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Quantifying the impact of watershed urbanization on a coral reef: Maunalua Bay, Hawaii

Eric Wolanski[a,b,*], Jonathan A. Martinez[c,d], Robert H. Richmond[c]

[a] ACTFR and Department of Marine and Tropical Biology, James Cook University, Townsville, Queensland 4810, Australia
[b] AIMS, Cape Ferguson, Townsville, Queensland 4810, Australia
[c] Kewalo Marine Laboratory, University of Hawaii at Manoa, 41 Ahui Street, Honolulu, HI 96813, USA
[d] Department of Botany, University of Hawaii at Manoa, 3190 Maile Way, Honolulu, HI 96822, USA

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ABSTRACT

Human activities in the watersheds surrounding Maunalua Bay, Oahu, Hawaii, have lead to the degradation of coastal coral reefs affecting populations of marine organisms of ecological, economic and cultural value. Urbanization, stream channelization, breaching of a peninsula, seawalls, and dredging on the east side of the bay have resulted in increased volumes and residence time of polluted runoff waters, eutrophication, trapping of terrigenous sediments, and the formation of a permanent nepheloid layer. The ecosystem collapse on the east side of the bay and the prevailing westward longshore current have resulted in the collapse of the coral and coralline algae population on the west side of the bay. In turn this has lead to a decrease in carbonate sediment production through bio-erosion as well as a disintegration of the dead coral and coralline algae, leading to sediment starvation and increased wave breaking on the coast and thus increased coastal erosion. The field data and resulting coral reef ecohydrology model presented in this paper demonstrate and quantify the importance of biophysical processes leading to coral reef degradation as the result of urbanization. Coral restoration in Maunalua Bay will require an integrated ecosystem approach.

1. Introduction

Increasing human population in most coral fringed oceanic islands has lead to the degradation of shallow water coral reefs as a result of modification of coastal watersheds by human activities (Cote and Reynolds, 2006). Data are lacking to quantify the apparent link between watershed development and coral reef degradation, but it is generally recognized that both physical and biological processes may contribute simultaneously to this degradation (Zann, 1994; Hunter and Evans, 1995; Costa et al., 2000; Fabricius, 2005; Riegl and Dodge, 2008). Because of the complexities of the biophysical links in coral reef ecosystems, it is often difficult to quantify the relative contribution of each land-based human activity to coral reef degradation, and to develop policies that integrate across the land–sea boundary. The field data and resulting coral reef ecohydrology model presented in this paper demonstrate and quantify the importance of biophysical processes leading to coral reef degradation as the result of urbanization, and quantify the relative contribution of various human activities.

The study site was Maunalua Bay (157° 45′ W, 21° 15′ N), Oahu, Hawaii (Fig. 1). The bay is 8 km long and has a fringing reef flat. The bay receives discharges from nine small watersheds, each typically 10 km^2 in size (e.g. the Wailupe watershed is 8.8 km^2, the Kamilo Iki watershed is 12.4 km^2, and the Kamilo Nui watershed is 10.8 km^2). Each stream drains across the reef flat through a small, often ill-defined, channel and a well-defined passage through the reef crest (Fig. 2).

When first mapped in 1855, the human settlements were few, the reef crest was observed to be near the ocean's surface where waves broke permanently, and there was a large lagoon ('Lake Maunalua' commonly known as Kuapa Pond, now a marina) on the east side of the bay (Fig. 3a). This same map shows that most of the peninsula separating the lagoon from the reef flat was too narrow for human settlement but it was continuous, i.e. Kuapa Lagoon was closed except during the highest spring tides when it overtopped, and during river floods when the peninsula would have been breached. Fishermen created permanent openings bridged by rock walls; by 1921 these rock walls, made visible as thin straight lines in Fig. 3b, closed most of the lagoon and only

* Corresponding author at: ACTFR and Department of Marine and Tropical Biology, James Cook University, Townsville, Queensland 4810, Australia.
E-mail address: eric.wolanski@jcu.edu.au (E. Wolanski).

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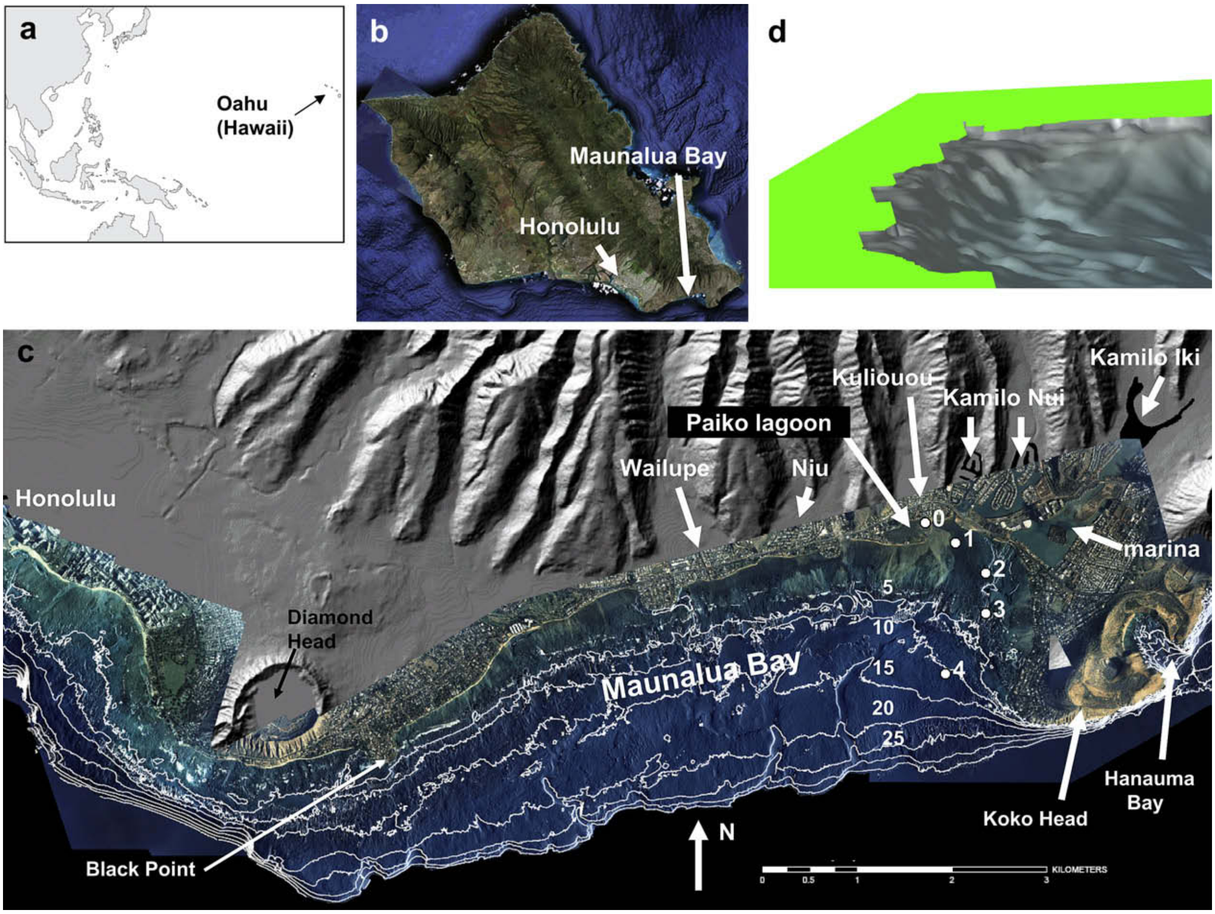

