Winds, Waves, Tides, and the Resulting Flow Patterns and Fluxes of Water, Sediment, and Coral Larvae off West Maui, Hawaii

By Curt D. Storlazzi and Michael E. Field

Photograph of sediment plumes off Kahana, West Maui, by E. Brown (NPS)

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Introduction

A series of recent studies has focused on the flow patterns and particle fluxes along the coast of West Maui, Hawaii, USA, from Honolua south to Puumana (fig. 1). From those studies a relatively good understanding has emerged of the physical processes that influence the relative amount of suspended sediment in nearshore waters and the circulation patterns that transport sediment and coral larvae along the coast and between islands. This report is a synthesis of our existing knowledge on the nature of flow and transport off West Maui.

Meteorology of West Maui and its Impact on Coastal Processes

The northeast trade winds occur throughout the year but are most consistent from April-November. These winds strike the northeast side of West Maui, are steered around the West Maui volcanic cone and most often approach the shoreline obliquely from the north in the study area (Fletcher and others, 2002). Insolation-driven heating and nocturnal cooling of the island cause the general trade wind speeds in the vicinity of the islands to vary from almost negligible at night to more than 10 meters/second in the afternoon, compared to about 5 meters/second in the open ocean (Storlazzi and others, 2006b). The wind speeds in the channels between the islands of Maui, Molokai, and Lanai are often 50-100% faster than those observed along west Maui due to funneling between the islands' large volcanic cones. These relatively rapid diurnal variations in wind speed result in a very thin (<1 meter) wind-driven oceanic surface layer. It is important to note that this thin surface layer is trade-wind controlled, and transport in the layer can be significantly different in rate and direction than the rest of the water column.

Precipitation patterns on West Maui result primarily from orographic uplift of air masses driven by the northeast trade winds. Due to orographic effects associated with the high (> 1400 meters) West Maui shield volcano, most of the precipitation (100-400 centimeters/year) falls on the northern face of the volcano while the south and southwest sides of the volcano receive less than 40 centimeters/year on average (Fletcher and others, 2002). This causes a north-south gradient in both stream flow and terrestrial sediment discharge along West Maui, with greater freshwater and sediment discharge to the north (between Honolua and Kahana) relative to the coast south of

