**Water Quality in Maunalua Bay: A Knowledge Domain**

Kristen Corey, Kelly Lariosa, Amy Markel, Stacey Torigoe, and Nate Wehr

**Introduction**

The State of Hawaii’s Department of Health declared Maunalua Bay to be an impaired water body (Department of Health 2006, Malama Maunalua 2009). Human activities, insufficient resources and management, a lack of education and understanding, urban planning and development strategies, and ineffective communication between stakeholders have all played a role in the degradation of Maunalua Bay (Wolanski et al. 2009). Degradation in Maunalua Bay includes reduction in water quality, erosion of beach and shoreline, decline in abundance of coral and native algae species (Malama Maunalua 2009).

Water quality measures the biological, chemical and physical attributes present in the water column including oxygen content, temperature, salinity turbidity, nutrient loading, amount of sediment, and presence of bacteria, metals and other toxins (Komoto 2008). Water quality is one of the main drivers of ecosystem health in Maunalua Bay greatly impacting ecosystem services such as fish stocks, recreational activities, aesthetic values, and transportation of sediments. Water properties are influenced by environmental, as well as anthropogenic factors present throughout the watershed. Pollution from both human and animal sources is a factor influencing poor water quality and a major cause of declining ecosystem health in Maunalua Bay (Wolanski et al. 2009).

In this study, we will identify sources of pollution by examining nutrient loads at various points throughout the Kuli’ou’ou Watershed. We will additionally address total suspended solids (TSS), turbidity, and chlorophyll, all of which are known contributors to declining water quality.
Maunalua Bay has experienced an overgrowth of invasive algae resulting from increased upstream nutrient loads, which negatively impact the health of the reef. Previously, research in Maunalua Bay has looked at mercury dynamics (Ganguli et al. 2014) and the alteration of sediment transport due to the removal of invasive mudweed (MacDuff et al. 2011). Our goal, however, is to look at the base causes of low water quality in Maunalua Bay, intending the results to determine the relationship between nutrient levels in the bay and nutrient uptake by macroalgae species. This information will inform Malama Maunalua in the development of a QAPP to further determine water quality in Maunalua Bay.

Conceptual Mapping

We designed our CMAP intending to explain the factors surrounding poor water quality in Maunalua Bay, Oahu. Given that the bay has been declared an impaired water body by the Hawaii State Department of Health, we are striving to answer the question: What are the causes and consequences of poor water quality in Maunalua Bay? Underlying water quality in the bay is a complex network of human activities and environmental responses. Following the DPSIR (Driver-Pressure-State-Impact-Response) framework, we traced anthropogenic pressures on water quality to drivers in the forms of invasive species and urbanization. We then looked at the way pressures (including increased inland erosion, freshwater plumes, and pollutants) influence water quality states (measured as indicators like turbidity, suspended solids, chlorophyll, and fecal coliform bacteria). These factors impact the health of humans and the ecology of the bay. Combined with potential responses to these indicators, we sought to capture the intricacies of water quality issues in Maunalua Bay. We made smaller maps linked to the larger water quality map to look at the intricacy of more in depth questions.
One of the main driving forces affecting water quality in Maunalua Bay is urbanization. Ongoing development and increased human activities throughout the watershed create several pressures contributing to degradation of the bay. Runoff coming from the erosion of poorly developed infrastructure and impervious surfaces is transported into the bay at high rates during heavy precipitation events due to extensive channelization creating large volume freshwater plumes. Freshwater plumes decrease salinity and carry sediments, other organic and inorganic suspended solids, and chemicals from agriculture and landscaping. Suspended solids transported via runoff increase turbidity and solids content, which hinder water clarity and directly impact the health of corals and fish. Chemical pollutants from leaching cesspools are also carried via subsurface groundwater. The accumulation of these pollutants also includes increased nutrient loads of phosphorus, nitrates, and ammonia, which facilitate the growth of both native and invasive algae. Increased nutrient loads also encourage phytoplankton growth (measured using chlorophyll concentrations as a proxy), which results in eutrophication, impacts water clarity, and is detrimental to the health of corals and fish. Humans dispose of contaminants such as heavy metals from industrial and consumer waste as well as aging water infrastructures, estrogen from birth control pills, food and beverages, as well as other pharmaceuticals and chemicals without realizing these pollutants have adverse effects on marine life. Additional pressures, such as invasive plants and feral animals, promote further watershed damage by increasing inland erosion and spreading diseases via fecal coliform bacteria generating adverse effects on the health of both humans and wildlife.