Fig. 1. (a–b) General location maps. (c) Bathymetry (depth in m) of Maunalua Bay and the location of the oceanographic mooring sites 0–3 and the streams mentioned in the text, together with key sites and a visualization of the coastal urbanization and the topography. (d) A 3-D rendering of the bathymetry of Maunalua Bay.

a small opening existed on the west side of the peninsula. In 1855 a large fish pond existed near the mouth of the Wailupe stream (Fig. 3a); this pond was created by constructing rock walls (Fig. 3c). This fish pond was later filled for a housing development. In 1900 mangroves and halophytes were fringing Kuapa Pond and man-made fish ponds in coastal waters (Fig. 3b and c). In 1890 the reef flat on the east side of the bay was sandy and extremely shallow at low tide (Fig. 3d). In 1927, Kuapa Pond was fringed by seasonal wetlands used as pastures (Fig. 3e), and urbanization was still minimal. In 1930 the coast was sandy on the west side of Maunalua Bay (Fig. 3f). Large-scale urbanization occurred since the 1960s when two navigation channels were dredged that traverse Maunalua Bay, one on the east side of Maunalua Bay and another, smaller, channel in the central region near the Wailupe stream mouth. The Kuliouou stream that historically discharged into Paiko Lagoon was diverted to flow directly into Maunalua Bay. All of the coastal plains and much of the surrounding hills have been urbanized (Fig. 3h), the surface area of Kuapa Pond was decreased by 30% when it was urbanized into a marina, the streams were channelized and lined with concrete (Fig. 3i), and new houses were constructed, and are still being constructed, on steep, highly erodible slopes with flimsy sediment curtains being used for mitigation; these curtains readily fold and fail to trap sediment during runoff events (Fig. 3j). The degree of urbanization in 2008 varied between catchments, examples being 33% in the Kamilo Nui catchment, 34% in the Wailupe catchment, and 56% in the Kamilo Iki catchment, with similar high values in all of the other catchments. Runoff from these hard surfaces is largely directed by pipes to the channelized streams, thus reducing groundwater recharge. The remaining parts of the catchment are designated as conservation areas and are degraded by invasive alien species of plants and by a large population of feral pigs and goats. As a result, erosion is prevalent within the upper regions of the catchment as well as along stream banks.

2. Methods

Four oceanographic moorings were deployed at sites 1–4 (see location map in Fig. 1) from August to December 2008. These sites formed a transect along the east side of the bay. Tidal height, salinity, temperature, dissolved oxygen concentration, pH, and suspended solid concentration (SSC) were measured at sites 1–3 using self-logging YSI (Yellow Springs Instruments) self-logging CTD-cum nephelometers moored nominally 1 m below the surface at low tide. The YSI instruments were equipped with wipers that cleaned the sensor every 5 min. The instruments logged data at 5 min intervals. At site 3, the vertical profiles of horizontal currents were measured at 10 min intervals using a bottom-mounted Workhorse ADCP from September to December 2008. In addition, the vertical profile of salinity, temperature, dissolved oxygen and SSC was measured at sites 0–3 at intervals of 1–4 weeks from a ship-born YSI CTD profiler-cum nephelometer. The nephelometers were calibrated at the Kewalo Marine Laboratory using sediment from site 1.

Other data sets were collected from a number of sources. The Wailupe stream discharge time-series data for October–December

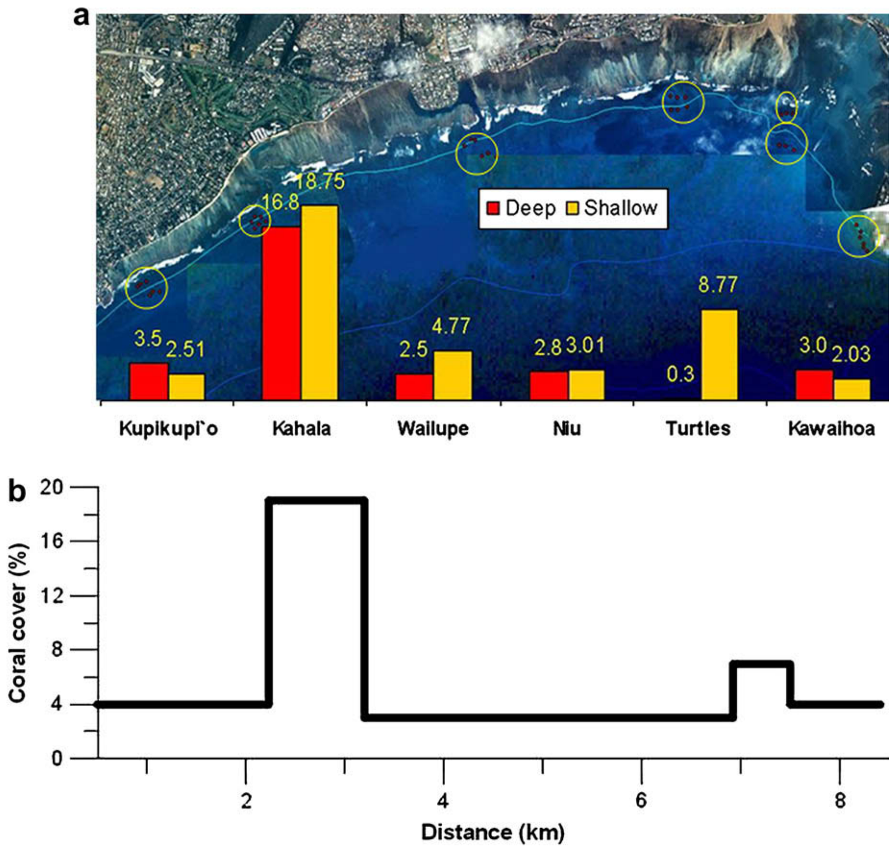

Fig. 2. (a) The observed distribution of coral cover in 2008 and the location of survey sites. (b) The predicted coral cover distribution.

2008 were provided by Dr. G. Tribble of the United States Geological Survey. No other stream was gauged. Local rainfall data for nearby Honolulu for the period 1947–2008 and the Niu watershed for 2008 were provided by NOAA. Wave height and direction data during a nearshore mooring off Honolulu (about 10 km to the west; see Fig. 1) were provided by the department of Ocean and Resources Engineering at the University of Hawaii (Sansone et al., 2008). About 1 million spot depth data points in Maunalua Bay were provided by the U.S. Army Corps of Engineers Shoals (Scanning Hydrographic Operational Airborne Lidar Survey) system. These data were averaged over a 50 m square grid to generate a bathymetric map of Maunalua Bay.

The water circulation was modeled following Wolanski and Spagnol (2003). The additional effect of wave breaking on the reef crest generating a sea level set-up and a circulation over the reef flat was modeled following Wolanski (1994). The final hydrodynamic model was verified against the field data from the ADCP at mooring site 3 (not shown).