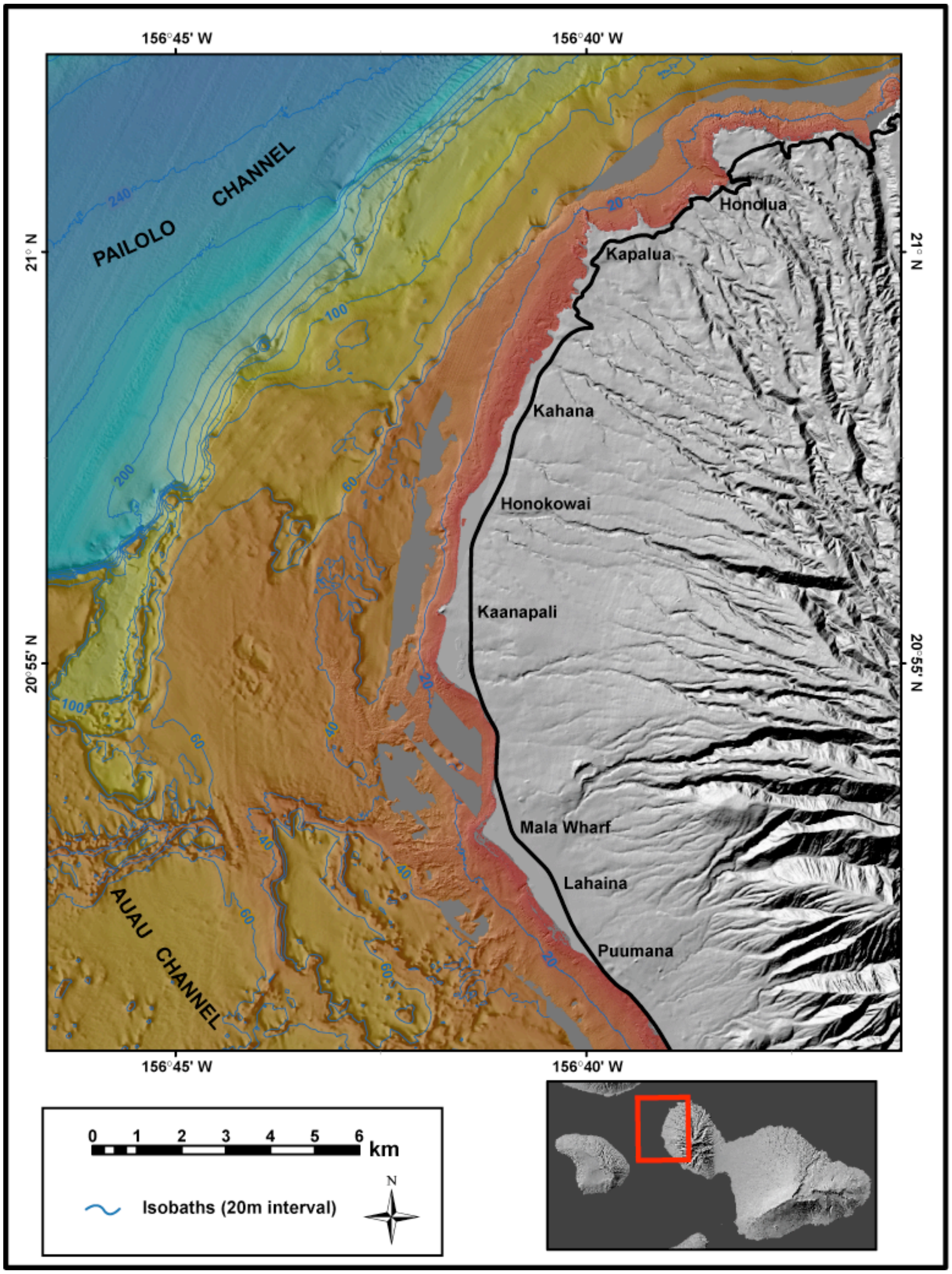

FIGURE 1. Map displaying topography and bathymetry of West Maui.

Honokawai. Most of the lower portions of the streams are perennial in nature, with flow occurring only during periods of heavy rain, typically during the winter months (Soicher and Peterson, 1996).

Tides

The tides off West Maui are of the mixed, semi-diurnal type, with a mean daily tidal range of 0.6 meter and minimum and maximum daily tidal ranges of 0.4 meter and 1.0 meter, respectively (Storlazzi and Jaffe, 2003, 2008; Storlazzi and others, 2004; Storlazzi and others, 2006b).

Waves

The wave climate off West Maui is dominated by four wave regimes: the North Pacific swell, northeast trade-wind waves, Southern Ocean swell and Kona storm waves (Moberly and Chamberlain, 1964). North Pacific swells are generated by strong winter (November-March) storms as they track from west to east across the North Pacific and have significant wave heights (H_s) ~ 3-8 meters and peak periods (T_p) ~ 10-20 seconds. The northeast trade-wind waves occur throughout the year but are largest from April through November when the trade winds blow the strongest; these waves have H_s ~ 1-4 meters but have very short periods (T_p ~ 5-8 seconds). The Southern swell is generated by storms in the Southern Ocean during the Southern Hemisphere winter; while the waves are typically small (H_s ~1-2 meters), they have very long periods (T_p ~ 14-25 seconds). Kona storm waves occur when local fronts or extratropical lows pass through the region and are neither frequent nor consistent in their occurrence. Kona storm waves typically have H_s ~ 3-5 meters and T_p ~ 8-12 seconds.

Additional information on waves and their influence on coral distribution has been derived from models (Storlazzi and others, 2005). Those authors found that maximum wave conditions were dominated by the large (8+ meters), long-period (22 seconds) North Pacific winter waves along the north shore of West Maui. Due to refraction, some of this wave energy wraps around the west end of the island, generating very high wave-orbital velocities at Honolua and Napili that rapidly decrease south towards Honokawai. The rest of the west shore of Maui is in the shadow of Molokai and is protected from these large North Pacific waves, which exhibit low wave-orbital velocities. Trade wind waves show a similar gradient in wave energy that decreases southward from Honolua as the coastline is increasingly sheltered by the West Maui volcano. Most of West Maui is sheltered from Kona storm waves and Southern Ocean swell, except for small windows south of Olowalu and to the east of Thousand Peaks. These findings were reinforced by the later work of Vitousek and others (2007), who modeled sediment transport along West Maui between Black Rock and Hanakao'o Point; their model results compared favorably to in situ data collected by Storlazzi and others (2004).

