

2. Intermittent breaching and closure, typically over the months from February through May.

3. Seasonal closure, in most years from around June through November.

Each year as the rainy season commences, Monterey County will monitor the rise of the water level in the lagoon and conduct artificial breaching if expected inflows to the lagoon are projected to cause a flood hazard to properties along the edge of the lagoon. In this regard, inflows to the lagoon primarily consist of discharge from the Carmel River, but can also include local and regional precipitation events, and wave overtopping events.

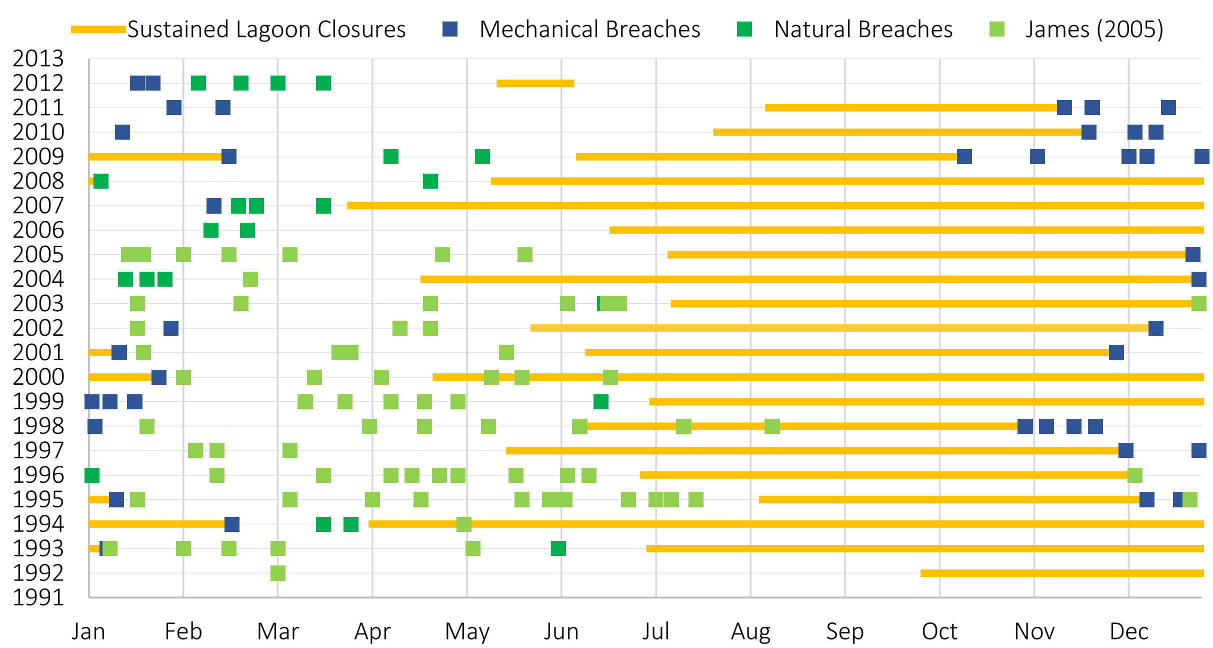

Figure 1-1: Overview of lagoon closures and breaches (1991-2013).

Discharge from the Carmel River typically diminishes or ceases over the summer months, which can cause the water level in the lagoon to decrease due to seepage and evaporation. For this reason, there is a concerted effort to initiate early sustained closure of the lagoon in order to retain as much water as possible for the summer months.

1.1. Project Objectives

The objective of this analysis is to evaluate what would be the natural behavior of the lagoon, breach alignment and location without intervention via mechanical breaching.

Because the lagoon has been managed for several decades, it is not straightforward to identify the natural lagoon behavior in terms of breach alignment and location. The present analysis arrives at conclusions about the lagoon morphology by examining known cases of the lagoon breaching naturally, and the observed lagoon behavior outside of mechanical breaching events.

1.2. Scope of Work

Moffatt & Nichol was retained by Denise Duffy & Associates to assess the natural breach alignment and location of the CRL.

The assessment was conducted based on review of aerial photo history, flow records, ocean wave conditions, and prior studies on the Carmel River State Beach (CRSB) and CRL. The work was performed with input from Balance Hydrologics, Inc. and Whitson Engineers on the subconsultant team lead by Denise Duffy & Associates as the prime consultant to Monterey County.

1.2.1. TAC Review Panel

The work was conducted with input and peer reviewed by a Technical Advisory Committee (TAC) consisting of the following panel members:

1. Dr. Mara Orescanin, Professor of Coastal Oceanography at the Naval Postgraduate School (NPS). Dr. Orescanin has experience with the morphology of coastal lagoons, sandbar build-up, erosion, and sediment transport, and familiarity with CRLM gained from field work on the beach and lagoon.

2. Dr. Doug Smith, Professor of Hydrology and watershed restoration at California State University, Monterey Bay (CSUMB). Dr. Smith has experience in lagoon and river flooding cycles, river sediment transport and flow, and familiarity with the Carmel River and CRL.

3. Larry Hampson, (retired) engineer and consultant for the Monterey Peninsula Water Management District (MPWMD). Mr. Hampson has expertise with flood management, and sandbar management and longstanding experience with the historical setting of the CRL and on the ground knowledge gained from observations and field visits.

4. Jeff Hagar, consultant for Hagar Environmental Science. Mr. Hagar specializes in water resource management and aquatic species conservation, and has experience with monitoring of salmonoid habitat in lagoon ecosystems on the central coast, and specific expertise with steelhead trout on the San Lorenzo River at Santa Cruz, CA.

2. Site Information

2.1. Carmel River Lagoon

Figure 2-1 shows the location of Carmel River State Beach (CRSB) where the Carmel River Lagoon (CRL) is located at the mouth of the Carmel River.