Collectively, these anthropogenic pressures have dire consequences for the biological, chemical, environmental, and physical state of Maunalua Bay and the diverse marine-life it encompasses. Water quality has many impacts directly influencing fish, coral, human, and
wildlife health. Corals are sensitive to water quality and impacted by changes in salinity, temperature, pH, turbidity, and chemicals such as estrogen and mercury carried in runoff. The entirety of Maunalua Bay provides an optimal site for recreational activities such as skiing, surfing, diving, swimming, and photography, which are also impacted by water quality.

Ongoing responses to improve water quality in Maunalua Bay include research, education and outreach to schools, residents, and business owners, community clean-up events, stormwater management, and algae removal. Stakeholders responding and taking action to ameliorate the consequences caused by the drivers and pressures are vital to the recovery of water quality in Maunalua Bay.

**Research Questions**

In our study of water quality in Maunalua Bay and the Kuliʻouʻou Watershed, we will be focusing on five primary research questions covering the topics outlined above. As is the case with much of scientific research, it is first necessary to establish the basic science behind the study system. In our case, the basic science is establishing the pattern of pollutants as they enter the watershed. We will be asking: at what point are pollutants entering the Kuliʻouʻou Watershed? We have hypothesized that the primary source of nutrients impairing Maunalua Bay will be input into the system by nearshore anthropogenic sources. As such, we predict nutrient levels will be highest near the mouth of the Kuliʻouʻou Watershed with progressively lower nutrient levels occurring both upstream and downstream of the watershed’s mouth.

Next, we intend to address potential trends in properties of water in Maunalua Bay. We are asking, what trends in nutrient loading exist in the bay based-on previous research on the watershed? We hypothesize previous data will show a negative correlation between nutrient
loads and coral reef health, and predict this will be easily recognized across each study examining the health of the bay.

In order to better understand the above questions, we are further asking what types of suspended particulates can be found within Maunalua Bay and how will this be represented by TSS? We hypothesize that suspended solids will primarily consist of sediment particles transferred by fluids due to terrestrial erosion and pollution--sediment binds to different pollutants and bacteria in the ocean, accumulates, and is continuously re-suspended through wave action; hence, resulting in a perpetual problem (Malama Maunalua 2009). We predict upstream suspended solids in the watershed will be comparable to suspended solids found in Maunalua Bay with major sources of suspended solids resulting from wastewater discharge and urbanized landscaping.

Next, our review of the nutrients throughout the watershed engages the question: how does nitrogen influence phytoplankton production in Maunalua Bay? Specifically, do nitrates and ammonia vary in relation to chlorophyll-a densities? We hypothesize that, because anthropogenic sources of excess nutrients have previously been linked to increases in phytoplankton and chlorophyll-a, increases in planktonic chlorophyll are directly linked to anthropogenic nitrogen contamination in the bay. We therefore predict a positive correlation will be shown associating between nitrates, ammonia, and chlorophyll-a.

Finally, we ask, how does nitrogen influence algal growth in Maunalua Bay and what is the greatest concentration seen in the algal species in the bay based-on species type: native or invasive? We hypothesize increases in algae growth along marine profiles indicate sources of nitrogen from anthropogenic sources in Maunalua Bay. We predict concentration of N15 to N14 will correlate with algal species in the bay, higher prevalence of algae will appear near
freshwater sources entering the bay, and more invasive algae species than native algae species will be present correlated to the increased nitrogen presence in the water.

**Proposed Methodology**

In order to establish a baseline regarding nutrient sources in the Kuli’ou’ou Watershed, we must first collect water samples from throughout the watershed. Water quality analyses will then be conducted by the University of Hawaii at Manoa’s SOEST-S Lab. Sites of water quality assessments will include: one half mile north of Kuli’ou’ou Road, the end of Kuli’ou’ou Road, near the Kuli’ou’ou Road elementary school, in Kuli’ou’ou Valley suburbs, at Kalanianaole Highway, at the Kuli’ou’ou Watershed mouth, two-hundred yards from the mouth into Maunalua Bay, five hundred yards into the bay, Paiko Lagoon, and Maunalua Bay Beach Park. Examining water quality at each of these sites will allow for a holistic summarization of pollutants in the watershed thereby allowing for the progress of pollutant build-up, and therefore sources, to be mapped at a simplistic level across the watershed gradient. If our budget (both time and finances) allow, additional samples will be collected at previously established Hawai‘i Department of Health sampling sites along the coast of Maunalua Bay.