Nearshore Circulation off West Maui

Until recently, the only studies investigating currents off West Maui looked at large-scale (order of 10s of kilometers) flow through the channels between the islands of Lanai, Molokai and Maui (Flament and Lumpkin, 1996; Sun, 1996). Using satellite data and a numerical model, Sun (1996) observed long-term mean flow through the channels driven by differences in sea-surface height across the island chain. Flament and Lumpkin (1996) noted that the flow in the upper water column out in the middle of the Pailolo Channel was primarily oriented east-west at 0-1.0 meters/second (mean = 0.04 meters/second) while the flow closer to the bed was oriented southwest-northeast, roughly parallel to the isobaths, at 0-0.5 meters/second (mean = 0.04 meters/second). Flament and Lumpkin (1996) also calculated that the majority of the current's energy was in the diurnal and semi-diurnal tidal frequencies.

Hatcher and others (2004) and Storlazzi and others (2006b) showed that surface flow, and likely coral larvae dispersal, offshore Honokawai during the 2003 summer coral spawning season was net alongshore to the south and offshore to the west, causing net projected transport of surface water to be to the south and offshore (fig. 2). The meteorologic and oceanographic data

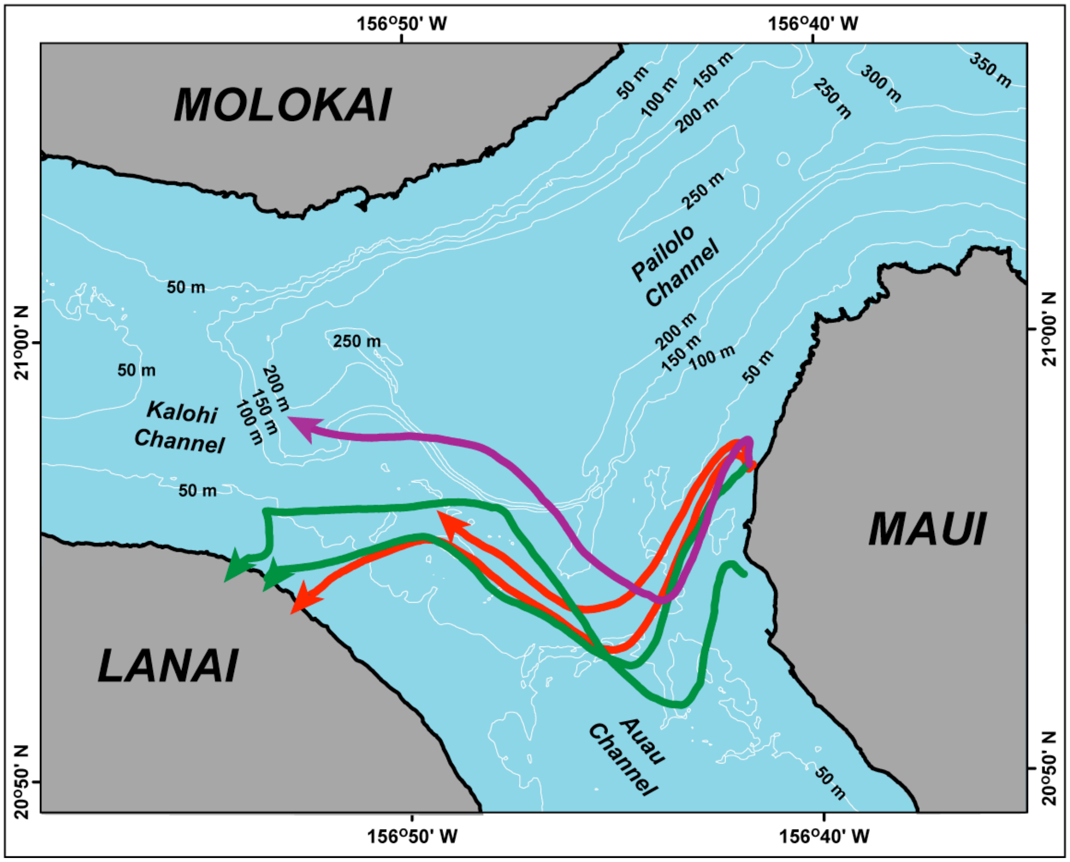

FIGURE 2. *Map of GPS drifter tracks displaying surface water dispersal patterns off West Maui during the 2003 summer coral spawning season. The colors denote different periods of spawning when the drifters were released.*