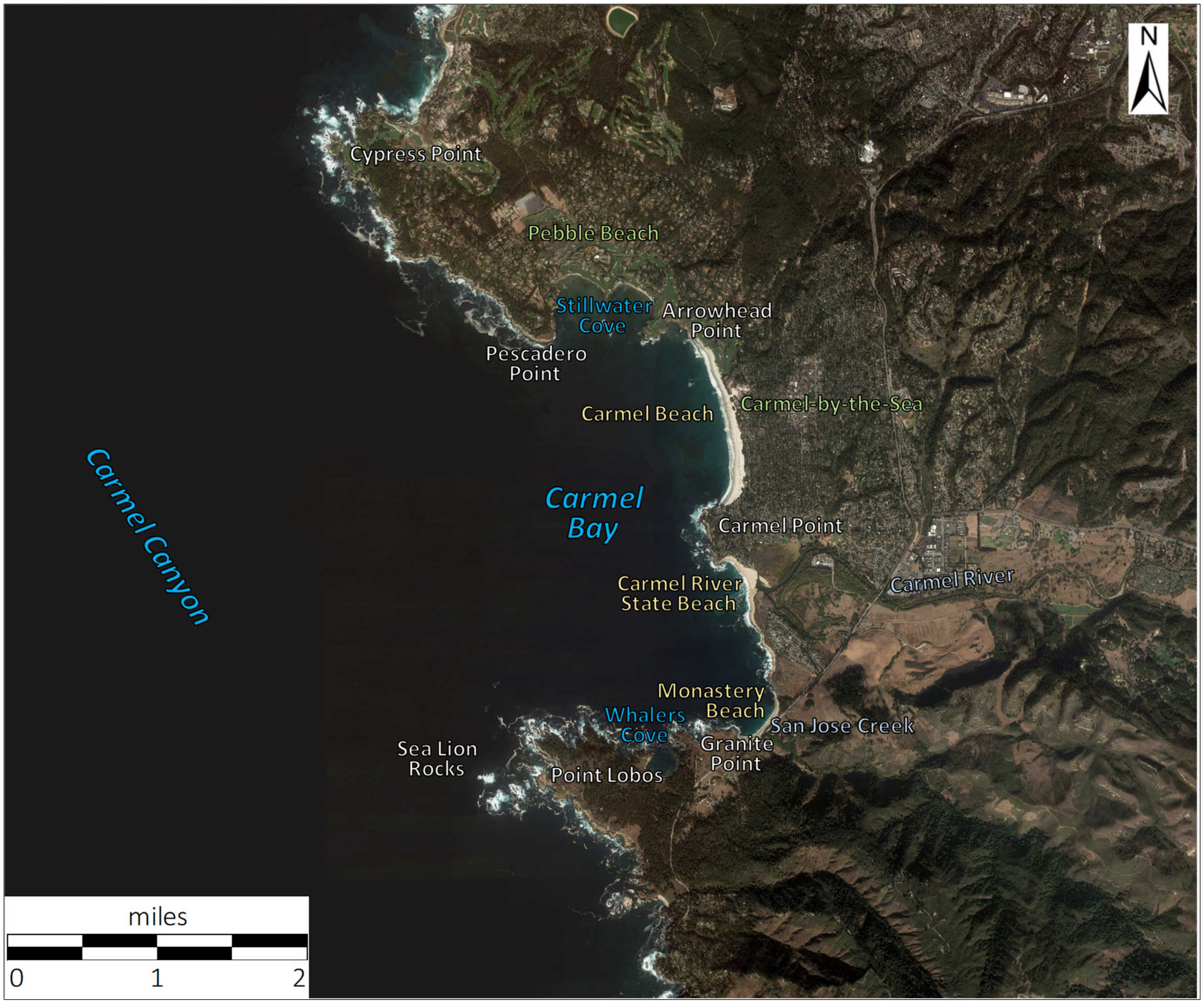

Figure 2-1: Carmel River State Beach site location.

The Carmel River drains approximately 250 square miles of the Santa Lucia and Sierra de Salinas Mountains into Carmel Bay. The Carmel River watershed has historically experienced large variations in seasonal and yearly discharge rates. A complex dynamic exists between the CRL and the Pacific Ocean. Figure 2-2 provides a closeup of the CRL and CRSB.

During times of low or no river discharge, waves build up the beach profile to form a sandbar along the CRSB shoreline. The sandbar closes off the mouth of the lagoon, which causes the lagoon to dam up. Some amount of outflow from the lagoon to the Pacific occurs via groundwater seepage through the beach sand. The lagoon water body also loses water due to evaporation, primarily over the summer months. When river discharge is minimal, the lagoon water level recedes to a base elevation that persists over the dry summer months.

When river discharge increases, the lagoon water level can rise rapidly and potentially reach or exceed the defined flood stage. This can occur at any time from late fall to early spring.

Figure 2-2: Carmel River State Beach and Carmel River Lagoon.

Management of the lagoon water level has therefore been implemented to mitigate flood hazards to properties along the north side of the lagoon. The management practices include monitoring of the lagoon water level and projected river inflows to the lagoon, and mechanical breaching of the lagoon. If inflows to the lagoon do not pose a flood hazard, no management action is carried out and the lagoon can breach naturally. Following a breach event (mechanical or natural), the incident waves can build up the beach and reform the sandbar, which closes the lagoon outlet. This can occur progressively or quite rapidly depending on the wave characteristics. When the annual rainy season ends, and depending on whether or not the outlet has been closed off naturally, the decision is made to mechanically close the outlet before the river flow subsides in order to maximize the volume of water stored in the lagoon leading into the dry season.

3. Wave Climate

The Carmel shoreline is exposed to wind-waves generated by local storm systems as well as swell waves originating from distant storms over the Pacific. Figure 3-1 shows the general angles of wave incidence from USGS (2006).

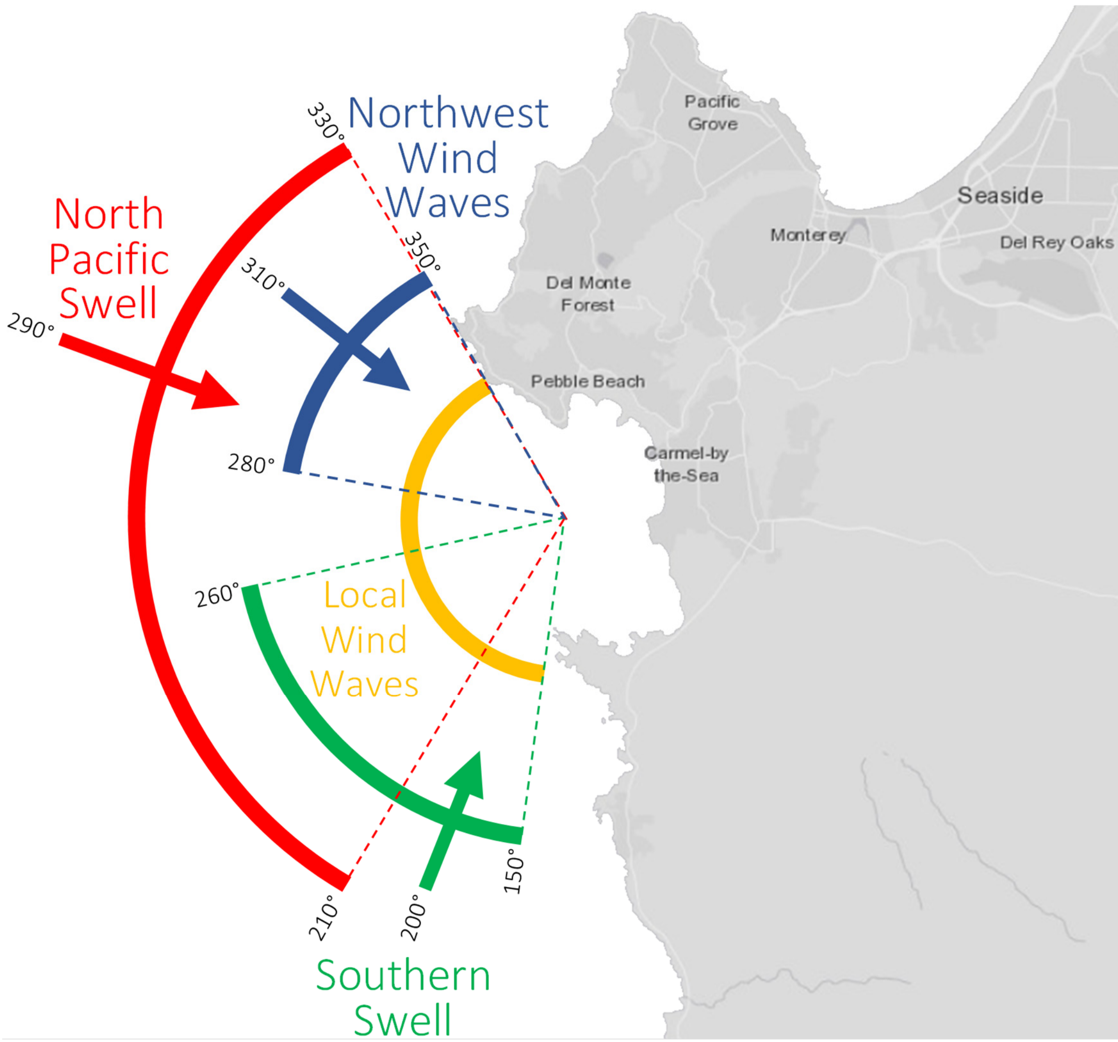

Figure 3-1: Angles of wave incidence at Carmel, adopted from USGS (2006).