Data on coral cover in 2008 were kindly provided by Manuel Mejia of The Nature Conservancy. Data on the density of herbivorous fish in 2008 were kindly provided by Alan M. Friedlander of NOAA and The Oceanic Institute. These data were used as an external parameter in the HOME coral reef ecosystem model of Wolanski et al. (2004) and Wolanski (2007), which was used to model coral cover in Maunalua Bay. The kinetic rates in the model were assumed to be the same as those in the Great Barrier Reef and in Fouha Bay, Guam.

Low-frequency sea levels and currents were calculated using Godin's (1991) "$A_{24}^2 A_{25}/24^2 25$" moving average filter to the original time-series data decimated to hourly intervals. Salinity is expressed in practical salinity units.

3. Results

During 1947–2008, the mean annual rainfall in Honolulu was 0.52 m. The rainfall varied seasonally, with a maximum during November–January, and a minimum in June, with a large interannual variability (Fig. 4). In 2008, there was a drought in January to April, normal rainfall from May to October and above average rainfall in November–December (Fig. 4). Rainfall in the Niu coastal valley followed a similar pattern to that observed in Honolulu in 2008 (not shown).

Micro-tides prevailed, alternating from semi-diurnal to diurnal (Fig. 5a). Even in the dry season (September 2008) when rainfall was negligible and there was no visible surface flow in the streams, there was a salinity gradient in Maunalua Bay, with fresher water inshore and saltier water offshore, and this resulted in higher salinities at high tide than at low tide at site 2 (Fig. 5a). This is likely the result of groundwater flow from the watersheds because Maunalua Bay has a number of springs discharging freshwater below mean low tide (Hitchcock, 1905). The suspended sediment concentration (SSC) was higher at high tide than at low tide, and also higher in the presence of waves with a significant wave height greater than 0.8 m. The SSC values at site 2 were always high, commonly peaking at 120 mg l^{-1} and seldom below 30 mg l^{-1} except on days with negligible waves. Throughout the dry season, a permanent nepheloid layer was always present along the transect on the east side of Maunalua Bay (Fig. 5b), while the salinity and temperature stratification was negligible (not shown). Our visual observations reveal that the nepheloid layer did not exist in the central and western regions of Maunalua Bay.

The tidal currents at site 3 were landward at the rising tide and seaward at the falling tide (Fig. 6a). The dissolved oxygen (D.O.)

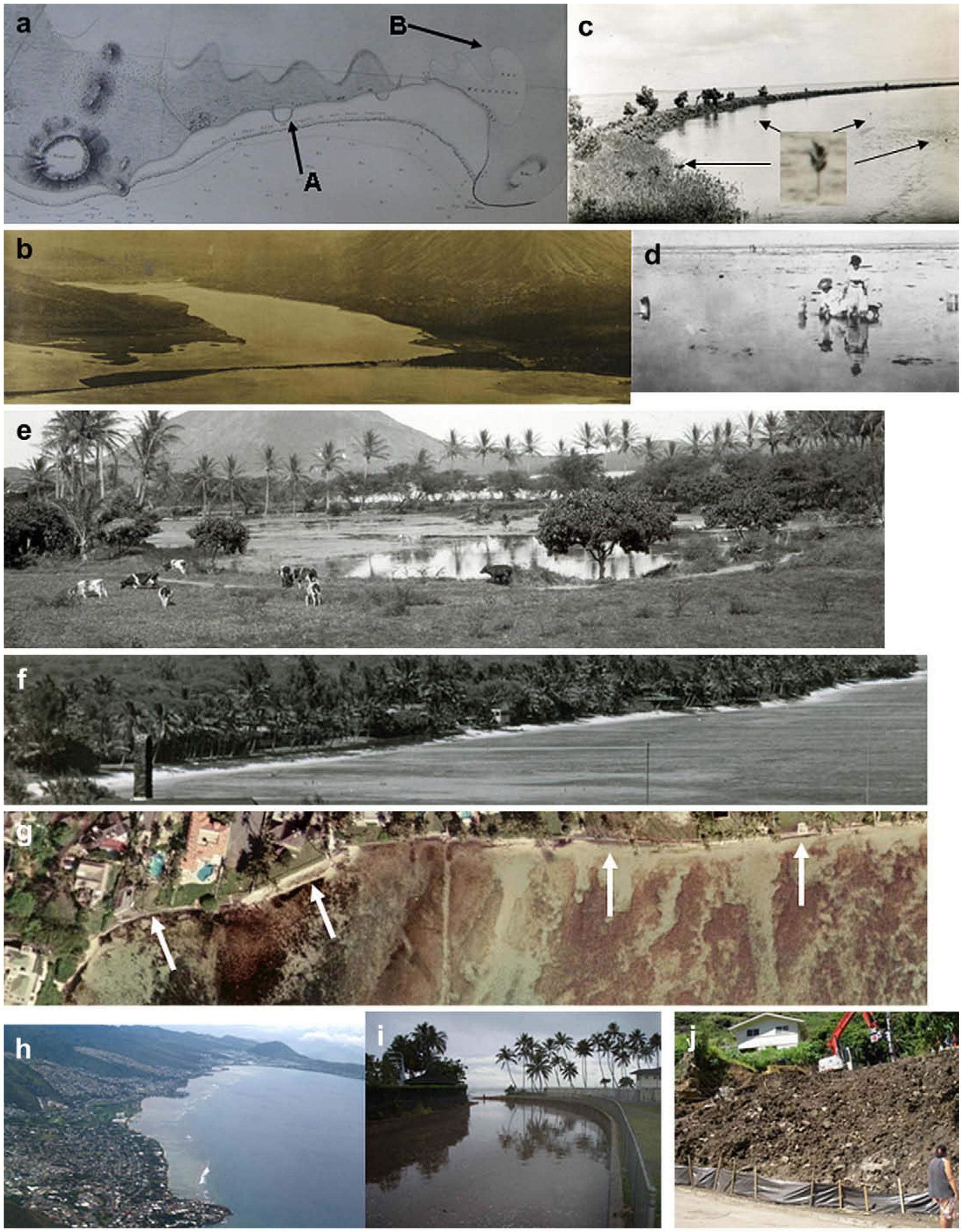

Fig. 3. (a) The 1855 map of Maunalua Bay. The caption in French reads "near surface reef where waves always break". The arrows point to (A) the Wailupe fish pond and (B) Lake Maunalua (Kuapa Pond, now a marina). Note from the uninterrupted peninsula that Kuapa Pond was closed. (b) An aerial photograph of Lake Maunalua (Kuapa Pond) on 23 June 1921. The straight line forming the peninsula on the left hand side is a rockwall. Mangroves and halophytes colonized the shore. (c) A photograph dated about 1900 showing a rock wall of the Wailupe fish pond; this pond was later filled for urban development. The inset shows invasive mangrove seedlings in the pond. Note from the ripples that the sediment was sandy and from the mangrove seedlings that the depth was only a few cm. (d) A photograph of Maunalua Bay dated 1890, showing a sandy substrate and patches of seaweeds. (e) A photograph dated 1927, of the wetlands fringing Lake Maunalua (Kuapa Pond). (f) A photograph dated 1930, of the sandy beach of the west side of Maunalua Bay. (g) A 2008 Google view of the same coast as in (f) showing the absence of a beach; the arrows point to seawalls. Photographs dated 2008 of (h) concrete lining of streams draining into Maunalua Bay, (i) the extensive urbanization of the Maunalua Bay catchments, and (j) the lack of care in preventing erosion at housing developments in the catchment as exemplified by the fact that much eroded sediment from this building site was already spread on the road and draining to the drains, from there it was flushed directly to the stream.

concentration appeared independent of the tide, being at a minimum late at night and maximum in the late afternoon and early evening. Superimposed on the tidal currents, the prevailing, low-frequency, longshore currents near the surface were westward, with a mean value of 0.08 m s^{-1}, and they fluctuated at periods of several weeks with the wind and wave conditions (Fig. 6b).