From both of these and previous studies (Flament and Lumpkin, 1996; Storlazzi and Jaffe, 2003) show that flow off West Maui in the Auau, Pailolo and Kalohi Channels is primarily controlled by the winds and tides. The general flow patterns and seawater properties show greater consistency during the summer months when the forcing by northeast trade winds is relatively steady, storms occur very infrequently and nearshore surface wave-induced flows are at a minimum. During the summer coral-spawning season (June-October), both the forcing (winds and tides) and the resulting flow and environmental patterns were relatively consistent, with northeast-southwest oscillating tidal currents with a superimposed net flow to the southwest and offshore. Similar forcing and response across multiple spawning periods resulted in comparable models of projected water and coral larvae pathways during the 2003 spawning season. Furthermore, since Hawaiian corals always spawns at the same time relative to the phase of the moon (Kolinski and Cox, 2003), these spawning events always occur during the transition from spring to neap tides and thus the relative magnitude of the tidal current forcing during each spawning period is relatively consistent. These consistent patterns, along with the similar paths that the drifters followed over multiple deployments, suggest that the temporally limited drifter trajectories from the study period are likely a good model for initial dispersal patterns off west Maui during the summer months when many of the Hawaiian corals spawn.

Studies by Storlazzi and Jaffe (2003, 2008), Storlazzi and others (2003, 2004) and Storlazzi and Presto (2005) measured tides and currents on the inner (< 30 meters) shelf and show that the tidal wave propagated from south to north in the study area. Similar to the findings of Flament and Lumpkin (1996), they observed that flow over the deeper portion of the fore reef was dominated by diurnal and semi-diurnal tidal currents, and to a lesser extent by lower frequency motions likely driven by wind-driven differences in sea level across the island chain, as modeled by Merrifield and others (2002), and/or the impingement of mesoscale eddies on the island chain as shown by Firing and others (2004). Over the reef flat, however, flows were primarily wind- and wave-driven, and they were often oriented at an angle (> 90°) to the flows concurrently measured out over the fore reef.

The summer months are characterized by consistent northeast trade winds and small waves, and under these conditions high-frequency internal bores are commonly observed off Kahana, there is little net flow or turbidity over the fore reef, and net flow on the reef flat is downwind to the southwest and turbidity is high (Storlazzi and Jaffe, 2003; 2008). When the trade winds wane or the wind direction deviates from the dominant northeast trade wind orientation, strong alongshore currents flow to the northeast, into the dominant trade wind direction, and lower turbidity is observed both on the reef flat and over the fore reef. During the winter, when large storm waves impact Kahana, strong offshore flow and high turbidity occur on the reef flat and the fore reef. Over the course of a year, trade wind conditions resulted in the greatest net transport of turbid water due to relatively strong currents, moderate overall turbidity, and their frequent occurrence. Near-surface current directions over the fore reef varied on average by more than 41° from those near the seafloor, and the orientation of the currents over the reef flat differed on average by more than 65° from those observed over the fore reef. This shear occurred over relatively short vertical (order~meters) and horizontal (order~100s of meters) scales, causing material distributed throughout the water column to be transported in different directions under constant oceanographic and meteorologic forcing.

Wave- and wind-driven flows appear to be the primary control on flow over shallower portions of the reefs while tidal and subtidal currents dominate flow over the outer portions of the reefs and insular shelf (Storlazzi and others, 2003; 2006a). When the direction of these flows counter one another, which is quite common, they cause a zone of cross-shore horizontal shear and often form a front, with turbid, lower-salinity water inshore of the front and clear, higher-salinity water offshore of the front (fig. 3). It is not clear whether these zones of high shear and fronts are the cause or the result of the location of the fore reef, but they appear to be correlated alongshore over relatively large horizontal distances (order~kilometers). When two flows converge or when a single flow is bathymetrically steered, eddies can be generated that, in the absence of large ocean surface waves, tend to accumulate material. Areas of higher turbidity and lower salinity tend to correlate with regions of poor coral health or the absence of well-developed reefs, suggesting that the oceanographic processes that concentrate and/or transport nutrients, contaminants, low-salinity water or suspended sediment might strongly influence coral reef ecosystem health and sustainability.