There are four different wave systems that affect Carmel Bay: 1) North Pacific swell waves originating from distant storms over the North Pacific, 2) Southern swell originating from distant storms in the South Pacific, 3) Northwest wind waves generated by regional wind systems, and 4) Local wind waves which can occur from any direction with open water. North Pacific swell waves are generated by extra-tropical storm systems, mid-latitude low-pressure systems, and cold fronts over the North Pacific, USGS (2006). Southern swell is generated by storms in the Southern Hemisphere and occurs in the summertime. Swell waves are characterized by long wave periods, typically from 8 to 18 seconds.

Northwest wind waves are generated by daily sea-breeze conditions and are more pronounced in the spring and early summer months, USGS (2006). Wind waves are generated by regional and local wind conditions and produce waves with shorter periods, typically from 3 to 8 seconds. Local storms can occur from October through April.

3.1. Wave Statistics

Wave statistics are summarized in the following. These distinguish between swell waves originating from distant storm systems over the Pacific, and wind-waves generated by the passage of regional storm systems. The wave statistics presented in the following are based on data from NDBC Station 46042 located 27 nm west of Monterey Bay at lat/lon 36.785°N 122.398°W in a water depth of 5,400 feet (1,645.9 m).

3.1.1. Swell Waves

Table 3-1 provides the offshore distribution of swell waves by month. Swell waves from the west (W) and west-northwest (WNW) exhibit a pronounced decrease over the summer months May through September and become much more prevalent over the months from October through April.

Swell waves from the directions north-west (NW), south (S), and south-southwest (SSW) have a pronounced increase over the summer months from May through September and a decrease over the winter months from October through April.

Swell waves from the directions south-southeast (SSE), south-west (SW), west-southwest (WSW), and north-northwest (NNW) are evenly distributed and occur with a constant low-level presence.

Table 3-1: Distribution of swell waves by month and offshore direction of incidence.

Month	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
JAN	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	1.9%	5.9%	1.2%	0.0%	9.2%
FEB	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	1.7%	4.0%	1.6%	0.0%	7.8%
MAR		0.0%	0.1%	0.2%	0.1%	0.2%	1.2%	4.7%	2.1%	0.0%	8.6%
APR		0.0%	0.3%	0.3%	0.2%	0.2%	0.8%	4.3%	2.6%	0.0%	8.7%
MAY		0.0%	0.8%	0.7%	0.2%	0.1%	0.4%	2.1%	3.6%	0.0%	8.0%
JUN		0.1%	0.7%	0.9%	0.2%	0.1%	0.2%	1.1%	3.9%	0.1%	7.1%
JUL		0.1%	1.3%	1.2%	0.3%	0.1%	0.1%	0.6%	4.0%	0.1%	7.9%
AUG	0.0%	0.2%	1.5%	1.0%	0.2%	0.1%	0.3%	0.7%	2.6%	0.0%	6.6%
SEP		0.1%	0.7%	0.9%	0.2%	0.1%	0.3%	2.3%	3.3%	0.1%	8.0%
OCT		0.0%	0.3%	0.4%	0.3%	0.3%	0.8%	4.0%	2.7%	0.0%	8.9%
NOV		0.0%	0.1%	0.1%	0.1%	0.1%	0.7%	4.8%	3.4%	0.0%	9.4%
DEC	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.9%	5.6%	3.0%	0.0%	9.8%
Total	**0.0%**	**0.5%**	**6.1%**	**5.7%**	**2.0%**	**1.7%**	**9.4%**	**40.1%**	**34.2%**	**0.4%**	**100%**

In general, there is a fairly even presence of swell waves across all months of the year. This indicates that the swell is persistent and occurs at all times of the year.

3.1.2. Wind-Waves

Table 3-2 provides the distribution of wind-waves by month. The percentage indicated in this table totals to 79%. The remainder of the time, winds are either calm or from overland directions (north to east-southeast).

Although the strongest storms occur over the winter months, the data indicates that the months with the most wind are from May through September.

Wind-waves from north-westerly (NW) and west-northwesterly (WNW) directions exhibit a pronounced increase over the summer months from May through September and wane over the months from October through April. 71% percent of wind-waves (out of a total of 79%) occur from these directions.

Wind-waves from the remaining directions are less frequent or calm over the summer months with a tendency to pick up slightly over the winter months.

Table 3-2: Distribution of wind-waves by month and offshore direction of incidence.

Month	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
JAN	0.2%	0.4%	0.4%	0.0%	0.0%	0.2%	0.0%	0.1%	0.7%		2.0%
FEB	0.0%	0.6%	0.3%	0.1%	0.2%	0.2%	0.2%	0.2%	1.0%	0.0%	2.8%
MAR	0.0%	0.3%	0.3%	0.2%	0.1%	0.0%	0.0%	0.3%	2.3%	0.0%	3.6%
APR		0.0%	0.1%	0.0%		0.0%	0.1%	0.6%	3.1%	0.2%	4.1%
MAY	0.1%	0.3%	0.1%		0.0%	0.0%	0.3%	1.9%	10.5%	0.8%	14.1%
JUN							0.0%	1.7%	12.2%	0.4%	14.4%
JUL							0.0%	2.4%	14.9%	0.3%	17.6%
AUG							0.0%	1.9%	17.2%	1.2%	20.2%
SEP								1.1%	9.9%	0.4%	11.5%
OCT	0.0%	0.1%	0.0%	0.0%			0.1%	0.7%	3.1%	0.1%	4.1%
NOV	0.0%	0.6%	0.2%	0.0%		0.0%	0.0%	0.3%	1.5%	0.2%	2.9%
DEC	0.0%	0.7%	0.3%	0.1%	0.1%	0.1%	0.2%	0.3%	0.9%	0.1%	2.8%
Total	**0.4%**	**1.6%**	**1.2%**	**0.3%**	**0.3%**	**0.4%**	**0.8%**	**9.0%**	**61.8%**	**2.9%**	**79%**

Additional wave statistics are provided in Appendix A with tables summarizing the distribution of wind-waves and swell waves by significant wave height and direction; and peak wave periods.

4. Beach Morphology

Figure 4-1 provides an overview of lagoon states (natural and managed) over the period from 1991 to 2013, compiled based on data from BH (2014) and MPWMD (2005). The horizontal yellow bars indicate periods of lagoon closure, i.e. with no outlet to the ocean. This period can start as early as April or May, but typically occurs over the summer months from July through November, at times extending into December and January. The blue squares indicate dates of mechanical lagoon breaching in order to reduce flood risk. This management action is initiated when the lagoon water level is high or projected to reach flood stage and typically takes place from November through January. The dark green squares indicate dates when naturally formed lagoon breaches have been observed, from BH (2014). The squares in light green indicate dates of additional observations by Greg W. James reported in MPWMD (2005). During this phase from around January to June/July, the lagoon will remain open for approximately 85% of the time and close intermittently[1]. Per MPWMD (2005) Carmel River inflows to the lagoon greater than 200 cfs will cause breaches to remain open 100% of the time during this phase. When inflows are between 200 and 20 cfs, the lagoon may close and breach intermittently, and when inflows are below 10 cfs wave action will typically close the breach.