One major rainfall event occurred during the 6-month long study on December 11, 2008 (Fig. 7a). High discharges resulted in all the streams draining into Maunalua Bay. The Wailupe stream discharge rose and fell rapidly within 1 day (Fig. 7a). The low-frequency sea level at site 0 rose during the rising stage of the flood and stayed elevated for the next 10 days, while that at sites 1 and 2

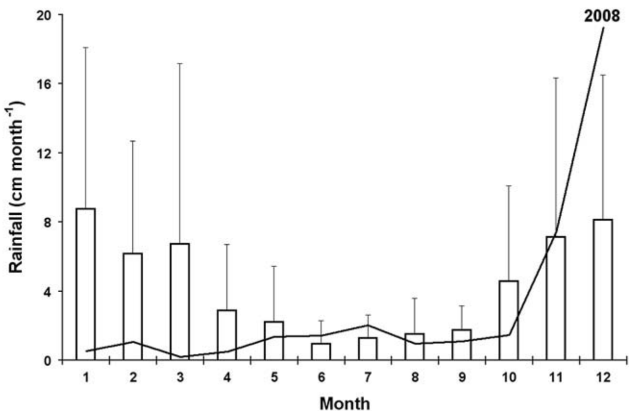

Fig. 4. The distribution of (bar plot) the mean monthly rainfall in Honolulu and (shown as error bars) its variance in 1947–2008, and (line plot) the monthly rainfall in the coastal plain of the Niu stream in 2008.

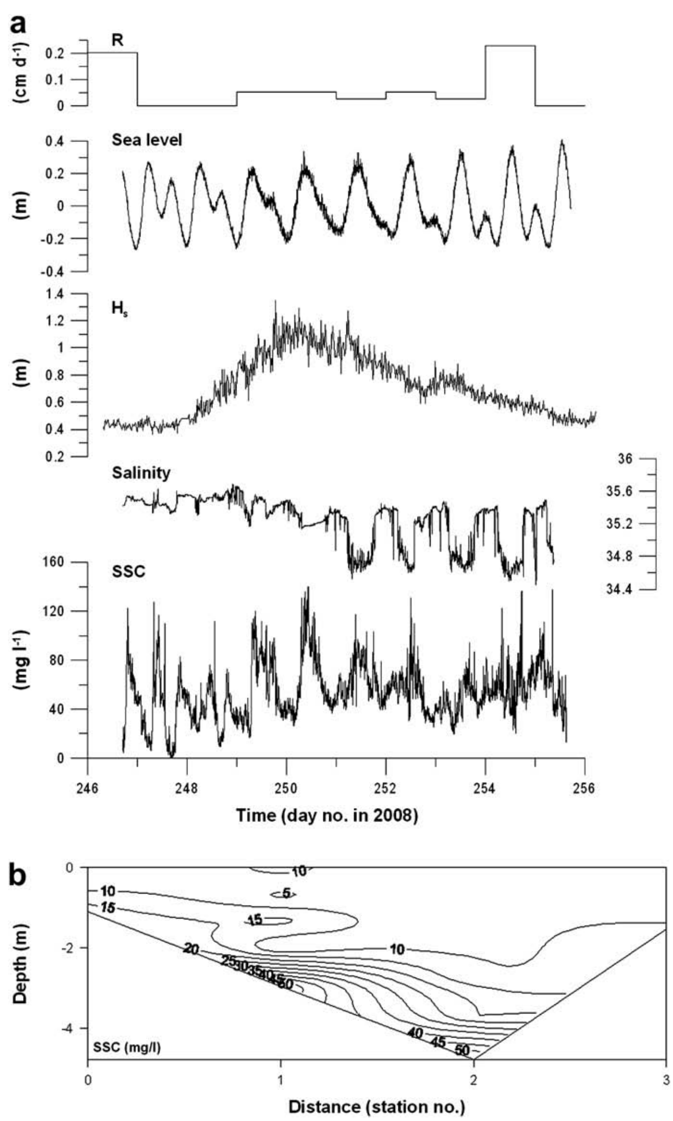

Fig. 5. (a) Time-series plot in the dry season of daily rainfall R, sea level, significant wave height, salinity, and suspended solid concentration SSC at mooring site 2. (b) Along-transect distribution of SSC on September 2, 2009.