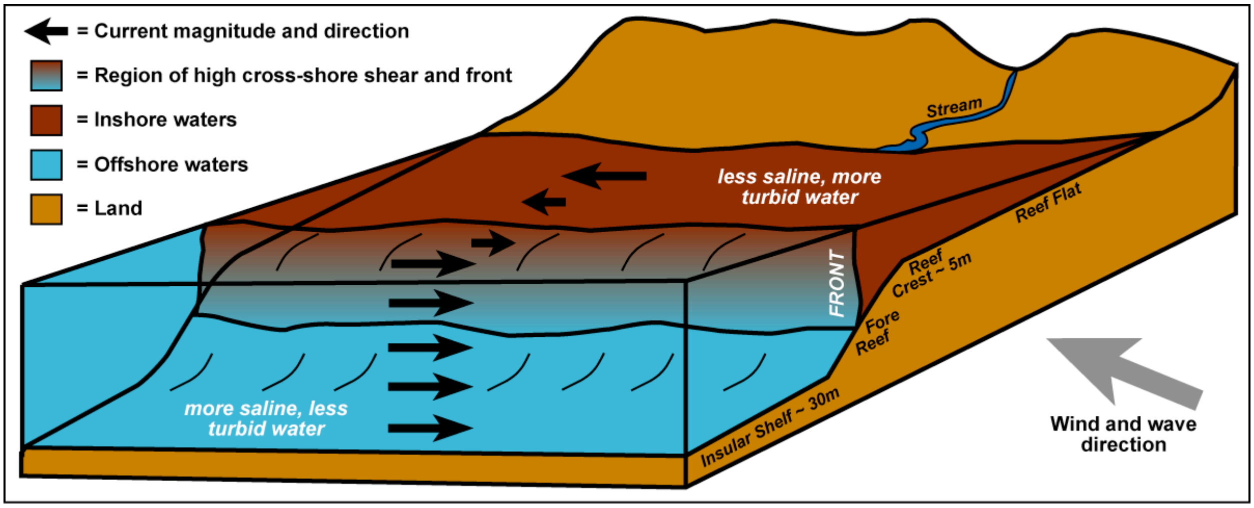

FIGURE 3. Schematic displaying the nature of flow and water column properties resulting in a front along West Maui. Higher turbidity and submarine groundwater discharge or freshwater runoff is typically found close to shore. Along the relatively straight sections of coast, net wave- and wind-driven flow close to shore is downwind. Flow farther offshore is upwind, causing zones of high cross-shore horizontal velocity shear and often fronts.

Coastal Transport

Eversole and Fletcher (2003) and Vitousek and others (2007) studied beach sand transport along West Maui and characterized Kaanapali as an alongshore system. Approximately 3 X 10^4 cubic meters of sand is driven to the north by south swell during summer months; forced by north swell the sand returns to the south in winter months. This volume of sand can result in dramatic beach-width changes of more than 50 meters in a few weeks. Vitousek and others (2007) suggested that rapid changes in beach width, such as those observed in the summer of 2003, are likely due to unusually high sea levels (15-20 centimeters above normal) resulting from a series of mesoscale eddies that arrived over spring and summer months (Firing and others, 2004). Seasonal beach profile changes at Kaanapali beach are pronounced.

Summary

These studies suggest the following conceptual model of meteorologic and oceanographic processes over the inner shelf off West Maui (fig. 4). The northeast trade winds striking the West Maui volcanic cone cause a strong north-south gradient in precipitation along West Maui throughout the year. This precipitation gradient, along with the large area of plowed agricultural lands on the uplands in this area causes, on average, more freshwater and sediment to be discharged from streams between Honolua Bay and Kahana than farther south. This stream discharge, along with submarine groundwater discharge, causes lower salinities and higher concentrations of fine-grained suspended sediment close to shore. Trade wind-induced currents transport the turbid, lower-salinity water south alongshore over the shallower reef areas. These flows appear to keep the turbid, lower-salinity water coherent alongshore, reducing dissipation by forcing these waters against the shoreline while the wave-generated turbulence tends to keep the fine-grained sediment in suspension, offsetting sediment settling due to gravity.