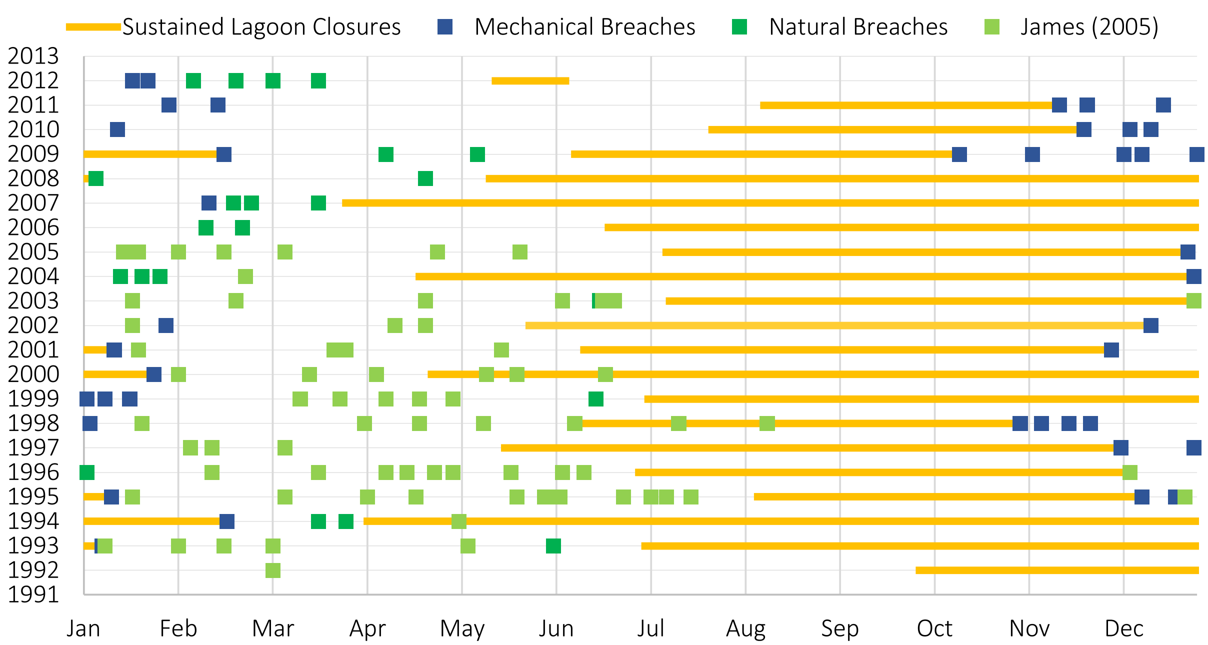

Figure 4-1: Overview of lagoon closures and breaches (1991-2013).

[1] In wet years the lagoon was observed to remain open almost 100% of the time. In drought years, approximately 50% of the time.

4.1. Littoral Transport Driven by Swell Waves

Figure 4-2 shows sediment transport patterns associated with swell waves occurring over the months of November through January where initial lagoon breaching usually takes place. During this time of the year, the swell wave climate is dominated by episodes of North Pacific swell. Swell episodes can last from hours to several days, depending on the magnitude and duration of the storm system of origin. During an episode of swell, the waves with the longest wave periods will arrive first, followed by waves with progressively shorter periods, for example initial swell waves with 18 second periods, transitioning to swell with 15 second periods, then 13 second periods and so forth until the swell front dies down.

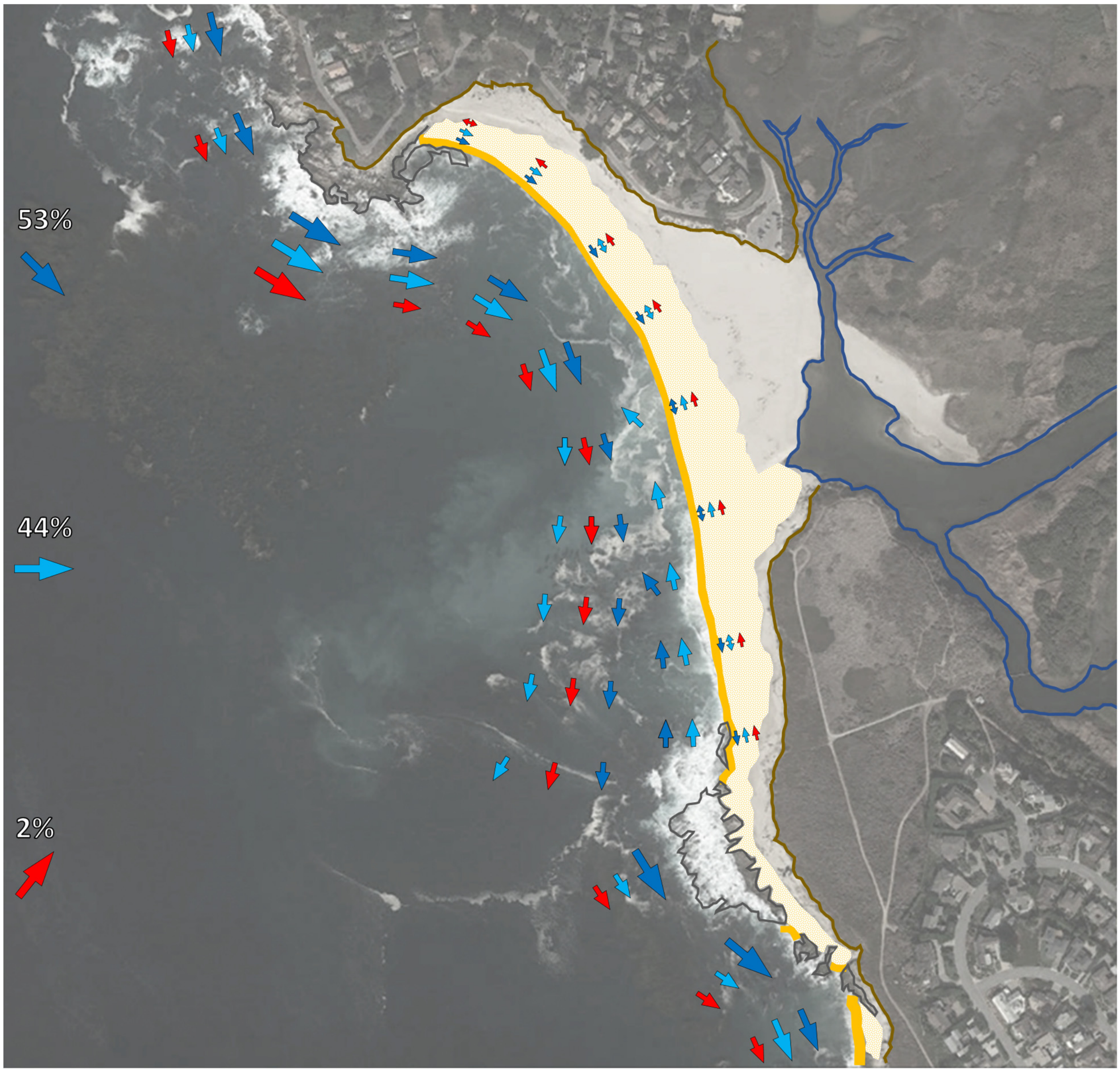

Figure 4-2: Sediment transport patterns associated with swell waves.

Offshore from Carmel Bay, North Pacific swell can arrive from a wide range of directions (Figure 3-1). These are grouped in Figure 4-2 into waves arriving from northwesterly directions (dark blue arrows), waves from westerly directions (light blue arrows), and waves from southwesterly directions (red arrows). These offshore directions of wave incidence are indicated by the three arrows on the left side of the figure. The percentage indicates the amount of time incident swell waves arrive from the respective direction. It can be seen that the majority of swell waves arrive from westerly and northwesterly directions and a limited amount of waves from southwesterly directions. The size of the arrows used in the figure (large, medium, and small) indicates the magnitude of the littoral transport. The littoral transport is the result of wave-driven processes. Wave breaking in the surf zones causes sediment to be mobilized and brought into suspension. The longshore current, also generated by wave breaking transports the sediment along the shoreline.