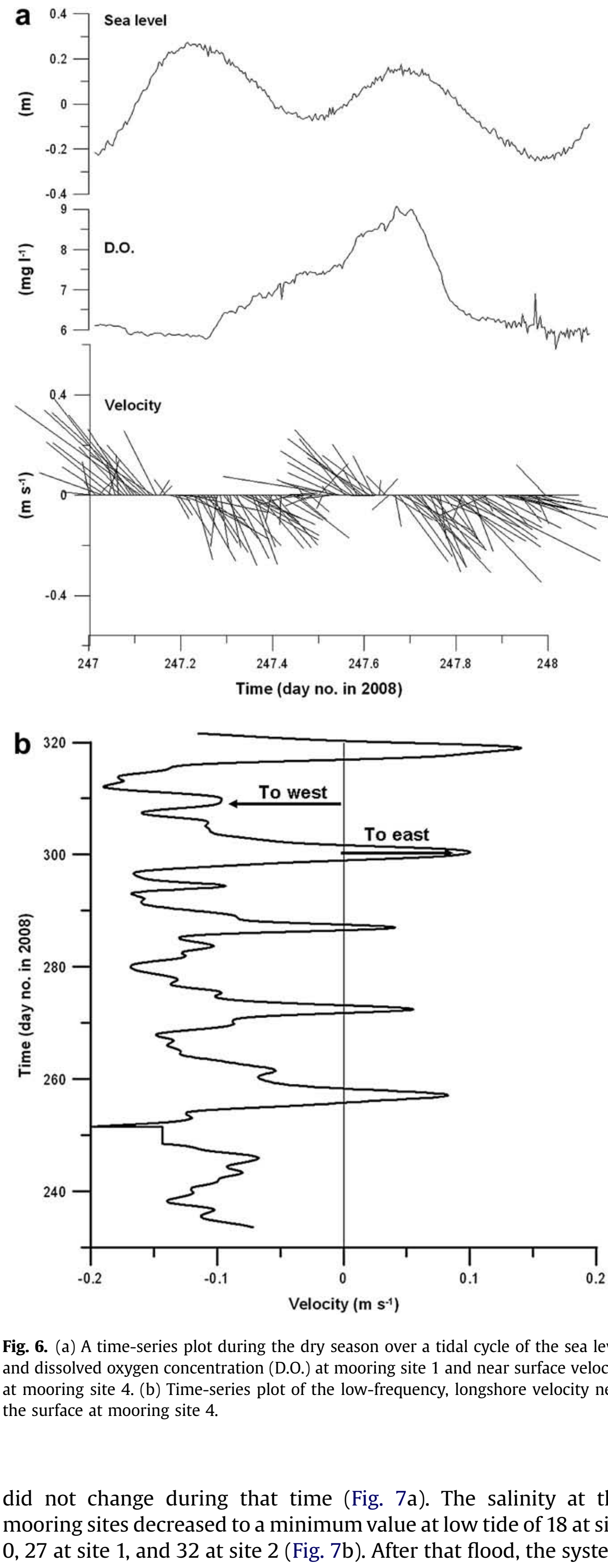

Fig. 6. (a) A time-series plot during the dry season over a tidal cycle of the sea level and dissolved oxygen concentration (D.O.) at mooring site 1 and near surface velocity at mooring site 4. (b) Time-series plot of the low-frequency, longshore velocity near the surface at mooring site 4.

did not change during that time (Fig. 7a). The salinity at the mooring sites decreased to a minimum value at low tide of 18 at site 0, 27 at site 1, and 32 at site 2 (Fig. 7b). After that flood, the system recovered slowly over several days, as exemplified by the minimum salinity that increased back to 32 at site 0 over the next 9 days, at site 1 over 6 days, and at site 2 over only 1 day. Simultaneously the SSC values rose during the rising stage of the river flood at sites 0 and 1. After the flood high SSC values remained at site 0 for about

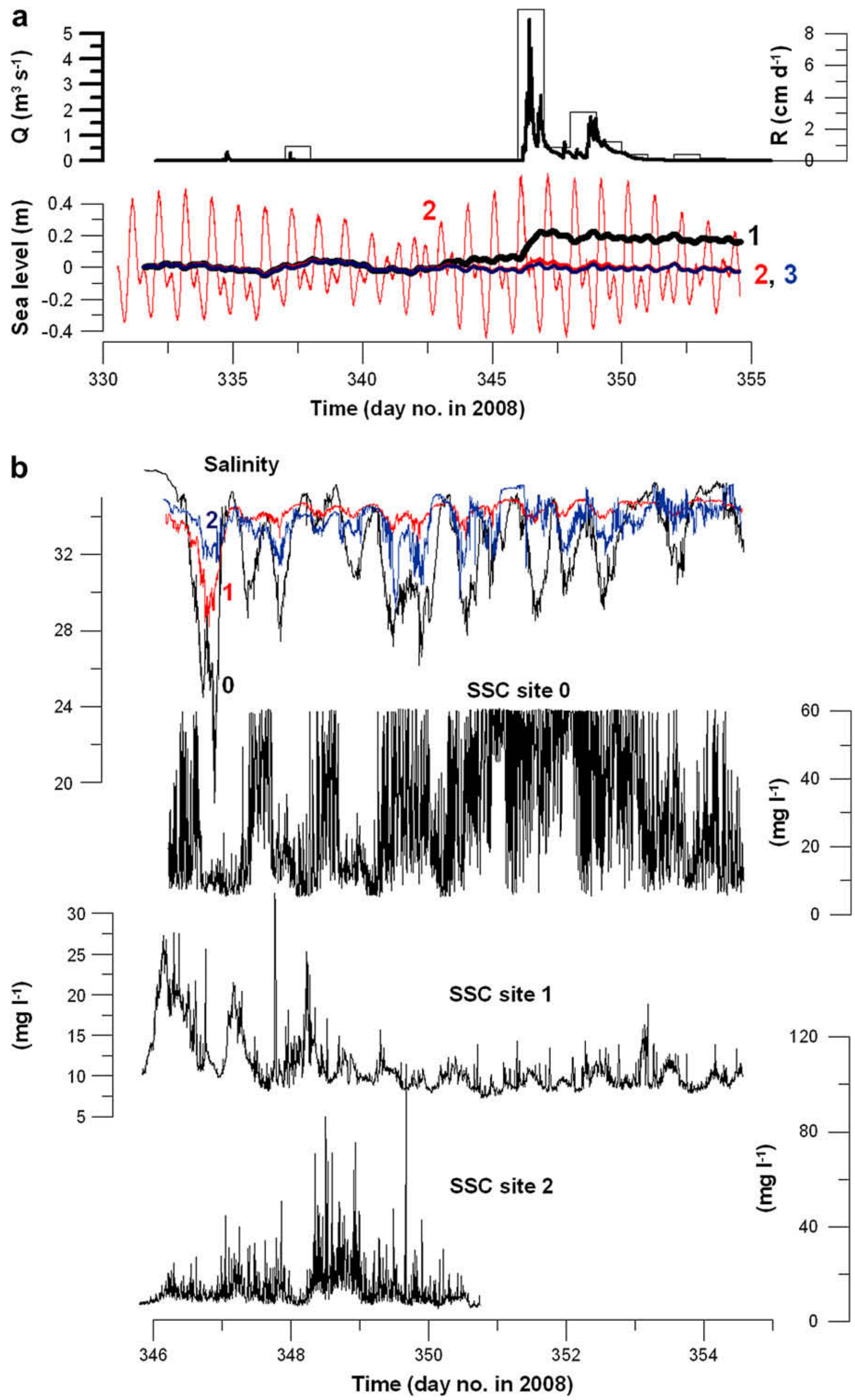

Fig. 7. (a) Time-series plot for the flood of December 2008 of the rainfall R and the Wailupe stream discharge, (thin line) the sea level at mooring site 1 and (thick lines) the low-frequency sea level at mooring sites 0, 1 and 2. (b) Time-series plot of the salinity and suspended solid concentration SSC at mooring sites 1, 2, and 3 for the flood of December 2008.

10 days, at site 1 for about 3 days, and at site 2 for about 2 days (Fig. 7b). This flood event formed a river plume with a marked vertical stratification in salinity that was absent before the flood and that persisted for at least 8 days after the flood (Fig. 8a). The SSC values in the nepheloid layer were greatly increased under the river plume (Fig. 8a).

Much of the fine sediment from the watersheds is discharged into the bay during the first flush at the rising stage of river floods. Based on the currents and SSC data at mooring site 1 during the first flush of the December 2008 river flood, about 20 tons of terrigenous fine sediment was discharged into Maunalua Bay through the dredged channel. This is the combined contribution of the Kuliouou, Kamilo Nui, and Kamilo Uki streams.