Water will be filtered, bottled, and frozen for nutrient and dissolved nitrate isotope analyses and filtered for particulate organic matter (POC) isotope and carbon:nitrogen ratio analyses, following Derse et al.’s (2007) protocol. A nutrient flow analyzer will be used to determine nutrient concentrations of the water samples, calibrated against United States Geologic Survey standards. Nitrates, nitrites, ammonium, total phosphorus, and carbon will be included in the analyses performed. We will also determine materials constituting TSS (mg/L). Real-time turbidity data in Maunalua Bay will be obtained from the Pacific Islands Ocean Observing
system website and measured in nephelometric turbidity units (NTU). Chlorophyll-a will be measured as biomass through a fluorimeter. Temperature and salinity of the water will be taken in situ using a YSI probe. Finally, algal presence will be measured at each of these sites. All samples will be collected at low tide to create consistency. Algal tissue nutrient content (nitrogen and phosphorous) vary between species due to physiological and morphological variation, so each species analyzed separately. To prepare the algal samples, they will be dried at 50 °C to a constant weight, and then ground and homogenized using a mortar and pestle. Two milligrams of the ground samples will be placed in silver capsules and exported for mass spectrometric analysis (Derse et al. 2007).

Additionally, we will be compiling existing water quality data for Maunalua Bay by conducting a meta-analysis of existing data. Our findings will be used to identify potential trends in properties of water throughout the watershed, as well as inform decisions for future research in the bay.

**Synthesis of Knowledge**

**Sources of Pollution**

In recent years, there has been a rapid increase in the number of studies examining water quality and the sources of pollution in our streams, rivers, and oceans. When identifying these sources of pollution, it is easy to identify point-sources of pollution (Grunwald and Norton 2000). For example, we now have the ability to rapidly address factories depositing runoff into a stream creating disturbances in the ecosystems. The problem we are now facing is the accurate identification and addressing of the effects of non-point sources of watershed pollution. These non-point source pollutants generally appear in the form of nutrient influxes coming from
agricultural lands, urban/suburban centers, and from other difficult to focalize points (Grunwald and Norton 2000). Creating further problems, even once we have identified these non-point source pollutions, they are difficult to address. One solution that has seen some success is the use of vegetation buffers to prevent the influx of nutrients directly into water (Osborne and Kovacic 1993, Ouyang et al. 2009, Arora et al. 2010). However, this solution is only effective in more open areas such as agricultural zones, where establishing a buffer is feasible.

When examining suburban and urban areas, implementing a buffer zone simply is not an option. There is no space to include vegetation to catch nutrients before they enter watersheds. Exacerbating the issue, these areas are often covered nearly entirely by impervious surfaces. These impervious surfaces prevent water from entering the ground and instead cause the water to flow rapidly into streams carrying anthropogenic nutrient sources with them (Paul and Meyer 2001). The immediate entry of anthropogenic nutrients in urban centers thereby provides an important obstacle in addressing watershed health.

**Impact of Feral Animals**

Invasive ungulates, such as wild pigs, greatly impact the ecology of both upland and lowland habitats (Barrios-Garcia and Ballari 2012). Found on nearly every continent, feral pigs are regarded as one of the most widely distributed mammals in the world (Long 2003). They have been found to disrupt soils and vegetation, altering characteristics of habitats and resource availability (Crooks 2002). Soil disturbance caused by feral pigs change not only physically, but chemically and microbially as well. This soil degradation results in soil erosion, runoff, and decreased water quality (Doupe et al. 2010, Fernanda-Cuevas et al. 2010). The increased runoff caused by feral pigs has been shown to result in the increased presence of sediments and woody
debris in nearby bodies of water (Dunkell et al. 2011a). Soil runoff has even been shown to cause
elevated water acidity (Doupe et al. 2009), introduce excess nitrogen (Fernanda-Cuevas et al.
2010), and cause previously contained viruses to reappear in human drinking water (Dunkell et
al. 2011b). Additionally, these negative effects can lead to declines in the growth of local flora
and fauna (Doupe et al. 2009, Fernanda-Cuevas et al. 2010).