The results show that irrespective of the offshore angle of wave incidence, the resultant direction of longshore transport along is generally southward in the deeper water along the shoreline. Closer to the shoreline, waves from northwesterly and westerly directions can set up a circulation pattern where the direction of sediment transport is northward along the southern part of CRSB.

The variation of the seabed and crenulate shape of the bay causes incident waves to undergo a significant amount of refraction. At the north end of CRSB, where the beach is sheltered behind Carmel Point, the transport direction is to the east-southeast along the beach, which explains why the headland is rocky (and not saturated with sand).

Wave runup over the beach is also able to transport sediment along the shoreline. This occurs when the wave runup is angled slightly with respect to the shoreline. This mode of transport is indicated by the small arrows shown on the beach in Figure 4-2 (swash zone). For northwesterly waves, the results show that the direction of sediment transport is generally southward along the beach, but there is an area at the center of the beach where the transport can be either northward or southward. For westerly waves there is a similar finding – the direction of transport is generally southward along the beach, but there is an area of the south end of CRSB where the transport can be either northward or southward. For southwesterly waves, the direction of transport is northward nearly all the way to the north end of CRSB. The areas of mixed transport directions are locations where open breach channels might tend to congregate. These areas correlate well with where breach channels have been observed in the field, i.e. at the north and south end, and central part of the beach.

4.2. Littoral Transport Driven by Wind-Waves

Figure 4-3 shows sediment transport patterns associated with wind-waves occurring over the months of November through January for wind-waves from northwesterly, westerly, and southwesterly directions.

Because wind-waves have shorter wave periods than swell waves they are not subject to the same degree of wave refraction as swell waves as they propagate into Carmel Bay. The relationship between sediment transport direction and wind-wave direction is therefore much more obvious. Wind-waves from west-northwesterly and westerly directions produce southward transport both in deeper water and within the swash zone on the beach. Wind-waves from southwesterly directions generally produce northward transport both in deeper water and within the swash zone.

The percentages noted along the left edge of the figures indicate that the majority of wind-wave event occur from northwesterly directions and from southerly directions. Wind-waves during these events develop during the passage of regional storm systems and are therefore relatively short-lived and highly episodic.

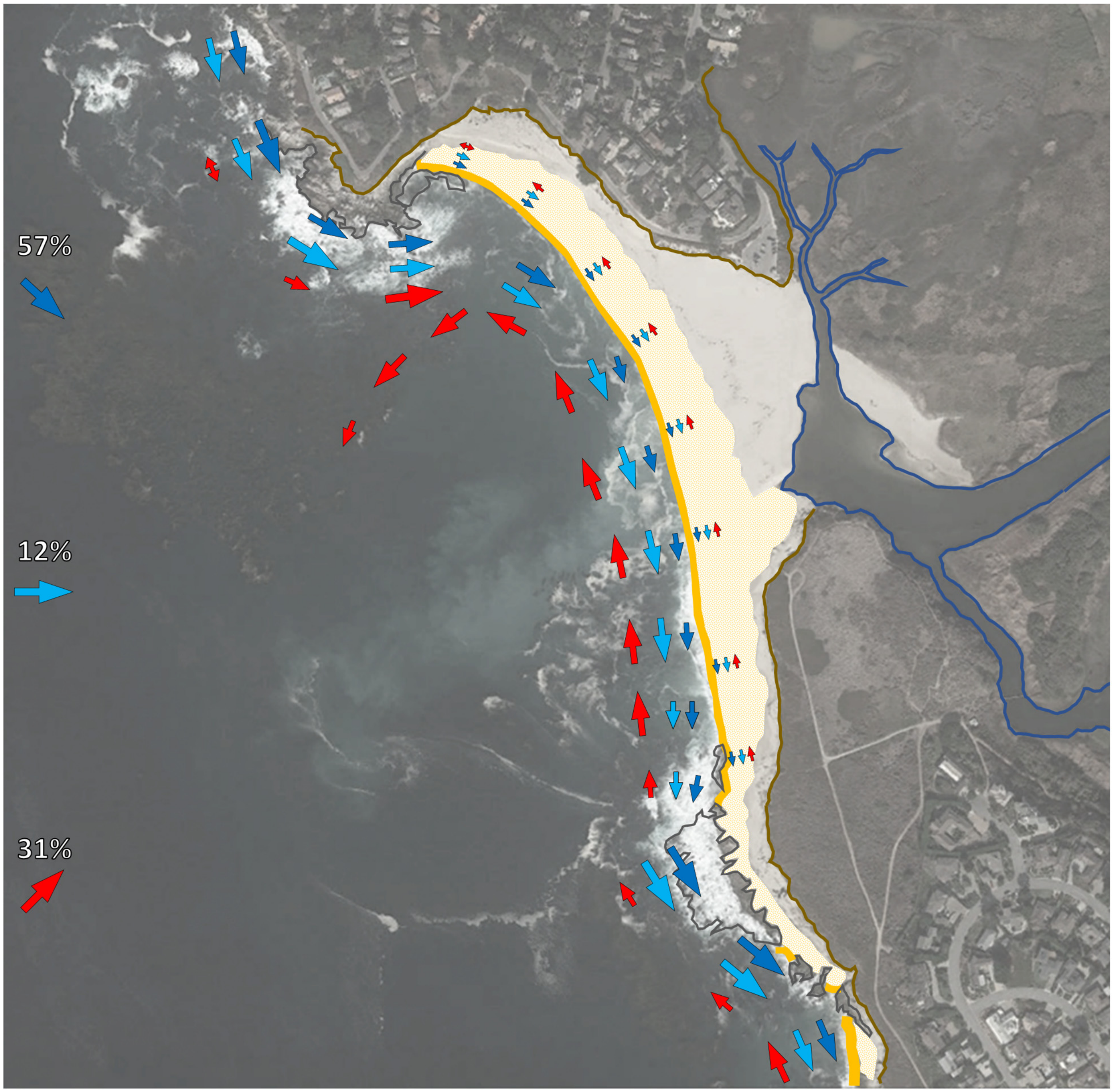

Figure 4-3: Sediment transport patterns for northwest wind-waves.

Figure 4-3 illustrates that a wave event associated with wind from northwesterly directions can transport significant amounts of sediment away from CRSB south along the coast. The process removes sediment both along the shore and out in deeper water with the net effect being a substantial depletion of sediment from the CRSB shoreline and seabed.

Southwesterly wind-wave events will produce a strong northward directed transport along the shoreline and in deeper water. However, in most cases these events will not bring sand to the area of CRSB, but will rather shift the sand along the shoreline up to the north end of CRSB. The net effect is that the width of the beach decreases along the south end of CRSB, while the beach widens at the north end of CRSB.

5. Lagoon and Beach Morphology

Figure 5-1 provides an overview of the processes that shape the CRSB and lagoon planform. Incident wave crests and wave troughs are indicated by the light blue solid/dashed lines. The crenulate shape of the bay and seabed contours cause incident waves to refract and diffract. Refraction causes incident waves to turn so the direction of wave propagation is approximately perpendicular to the seabed contours. Diffraction is spreading of wave energy and occurs in the lee of the headland (Carmel Point) at the north end of the beach.