4. Discussion

The area is semi-arid with a mean annual rainfall of only 0.52 m. Long, severe droughts do occur such as in 1998 when the annual

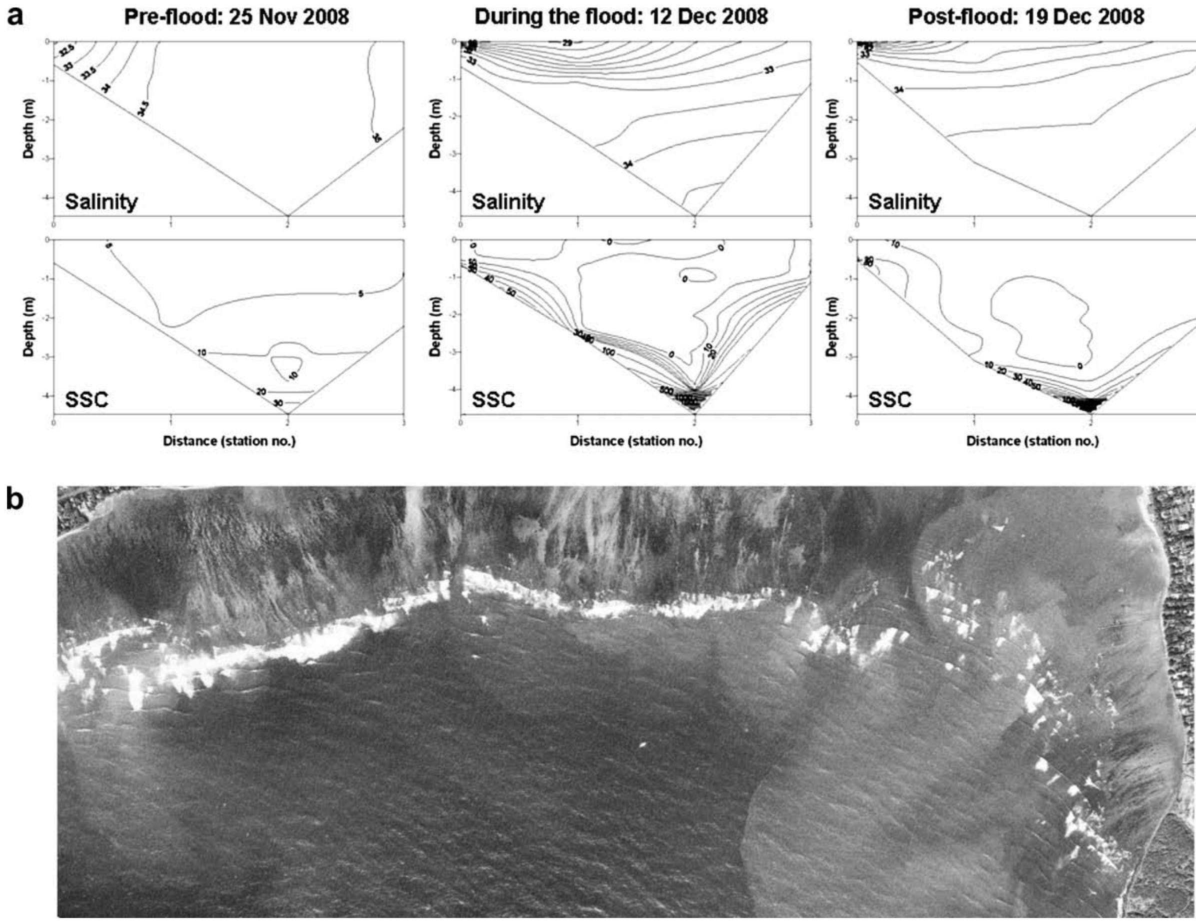

Fig. 8. (a) Along-channel distribution of salinity and suspended solid concentration (SSC, mg l^{-1}) for the flood of mid-December 2008. (b) Aerial photograph, dated January 19, 1959, i.e. during the wet season, showing turbidity plumes over the east and central regions of Maunalua Bay exiting the reef flat through reef passages and spreading offshore from there.

rainfall was only 0.11 m. Wet years also occur, such as in 1965 when the annual rainfall was 1.1 m.

The catchment has been heavily urbanized particularly over the last 40 years. This study provides an opportunity to assess the impact of urbanization on the Maunalua Bay ecosystem, which is applicable to many other areas in Hawaii and elsewhere. No historical data exist on coral cover on the reef slope. Some data are available for coral cover on the reef flat in 1922–1925 (Pollock, 1925) when coralline algae prevailed over the reef flat and the coral cover was patchy, averaging 3% over the whole of Maunalua Bay but with zones of live coral cover of up to 50% in bands about 25–33 m in width that started 10–16 m from the reef crest and extended mainly on the western side of the bay. In February 2008, we observed that these coral patches over the reef flat were dead and that the coral cover was virtually nil over the reef crest. The coral cover was less than 5% over most of the reef slope except in two localized areas where it peaked at 19% and 9%, respectively (Fig. 2). There are no historical data on the herbivorous fish population.

In 2008 the herbivorous fish population density in Maunalua Bay was only 5–10% of that which occurs on inshore and mid-reefs of the Great Barrier Reef (Wolanski et al., 2004), and this may be due to overfishing.

The minimum salinity (about 20) at site 0 was so low that the salinity on its own would be sufficient to prevent corals growing at this site; but corals can usually survive exposure to 28 and 32 for some time (Fabricius, 2005) as encountered at sites 1 and 2, so it is unlikely that it is low salinity alone that is killing coral at those sites. Coral degradation in Maunalua Bay correlates with changes in the surrounding watershed and in the flushing rate of the bay following urbanization. The depth over the reef crest seldom exceeds 1 m, except on the east side of the bay where it is slightly deeper. Water depth over the reef flat is shallower than over the reef crest, thus preventing water stagnation, and the reef flat was thus likely flushed swiftly, daily, by the tides before urbanization. Following urbanization, increased levels of sedimentation occurred in the bay, creating stagnation zones; the marina on the east side was dredged to a depth much deeper than the original Kuapa Lagoon; the construction of a seawall and openings permanently opened the marina to Maunalua Bay and increased the residence time of water in the bay. The deeper waters in the marina and its narrow opening create a tidal jet that is topographically steered by the navigation channel dredged across the reef flat. This jet, together with the currents generated by wave breaking on the reef crest, generates a quasi-permanent re-circulating flow, i.e. stagnation, on the east side of Maunalua Bay (Fig. 9a). Thus the waters on the east side are poorly flushed, having a residence time on the order of 7–10 days as demonstrated by the long retention time of the river plume. The marina on the east coast plays a substantial role in trapping runoff water after a flood, and releasing it slowly over 7 days, as evidenced by the long-duration rise in mean sea level and the low salinity at site 0 after the mid-December 2008 flood. This circulation pattern helps trap fine sediment inshore and explains the presence of a permanent nepheloid layer on the east side of Maunalua Bay. It also explains the transformation of the east coast from sandy to