Kaller and Kelso (2006) found an increase in pathogens and gastropods in streams where
feral pigs were present, and streams in Australia affected by feral pig rooting were found to
contain higher amounts of nitrate (Singer et al. 1984). Conflicting information exists regarding
the effects feral pigs have on nutrient and sediment loads; one Hawaiian study found feral pigs
have no impact on total suspended solids and actually decrease runoff (Dunkell et al. 2011a),
while another found feral pigs increase the amount of total suspended solids with no effect on
runoff (Browning 2008). Efforts to mitigate feral pig impacts have included the use of fencing,
but Doupe et al. (2010) found no effect on fish and macroinvertebrate composition when
comparing fenced and unfenced lagoons. However, few studies exist examining the impacts of
fencing on downstream ecology.

Feral cats are also abundant throughout the Hawaiian Islands and are known carriers of
Toxoplasma gondii (Wallace 1973). Toxoplasmosis, the disease resulting from T. gondii
bacteria, has been reported in Hawaii since the 1950’s (Tilden 1953). Studies show that T. gondii
oocysts are able to enter marine environments via municipal sewage or storm water runoff,
which travel into downstream ecosystems (Lindsay et al. 2003). Humans and animals can both
be infected by toxoplasmosis upon ingestion of sporulated oocysts shed in cat feces (Dubey and
Beattie 1988). A study conducted on Mauna Kea, Hawaii found roughly 35% of feral cats
surveyed were carriers of T. gondii antibodies; urban cat populations in Honolulu are more
colonial than the rural populations of Mauna Kea, and therefore may spread *T. gondii* more easily (Danner et al. 2007).

**Suspended Solids and Turbidity**

Suspended solids are one of several pressures driven by human activity leading to the degradation of water quality throughout the Kuli’ou’ou Watershed. Suspended solids consist of plankton, algae, sediment, and other particles such as soot, dust, and pollen larger than two microns in size (Komoto 2008). High levels of TSS are a major cause for concern in Maunalua Bay; not only do these particles absorb heat from sunlight, but they also prevent sunlight from reaching bottom-dwelling flora (Mitchell and Stapp 1992). Consequently, surface temperature increases and photosynthesis becomes inhibited. The warmed water results in lower levels of dissolved oxygen, exacerbated by fungi and bacteria decomposing plant materials (Mitchell and Stapp 1992).

Alongside suspended solids, measuring turbidity is another key component of testing water quality. Turbidity measures the clarity or cloudiness of a liquid expressed as the amount of light scattered by material in the water (Komoto 2008). While turbidity does not directly indicate health risks, turbidity and TSS can be used as indicators of potential water pollution because metals and bacteria attach to particles (Environmental Protection Agency 2005). Wastewater discharge, poor infrastructure in urbanized areas, landscaping, agriculture, stormwater runoff, impervious surfaces, and many other sources can all contribute to high levels of suspended solids and turbidity, hence resulting in further degradation to watersheds (Komoto 2008).

While more studies regarding suspended solids and turbidity are needed to provide further awareness and understanding as they relate to upholding best management practices in
Maunalua Bay, research, clean-up efforts, and outreach by the community, fishermen, and organizations such as Malama Maunalua and NOAA have been ongoing for several years. Since investigation of the bay by Malama Maunalua began in 2006, it has been found that water discharged into the bay from channels during heavy precipitation events are released in volumes greater than the bay’s natural capabilities of processing and transporting. The suspended load, sediment particles transferred by fluids, constitutes a significant portion of TSS and is the leading land-based threat to marine organisms (Malama Maunalua 2009). Turbulence causes these sediments to remain in suspension generating repeated damage to Maunalua Bay (Malama Maunalua 2009).

Although recovery of the bay is a work in progress, policy has been developed to facilitate improvements. The Hawai‘i Administrative Rules (HAR) 11-54-4 criteria states all water needs to be free of pollutant materials including construction, earthworks, agriculture, cultivation, industrial, commercial, and/or recreational developments (Department of Health 2014). Further, the Maunalua Bay Action Plan has set long-term goals concerning polluted runoff and sediment: 1) to understand sediment transport patterns and impacts by 2009; 2) to decrease sediment and non-point source discharges at Wailupe and Kuli’ou’ou by 2016; and 3) to have all ten Maunalua watersheds participate in management planning with the goal of recovering watershed function by 2020 (Malama Maunalua 2009).