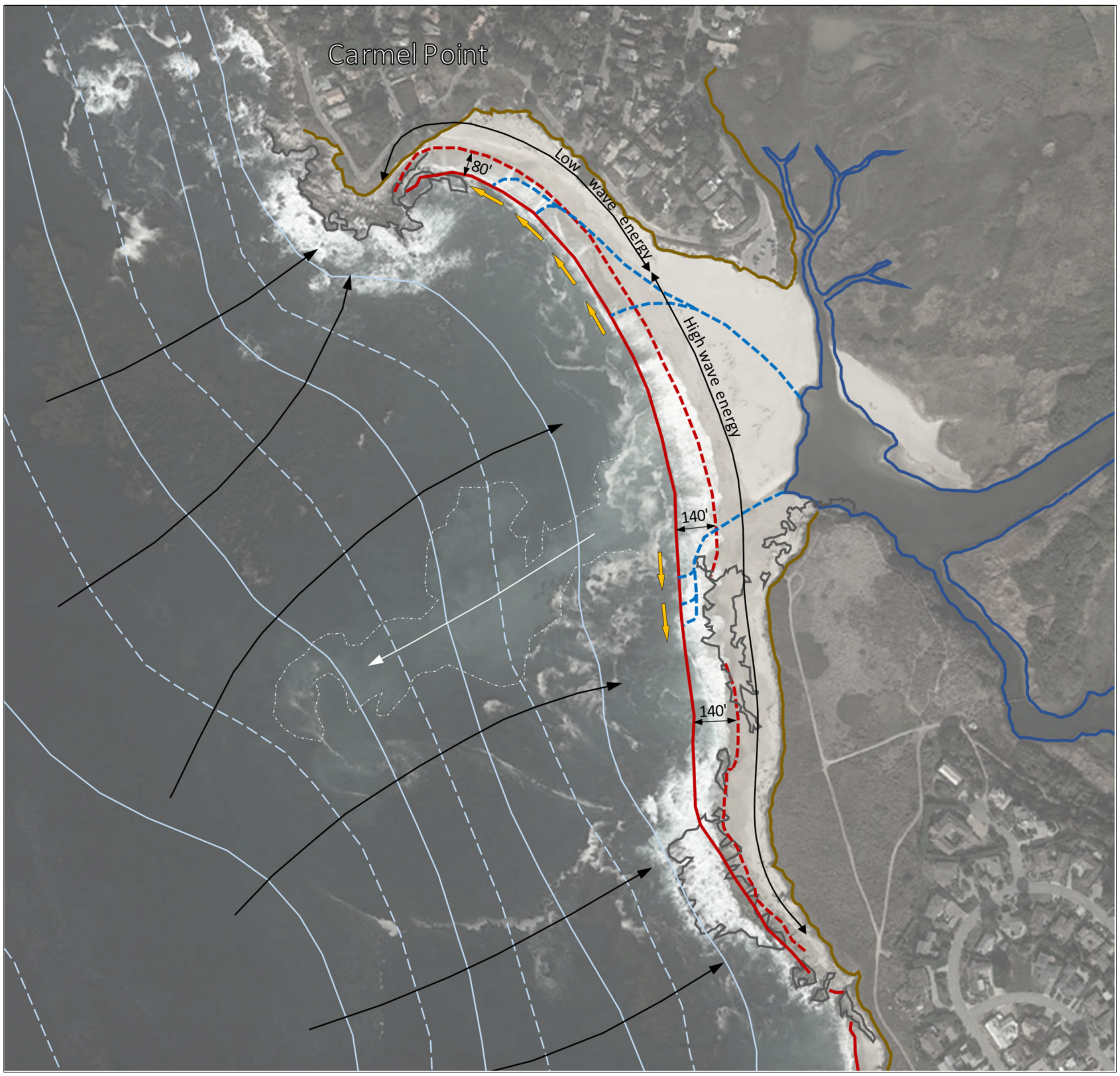

Figure 5-1: Overview of CRSB seasonal variation and lagoon morphology.

Refraction causes the incident waves to converge on the headland at Carmel Point and the rock outcrop located at the south end of CRSB at the transition to Ribera Beach (black arrows in figure). Diffraction occurs primarily in the lee of the headland at Carmel Point. Because of the dispersal of wave energy in this area, the northern portion of CRSB is an area of low wave energy compared to the beach to the south, which is an area of relatively high wave energy.

Summer swell waves tend to build up the beach, while winter storm waves pull sand off the beach into deeper water. The typical summer beach extent is indicated by the solid red line, while the narrower winter beach planform is indicated by the dashed red line. Because of the wave diffraction effects at the north end of the beach and the low wave energy versus high wave energy zones, there is less variation of the beach width at the northern (on the order of 80 feet) end and more variation at the center and south end of the beach (on the order of 140 feet) between the summer and winter planforms.

The general Carmel River and lagoon planform is indicated by the solid blue line. Example paths showing migration of lagoon breaches are indicated by the dashed blue lines. The breaches can migrate south if the wave-driven littoral transport is southward (yellow arrows); and can migrate north if the direction of littoral transport is to the north. Migration of lagoon breaches occur when there is a significant discharge from the Carmel River (which keeps the breach channel open), while the littoral transport tries to close the beach. If the discharge from the river decreases, the littoral transport can close the breach. Closure of a breach can occur due to littoral transport (along the shoreline in the plan view), and also due to vertical buildup of sand deposited with wave runup.

Northward lagoon migration has historically reached the northern end of the beach where it terminates at the rock outcrop at Carmel Point. Southward migration is limited by the rock outcrops at the south end of the beach. If the beach level is high, these outcrops are typically buried under the sand but appear when the beach level lowers.

5.1. Lagoon Morphology Prior to Breaching

The drivers behind the initial lagoon progression each season consist of two mechanisms. One mechanism is enlargement of the lagoon as the water level in the lagoon rises in response to inflow from the river. This causes the planar extent of the lagoon to widen out over the sandbar.

An effect that can promote northward or southward migration as the lagoon expands is believed to be incident wave action in combination with seepage outflow. An example of seepage outflow is indicated by the white dotted outline in Figure 5-1 and white arrow directed offshore.

Figure 5-2 shows show wave action at the shoreline can affect lagoon progression. A dynamic balance can develop between seepage outflow from the lagoon and sediment transport processes at the shoreline. As the lagoon water level rises due to discharge from the Carmel River in the fall and winter, the planar area of the lagoon will widen over the sandbar and move the shoreline of the lagoon closer to the shoreline on the ocean side of the sandbar.