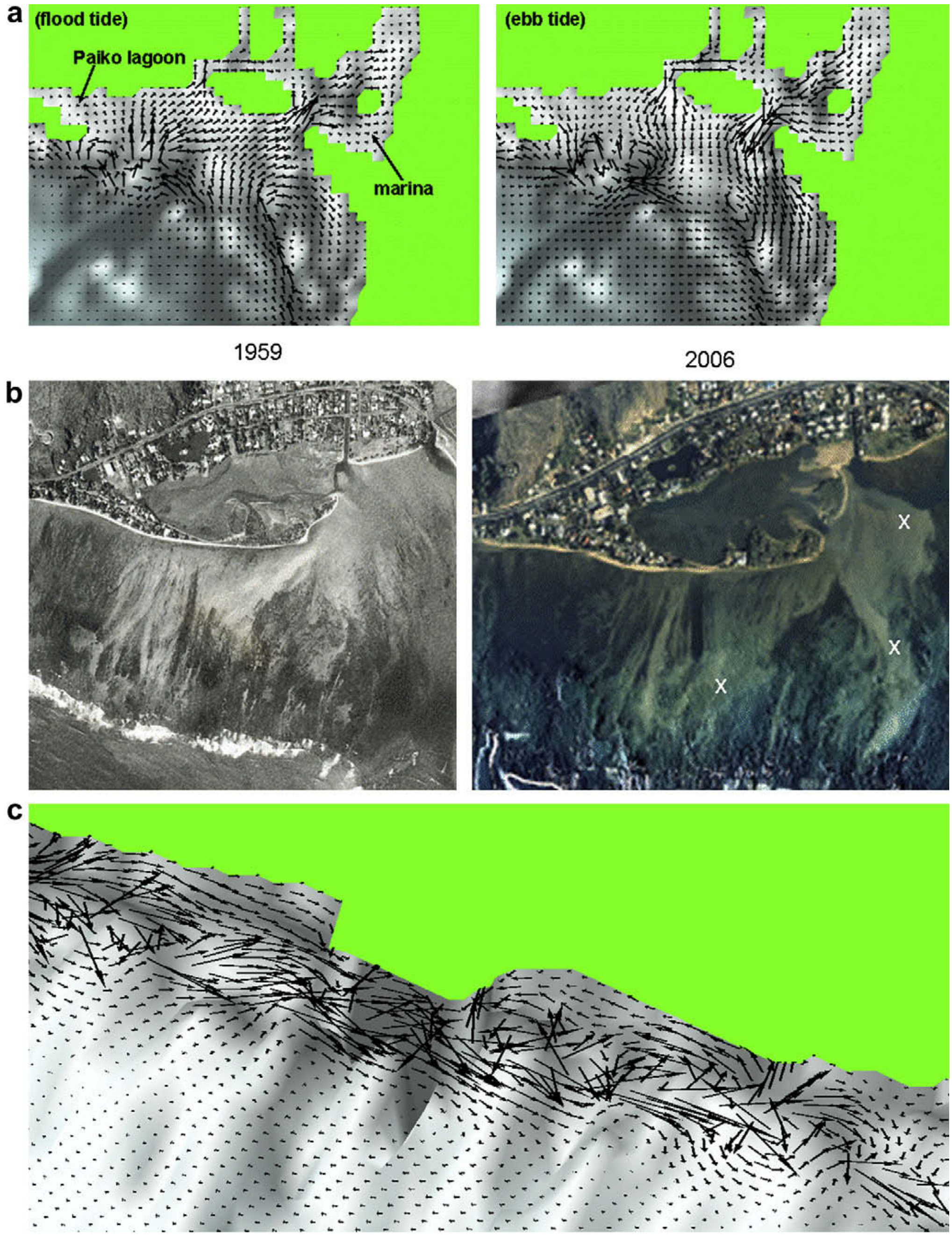

Fig. 9. (a) Predicted depth-averaged water circulation on the east side of Maunalua Bay at flood and rising tide for a 1 m swell from the south breaking on the reef flat. (b) Aerial photographs in 1959 and 2006 of the area around the Paiko peninsula showing (X) sediment accumulation over the reef flat. (c) 3-D rendering of the predicted depth-averaged water circulation in the central region of Maunalua Bay for a 1 m swell from the south breaking on the reef flat.

muddy in the last 100 years, and the on-going spread of muddy sand banks infilling the reef flat on the east side of Maunalua Bay (Fig. 9b). There are no reliable data of the nutrient concentration in the streams discharging into Maunalua Bay. Data from other hardened streams draining urbanized watersheds in Oahu Island suggest high-nutrient concentrations with the potential to degrade coral reefs and seagrass beds dependent on the residence time (Laws and Roth, 2004). The long residence time of waters in Maunalua Bay, particularly on the eastern side, facilitates this degradation.

The observed coastal degradation is tied to urbanization of the watershed and the channelization of the associated streams, which inhibit groundwater recharge. As a result peak flows in the streams are increased, enabling the river plumes to spread further in Maunalua Bay. Prior to urbanization, Maunalua Bay in 1905 was the site of large, permanent springs in the ocean, as a result of groundwater discharges (Hitchcock, 1905). The groundwater recharge and storage are expected to be much smaller at present. The Wailupe stream flow data following the December 2008 flood showed that the thickness of the groundwater storage was only 2.5 cm. This also implies that the streams now dry out much faster after rain than before urbanization occurred.

The runoff water is presumably enriched in nutrients that sustain the algae growing over the dead corals, smothering living corals and preventing recruitment of coral larvae. The filling of the fish ponds and parts of Kuapa Lagoon for urban developments has

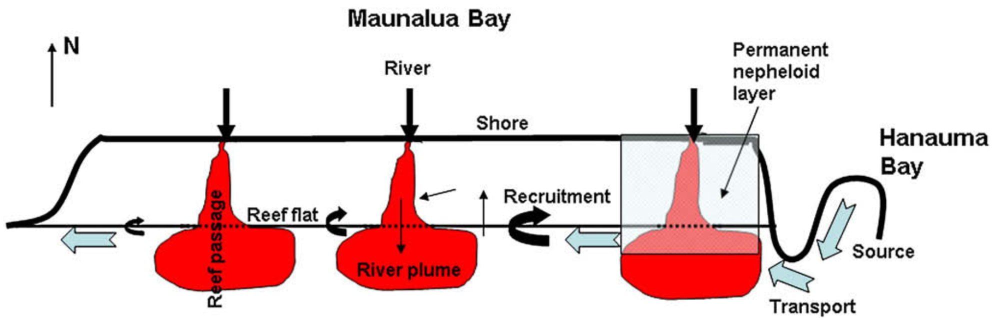

Fig. 10. A sketch of the biophysical processes controlling coral cover in Maunalua Bay.

destroyed the halophytes and mangroves that historically trapped terrigenous sediment.

Much of the material forming the nepheloid layer is organic and likely made of algal detritus from the algal mats (R.H. Richmond, unp. data). As a result, the east side of Maunalua Bay is nutrient-enriched, as evidenced by the large diurnal fluctuations in dissolved oxygen concentration presumably due to algal photosynthesis during the daytime and respiration at nighttime.

In the central and western regions of Maunalua Bay, waves breaking on the reef crest are predicted to be the dominant flushing mechanism as oceanic waters flooding over the reef crest exit through the nearest reef passage (Figs. 9c and 10). Thus the reef flat in those areas is well flushed, with a residence time of less than 1 day, precluding the formation of a nepheloid layer.

Turbid plumes are present throughout Maunalua Bay following rain events and due to re-suspension of sediments accumulated within benthic algal mats, exiting the reef flat through reef passages (Fig. 8b). Our visual observations reveal that these turbid plumes were present in both the wet and dry seasons on the east side, while they existed in the central and western regions only during the wet season.