Phytoplankton

Chlorophyll-a, or phytoplankton biomass present in water, is another indicator of water quality in Maunalua Bay. Increases in chlorophyll-a are linked to eutrophication and are important indicators for links between terrestrial and aquatic ecology (Marcionilio et al. 2016).
Vegetation, land-based nutrient contamination, and local landscape ecology can all influence chlorophyll-a levels (Marcionilio et al. 2016). Eutrophication can create deoxygenated zones detrimental to coral and fish (Duprey et al. 2016). Increased chlorophyll concentrations have even been linked to decreases in fish biomass (Napiórkowska-Krzebietke et al. 2016).

Excess nutrients in estuaries may be linked to increases in chlorophyll-a. The reduction of nutrient enrichment from human activities in the Baltic Sea has been directly connected with a reduction in eutrophication events caused by algal blooms (Andersen et al. 2017). Ammonia, nitrates, and nitrites are different forms of nitrogen contamination; excess nitrates in water can be toxic to aquatic organisms (Water Quality Citizen Science Guide 2004). Nitrates in estuarine and marine ecosystems can be moved by municipal wastewater injection wells, subsurface groundwater discharge (Amato et al. 2016), or directly from surface runoff (Filippino et al. 2017). In Hilo Bay, chlorophyll-a and dissolved organic nitrogen decreased, and nitrates increased during storm events (Wiegner et al. 2013). In the James River estuary, salinity, shifts in algal species composition, fluctuations in Chlorophyll-a and biomass concentrations, and changes in nitrogen concentrations, uptake rates, and primary productivity were altered following Hurricane Irene (Filippino et al. 2017).

The watershed of Maunalua Bay has been substantially altered in favor of impermeable surfaces with streams having been transformed into channelized systems delivering large volumes of freshwater into the bay (Malama Maunalua 2009) resulting in stormwater runoff events flushing large amounts of contaminants into the bay; Laws and Roth (2004) found that hardening of Waimānalo Stream led to abnormally high nitrate levels in the estuary. Additionally, groundwater discharge contaminated with nitrates is a likely pathway for nitrogen to enter watersheds (Amato et al. 2016). In normal offshore waters of Hawaiʻi, concentrations of
nitrates and ammonia should be no more than 1 mg/L, although Department of Health standards vary by area (Water Quality Citizen Science Guide 2004).

Increased loads of land-based nitrogen and phosphorus from runoff and groundwater have been linked to adverse impacts on coral reefs (Brown et al. 2016). Changes in nitrogen isotope fractionation favoring N-15 can be used to trace groundwater contamination from cesspool leaching, fertilizer, and other human-linked runoff (Anders 2003, Amato et al. 2016). Shifts in dissolved nitrogen and phosphorus can be directly connected to changes in phytoplankton and diatom communities; for example, in the Daya Sea, increased dissolved inorganic nitrogen was associated with greater concentrations of phytoplankton (Wu et al. 2017).

In Maunalua Bay, McGowan (2003) traced increased levels of nutrients and lowered salinity to submarine groundwater discharge from beach seepage and offshore springs. More recently, Richardson et al. (2016) found high concentrations of cesspool-linked isotopes of NO$_3^-$ in submarine groundwater discharge from the Waialae West aquifer above Wailupe beach, as well as high nutrient fluxes in the Black Point region; NO$_3^-$ levels increased with proximity to the coast. The heavy urbanization that has taken place in the watershed of Maunalua Bay and its associated effects (channelization, installation of impermeable surfaces and underground septic systems) are likely sources for increased nutrients and decreased salinity in the bay that facilitate algal growth (Wolanski 2009).