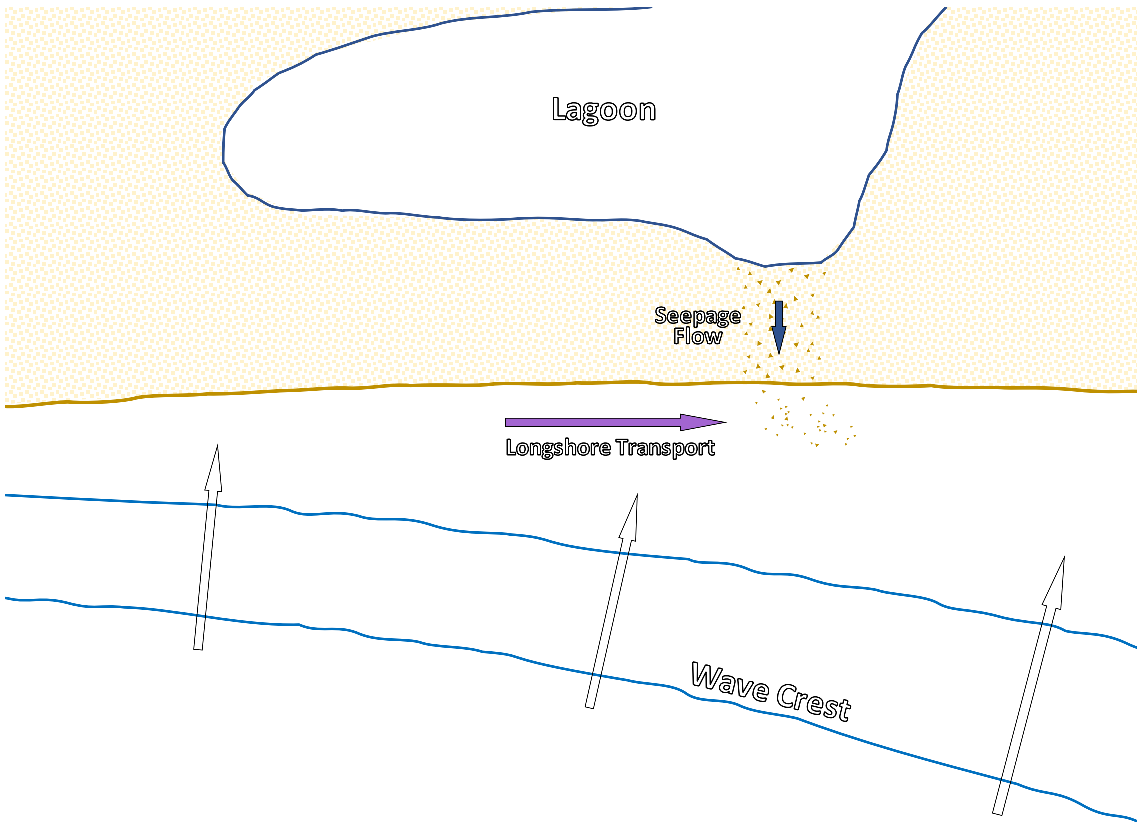

Figure 5-2: Wave-driven processes affecting lagoon formation.

At the same time, a seepage outflow sets up between the lagoon and the ocean driven by the lagoon water level being higher than the ocean level. Sediment is winnowed out with the seepage flow and moved away with the longshore transport, while wave runup and overwash maintains the sandbar. The combined process can induce migration of the lagoon potential breach north or south along the beach depending on the incident wave direction.

This process indicates that migration of the potential breach location is to a large extent driven by wave action and the direction of sand transport at the shoreline either northward or southward. This mechanism also explains why some years see formation of both a southerly and northerly spur off the lagoon, i.e. the direction of sand transport changed over the course of lagoon progression.

5.2. Lagoon Morphology after Breaching

Figure 5-3 shows how wave action affects lagoon breach migration. As waves propagate towards the shoreline, they are subject to refraction due to their angle of incidence relative to the change in water depth. The process turns the incident wave crests so they are nearly parallel to the shoreline. However, as waves break in the surf zone the direction of wave motion may still have a small angle relative to the shoreline. This produces a net longshore transport of sediment, indicated by the purple arrow in the figure. Wave runup on the beach follows a zig-zag motion as indicated by the orange lines in the figure. The process deposits sand on the sandbar with the wave runup and occasional wave overwash. This wave-driven sediment transport process actively builds up the sandbar.

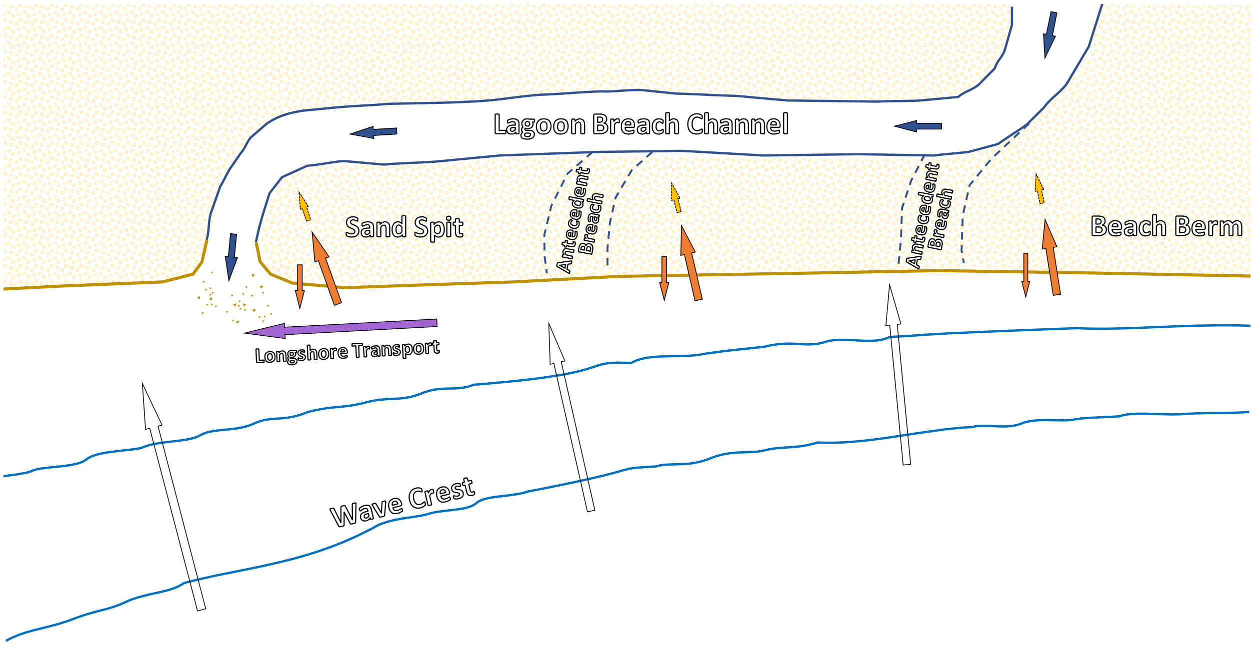

Figure 5-3: Wave-driven processes affecting lagoon breach migration.

When sufficient outflow from the lagoon maintains an open breach channel, sediment will be move within the breach channel. Field data has shown that as long as discharge from the river is higher than 10 cfs (Thornton, 2005), the breach channel will tend to remain open. Where the breach channel outflow encounters the active swash zone on the beach, an equilibrium can develop where the outflow keeps the breach channel open whereas wave action continually seeks to close off the breach channel. The result is migration of the breach channel, shown right to left in the figure. The dashed blue lines indicate antecedent breach channels, going from right to left. Recent field observations of breach channel migration were conducted by Jeffrey Scooler in his 2017 Thesis, NPS (2017). Thornton (2005) found that the lagoon breach channel can migrate north or south by 5 to 40 feet per day and in extreme cases 150 feet per day.

6. Conclusions

The analysis finds that lagoon formation is primarily driven by discharge from the Carmel River, i.e. the planar extent of the lagoon grows as the volume of water contained within the lagoon increases. The analysis demonstrates that the morphological evolution of the lagoon is affected by wave-driven processes which can influence whether the lagoon migrates north, south or central to the beach in a given year. The ability of wave action to affect migration of the lagoon increases the closer the edge of the lagoon is to the shoreline, and dominates once a breach has taken place and a breach channel formed. In this case, the direction of littoral transport, either north or south along the beach, strongly affects migration of the lagoon breach channel, which follows the littoral transport direction.

The analysis finds that there is no preordained directionality with respect to whether the lagoon migrates north, south or central to the beach in a given year. Depending on the angle of incidence of waves and their duration, wave-driven longshore littoral processes can induce northward or southward migration of the lagoon. The analysis finds that there are certain wave conditions that have a tendency to temporarily stabilize lagoon breach channels at the north end of the beach and at the central portion of the beach, while wind-wave events often cause a southward migration of the lagoon breach channel. This is likely the explanation behind why many of the lagoon breach channels are observed to appear in approximately the same areas of the northern, central, and southern portion of the beach.

However, it should be noted that these observations are after a breach has occurred and a breach channel formed. The analysis has not found any indication that there is a preferred location where breaches would naturally tend to occur.