Bio-erosion of coral skeletons, coralline algae and the limestone remnant of past coral reef growth generated the majority of the calcareous sediment that formed the sandy beach on the west side of Maunalua Bay and that existed in the 1940s (Fig. 3f). This calcareous sand has disappeared, as a result of coastal erosion, which instigated the construction of stone and cement seawalls along much of the western shore of Maunalua Bay (Fig. 3g).

The disappearance of the sandy beach in the central and western regions of Maunalua Bay can be explained by the absence of coralline algae and live coral (Fig. 2) as a source of calcareous sediment. In the past this calcareous sediment would have been produced throughout the year at rate of about 4 kg $CaCO_3$ m^2 $year^{-1}$ (Kinsey, 1985) and would thus have maintained the sandy beach.

The application of the HOME coral reef ecosystem model requires the assumption that the observed distribution of live coral (Fig. 2a) is at a steady state. Without that assumption, the observed distribution of coral cover would be only a snapshot in time and space, and this would be insufficient for model verification. Unfortunately, no time-series data on coral cover are available.

In the absence of a healthy coral reef within Maunalua Bay to provide coral larvae to maintain a coral population by self-recruitment, we assumed that (1) 60 years ago the reef was healthy with a 40% coral cover in Maunalua Bay, (2) the protected and relatively healthy coral ecosystem of Hanauma Bay (Wedding and Friedlander, 2008) now provides the bulk of the incoming coral larvae, and (3) these coral larvae are transported by the observed longshore low-frequency westward currents in Maunalua Bay (Fig. 10). The HOME model predicts a coral distribution that agrees with the empirical observations (Fig. 2). The same coral distribution in 2008 is predicted whether the coral cover 60 years ago was 20, 40, or 60%; thus the model predictions are independent of the initial conditions. While other hypotheses may be possible to explain the present (low) coral cover in Maunalua Bay especially if the situation is not at a steady state, the model suggests that (1) much of the larval supply is destroyed by the permanent high turbidity on the east side and by the river plumes elsewhere, (2) coral larvae reaching Maunalua Bay cannot find suitable substrata for recruitment (see Richmond, 1997), and (3) the remaining larvae are too few to replenish the impoverished populations on the west side of the bay, thereby leading to a coral and coralline algae population collapse, which in turn leads to a decrease in carbonate sediment production through bio-erosion as well as a disintegration of the dead coral and coralline algae and the formation of a smoother surface which presents less friction to waves, in a similar manner as in the Seychelles (Sheppard et al., 2005). These processes lead to sediment starvation and increased wave breaking on the coast, thus increased coastal erosion now prevalent on the west side of Maunalua Bay, which resulted in the need to armor the coast with cement and rock walls.

The model also suggests that the recovery of the coral population is hindered by the small numbers of herbivorous fishes, which are too small to significantly browse the algae.

A community group is actively promoting a return to a healthy and productive Maunalua Bay, which includes seagrass and coral restoration and recovery of fish populations. Our study suggests that recovery is a daunting task that will require an ecosystem approach involving a number of measures including (1) proper land use management in the surrounding catchment to address the issue of pollution and excess nutrients and fine sediment from land runoff (see examples in Laws and Ferentinos, 2003 and Laws and Roth, 2004), (2) recovering the groundwater storage to decrease peak stream flood flows, (3) the replenishment of the herbivorous fish population, (4) engineering measures to remove the marina-induced recirculation by cutting new outlets through the peninsula, (5) physically removing the recent terrigenous, muddy, sediment deposits on the east side of the bay, (6) re-establishment of coastal wetlands (including both fishponds and native halophytes) to trap sediments and slow freshwater discharges, (7) re-directing the Kuliouou stream to flow into Paiko Lagoon as it did historically to trap sediments and slow river plume intrusion in Maunalua Bay, and (8) physical interventions to enable the re-establishment of seagrass and corals over the present invasive algal mats.

Acknowledgements

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References

Costa, O.S., Leao, Z.M.A.N., Nimmo, M., Attrill, M.J., 2000. Nutrification impacts on coral reefs from northern Bahia, Brazil. Hydrobiologia 440, 307–315.
Cote, I.M., Reynolds, J.D., 2006. Coral Reef Conservation. Cambridge University Press, Cambridge, 588 pp.
Fabricius, K., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin, 125–146.
Godin, G., 1991. The analysis of tides and currents. In: Parker, B.B. (Ed.), Tidal Hydrodynamics. Wiley, New York, pp. 675–709.
Hitchcock, C.H., 1905. Fresh-water springs in the ocean. The Popular Science Monthly 67, 673–683.
Hunter, C.L., Evans, C.W., 1995. Coral reefs in Kaneohe Bay, Hawaii: two centuries of western influence and two decades of data. Bulletin of Marine Science 57, 501–515.
Kinsey, D.W., 1985. Metabolism, calcification and carbon production: I. System level studies. In: Proc. of the 5th International Coral Reef Congress, vol. 4, Tahiti, pp. 505–526.
Laws, E.A., Ferentinos, L., 2003. Human impacts on fluxes of nutrients and sediment in Waimanalo Stream, O'ahu, Hawaiian Islands. Pacific Science 57, 119–140.
Laws, E.A., Roth, L., 2004. Impact of stream hardening on water quality and metabolic characteristics of Waimanalo and Kaneohe streams, O'ahu, Hawaiian Islands. Pacific Science 58, 261–280.
Pollock, J.B., 1925. Fringing and fossils coral reefs of Oahu. B.P. Bishop Museum Bulletin 55, 1–62.
Richmond, R.H., 1997. Reproduction and recruitment in corals: critical links in the persistence of reefs. In: Birkeland, C.E. (Ed.), Life and Death of Coral Reefs. Chapman and Hall, NY, pp. 175–197.
Riegl, B., Dodge, R., 2008. Coral Reefs of the USA. Springer, Syracuze and Heidelberg, , 806 pp.
Sansone, F.J., Pawlak, G., Stanton, T.P., McManus, M.A., Glazer, B.T., De Carlo, E.H., Bandet, M., Sevadjian, J., Stierhoff, K., Colgrove, C., Hebert, A.B., Chen, I.C., 2008. Kilo Nalu: physical/biogeochemical dynamics above and within permeable sediments. Oceanography 21, 173–178.
Sheppard, C., Nixon, D.J., Gourlay, M., Sheppard, A., Payet, R., 2005. Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. Estuarine. Coastal and Shelf Science 64, 223–234.
Wedding, L.M., Friedlander, A.M., 2008. Determining the influence of seascape structure on coral reef fishes in Hawaii using a geospatial approach. Marine Geodesy 31, 246–266.
Wolanski, E., 1994. Physical Oceanographic Processes of the Great Barrier Reef. CRC Press, Boca Raton, Florida, 194 pp.
Wolanski, E., 2007. Estuarine Ecohydrology. Elsevier, Amsterdam, 157 pp.
Wolanski, E., Spagnol, S., 2003. Dynamics of the turbidity maximum in King Sound, tropical Western Australia. Estuarine, Coastal and Shelf Science 56, 877–890.
Wolanski, E., Richmond, R.H., McCook, L., 2004. A model of the effects of land-based, human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia. Journal of Marine Systems 46, 133–144.
Zann, L.P., 1994. The status of coral reefs in South Western Pacific Islands. Marine Pollution Bulletin 29, 52–61.