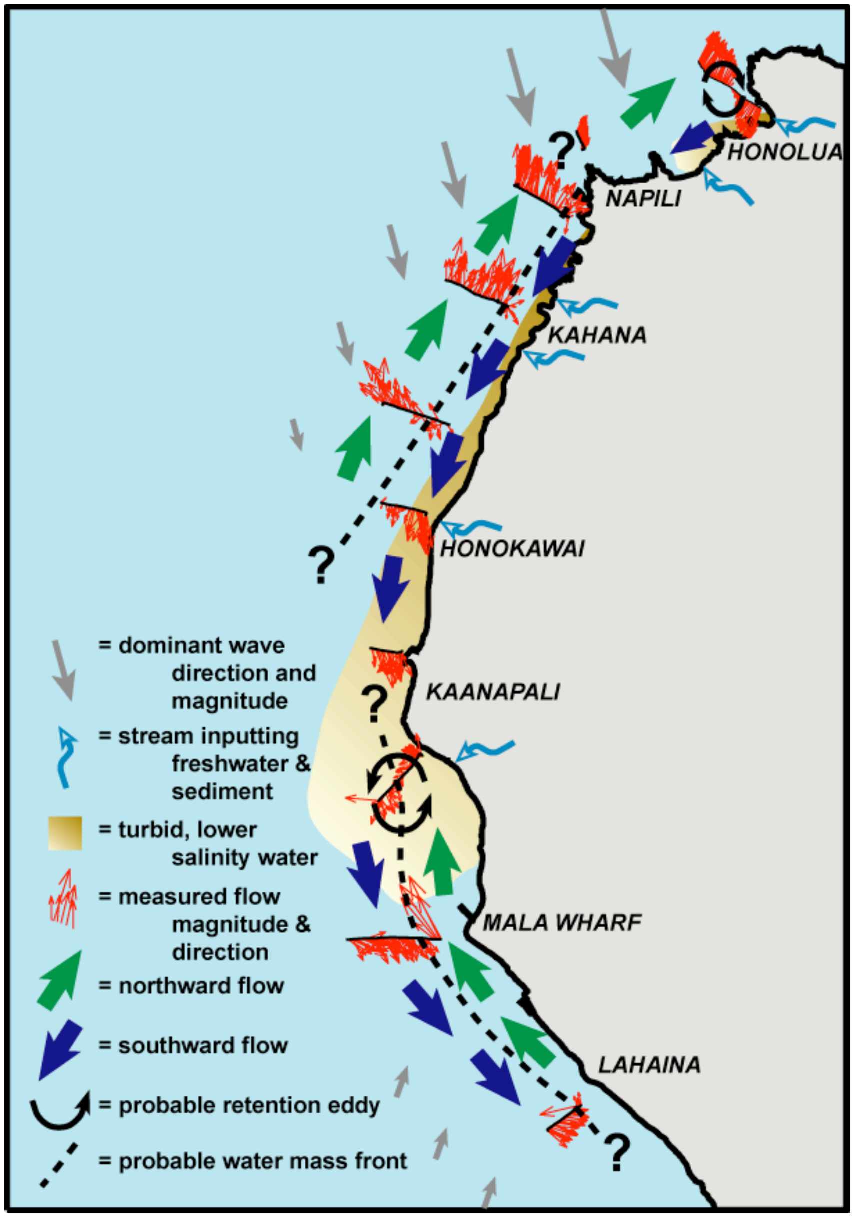

FIGURE 4. *Schematic diagram of the dynamics of flow and turbidity along West Maui. Higher turbidity and freshwater effluence or runoff is typically found close to shore. Net wave-driven flow close to shore is to the south in the northern part of the study area and to the north in then southern portions of the study area, causing convergence in the region between Mala Wharf and Kaanapali. Flow further offshore is typically the opposite of that observed inshore, with offshore flow to the north in the northern portion of the study area and to the south in the southern portion of the study area.*

Together, these two factors persistently create relatively high levels (order of 10's of NTUs) of turbidity close to shore in the Kahana region. The turbid, lower-salinity, southward-flowing inshore jet over the shallower portions of the reefs in the northern part of the study area appears to veer offshore between Honokawai and Kaanapali. It is not clear, however, exactly where the offshore veering of these turbid waters occurs due to the highly variable currents measured in this area. The flow close to shore offshore of Lahaina heads north past Mala Wharf; its fate north of there is unknown. The region between Mala Wharf and Kaanapali appears to be a zone of eddy formation. These eddies, along with the lack of large ocean surface waves (due to shadowing by the surrounding islands), help to retain fine-grained sediment in this area, causing persistent high turbidity (order of 10's of NTUs) despite the absence of fluvial discharge. In contrast, turbid freshwater water is likely not retained in Honolua Bay during the winter when stream discharge is the greatest due to the rapid flushing and mixing of the bay by large North Pacific storm waves.

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