While wave-driven processes are found to significantly influence the migration of the breach, it is primarily the inflow to the lagoon from the Carmel River that controls breaching and closure of the lagoon. Field observations have established that following the seasonal initial breach event, the lagoon will close temporarily and breach intermittently until its seasonal closure. Closure has been found to occur when discharge from the Carmel River decreases to around 10 cfs or lower. At flows of 20-200 cfs the lagoon may close and breach intermittently. During inflows higher than 200 cfs, a breach will remain open for as long as the discharge persists.

Because of the random nature of the wind and wave climate and significant variation in precipitation from year to year, lagoon breaching is highly dynamic and episodic. Irrespective of the ability of waves to close off a breach channel, it is still the discharge from the river that governs when a breach will occur, and when an open breach channel might close and subsequently re-form.

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Appendix A:

Wave Statistics

Wind Waves

Wind-waves are waves generated by local storm systems. The most significant storms typically occur over the winter months from directions over the sector from south to northwest. Table A-1 summarizes statistics for wave conditions for these storms, based on data from NDBC Station 46042 located 27 nm west of Monterey Bay at lat/lon 36.785°N 122.398°W in a water depth of 5,400 feet (1,645.9 m).

Table A-1: Distribution of wind-waves by significant wave height and direction.

H_S (feet)	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0 - 2								0.0%	0.0%		0.0%
2 - 4	0.0%	0.0%	0.03%	0.0%	0.01%	0.2%	0.3%	2.4%	6.7%	0.5%	10.1%
4 - 6	0.0%	0.6%	0.7%	0.1%	0.1%	0.3%	0.5%	5.9%	39.1%	2.6%	50.0%
6 - 8	0.0%	0.9%	1.2%	0.3%	0.2%	0.1%	0.2%	2.6%	22.2%	1.6%	29.3%
8 - 10		0.7%	1.4%	0.3%	0.1%	0.1%	0.1%	0.7%	3.8%	0.2%	7.4%
10 - 12		0.5%	0.8%	0.11%	0.02%	0.0%	0.0%	0.1%	0.7%	0.02%	2.2%
12 - 14		0.2%	0.3%	0.0%	0.02%	0.0%	0.0%	0.01%	0.10%	0.0%	0.7%
14 - 16		0.06%	0.06%		0.0%				0.02%		0.1%
16 - 18		0.01%	0.01%	0.0%							0.0%
Total	**0.1%**	**3.0%**	**4.5%**	**0.9%**	**0.4%**	**0.7%**	**1.2%**	**11.7%**	**72.6%**	**4.9%**	**100%**

Table A-2 summarizes peak wave periods for wind-waves by significant wave height and direction.

Table A-2: Average peak period of wind-wave periods (in seconds) by significant wave height and direction.

H_S (feet)	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
0 - 2								4.3	6.7	
2 - 4	5.3	4.5	4.3	4.3	7.2	6.9	7.2	6.8	6.5	5.0
4 - 6	5.2	5.2	5.3	5.8	6.7	7.2	7.3	6.9	6.8	6.1
6 - 8	6.1	5.8	6.0	6.5	7.3	7.3	7.3	7.2	7.3	7.1
8 - 10		6.6	6.7	7.1	7.2	7.2	7.5	7.4	7.5	7.4
10 - 12		7.1	7.2	7.2	7.2	7.5	7.0	7.4	7.6	7.5
12 - 14		7.5	7.4	7.3	7.7	7.7	7.7	7.7	7.7	7.7
14 - 16		7.7	7.6		7.7				7.7	
16 - 18		7.7	7.7	7.7						

Swell Waves

Information on swell waves is provided in the following. Swell waves characterize waves with long wave periods, exceeding 8 seconds. At Carmel the primary direction of swell waves incidence is from west-northwest to northwest. There is also a smaller percentage of swell arriving from southerly to south-southwesterly directions.

Table A-3: Distribution of swell waves by significant wave height and direction.

H_S (feet)	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0 - 2			0.0%	0.006%	0.002%	0.001%	0.001%	0.005%	0.0%		0.023%
2 - 4	0.0%	0.2%	1.7%	2.1%	0.9%	0.5%	1.2%	2.3%	1.5%	0.06%	10.5%
4 - 6	0.017%	0.3%	2.1%	2.2%	0.9%	0.8%	3.5%	9.1%	8.6%	0.3%	27.8%
6 - 8	0.002%	0.0%	0.4%	0.4%	0.2%	0.4%	3.0%	10.0%	11.2%	0.4%	26.0%
8 - 10		0.01%	0.1%	0.1%	0.1%	0.2%	1.9%	7.3%	7.6%	0.2%	17.4%
10 - 12	0.0%	0.02%	0.06%	0.03%	0.05%	0.1%	1.0%	4.1%	4.2%	0.06%	9.7%
12 - 14		0.03%	0.06%	0.03%	0.02%	0.06%	0.6%	2.1%	2.1%	0.03%	5.0%
14 - 16		0.03%	0.04%	0.01%	0.009%	0.04%	0.3%	0.9%	0.8%	0.01%	2.1%
16 - 18		0.02%	0.02%	0.004%	0.003%	0.020%	0.1%	0.4%	0.3%	0.01%	0.9%
18 - 20		0.006%	0.01%	0.000%	0.001%	0.007%	0.05%	0.2%	0.1%	0.0%	0.3%
20 - 22		0.003%	0.002%	0.0%		0.005%	0.05%	0.1%	0.0%	0.0%	0.2%
22 - 24			0.0%			0.004%	0.03%	0.02%	0.01%		0.1%
24 - 26						0.0%	0.013%	0.01%	0.000%		0.02%
26 - 28							0.0%	0.00%	0.000%		0.01%
28 - 30							0.0%	0.002%	0.000%		0.009%
30 - 32							0.0%	0.000%			0.001%
32 - 34							0.0%	0.0%			0.001%
34 - 36							0.0%				0.000%
Total	**0.0%**	**0.6%**	**4.4%**	**4.8%**	**2.1%**	**2.1%**	**11.8%**	**36.4%**	**36.6%**	**1.1%**	**100%**

Table A-4 summarizes peak wave periods for swell waves by significant wave height and direction.

Table A-4: Average peak period of swell waves (in seconds) by significant wave height and direction.

H_S (feet)	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
0 - 2			13.0	13.3	14.0	12.7	12.5	10.3	9.3	
2 - 4	16.8	14.5	14.4	14.7	14.4	13.1	12.3	11.2	9.7	10.1
4 - 6	15.7	14.6	15.3	15.6	15.0	13.4	12.8	12.0	10.0	10.0
6 - 8	18.9	14.8	15.8	16.1	14.0	12.5	13.2	12.9	10.5	9.7
8 - 10		10.9	12.5	13.2	10.7	11.6	13.5	13.4	11.1	9.9
10 - 12	10.5	9.1	9.4	9.5	9.8	12.2	13.9	14.0	11.8	11.0
12 - 14		9.2	8.8	9.1	10.3	12.8	14.0	14.4	12.5	11.2
14 - 16		9.1	9.1	9.3	10.8	13.4	14.6	14.7	13.1	11.8
16 - 18		9.5	9.5	10.0	10.8	14.4	15.2	15.1	13.2	11.2
18 - 20		10.0	9.7	10.0	12.1	15.3	15.4	15.6	13.1	12.0
20 - 22		10.1	9.5	9.8		16.3	15.8	16.0	13.8	11.9
22 - 24			9.1			17.7	16.1	16.6	14.0	
24 - 26						17.2	16.1	16.4	13.8	
26 - 28							16.6	17.2	14.8	
28 - 30							17.2	16.7	14.8	
30 - 32							19.1	19.1		
32 - 34							17.4	19.1		
34 - 36							19.1			