Historical data from Department of Health and Environmental Protection Agency databases reveal no prior sampling of chlorophyll-a having been performed in Maunalua Bay, but a Pacific Islands Ocean Observation System probe just offshore of the marina measures chlorophyll-a continuously (Environmental Protection Agency 2005, Department of Health 2014).
Initial monitoring conducted as a part of our project and the establishment of methodology will allow for the continued quantification of human impacts on the bay. Nitrogen in Maunalua Bay, particularly nitrates and human-linked nitrogen-15 isotopes, is likely linked with chlorophyll density, since excess nitrogen has been previously associated with elevated phytoplankton biomass. If this is the case, then reduction of nitrogen use and denitrification of groundwater could potentially be methods for indirectly improving water quality in Maunalua Bay.

Nutrient Uptake by Algae

As discussed above, land-based pollutants include sediment discharge, increased nutrients, pesticides, and heavy metals, and are thought to be the leading cause of alterations to reef community structure in the Main Hawaiian Islands (Friedlander et al. 2008). Reducing pollutant load to surface water and groundwater, improving understanding of links between land-based pollution and coral reef health, and increased awareness of pollution prevention have all been identified as goals statewide (Friedlander et al. 2008). The Hawaii Department of Health has banned the development of new cesspool systems on O‘ahu and Kaua‘i. Derse et al. (2007) found that, based on the isotopic signature of nitrogen found in macroalgae, the primary source of nitrogen was fertilizer rather than domestic sewage. The relationship in nearshore areas between the major benthic species is a balancing act between primary producers, corals, turf algae, coralline algae, and macroalgae (LaPointe 1997). Reduced herbivory, a consequence of overfishing, is not the only influence on these balances between primary producers nor the only factor causing algal overgrowth (LaPointe 1997). Freshwater control is critical to support the
health of nearshore fisheries and is often contested in community legal proceedings (Vaughan and Ayers 2016).

The field of coral ecology generally accepts that algae overgrowth affects the overall health of reef environments. Some distinctions exist between turf, coralline, and macroalgal species, but because the physiology and morphology of algal species and other marine plants is complex, it is often overlooked. The onset of invasive algae replacing the native edible macroalgae species (limu) has been noted by long-term residents and has correlated with declines in coral species, previous agriculture, the development of housing and golf courses, and the aging and increase of cesspools in the area. By examining the correlation between algal species and nutrient loads in Maunalua Bay, we will help biologists further understand the complexity of relationships between marine and terrestrial ecosystems thereby aiding policy officials in making educated development plans and diminish downstream effects.

Meta-Analysis of Prior Work on Maunalua Bay

Several water quality studies have been performed for Maunalua Bay, providing a starting point for future research. Richardson et al. (2016) examined nutrient loads associated with groundwater discharge in two points, Black Point and Niu, in Maunalua Bay. NO₂ and NO₃ concentrations were found to be 3.5 times higher at Black Point than Niu. Additionally, dissolved silicate (DSi) and ammonia (NH₄⁺) concentrations were found to increase with the tide, while NO₂ and NO₃ concentrations dropped as the tide and salinity rose.

A study conducted by the US Geological Survey (2014) evaluated sediment dynamics at seven points within Maunalua Bay. They found that turbidity values varied between 0.16 and 136.57 NTU, with a mean turbidity of ± one standard deviation of 2.68±4.35 NTU. The highest
turbidity values were found during and shortly after a large storm event; this storm event introduced large quantities of terrigenous sediment into the system. Other periods of elevated turbidity occurred during periods when larger-than-normal waves impacted the bay. Interestingly, turbidity in northwestern shallow waters was higher than northeastern shallow areas of the bay. These points of high turbidity were also areas where sediment-rich, freshwater entered the bay. The report suggests two possible outcomes of the observed data: (1) sediment and freshwater inputs are greatest in the central and western areas of the bay, which impacts the fore reef by elevating turbidity values; or (2) westward transport of sediment along the northern bay’s reef flat by the northeast trade winds elevates turbidity values along the fore reef along the central and western portions of the bay. The State of Hawaii Department of Health sets the maximum allowable wet season mean turbidity level at 0.50 NTU. The mean turbidity values for the period of study at three points in the bay exceeded this threshold, and the mean turbidity value at a fourth site was barely below that threshold at 0.46 NTU.

The same US Geological Survey (2014) study identified sediment type and size within the seabed and within sediment traps placed in the seven main points in Maunalua Bay. The grain size of the seabed at most sites primarily consisted of sand, with a small amount of gravel. In the sediment traps the grain size was mostly sand, but also included a large amount of mud, suggesting that fine-grained muddy sediment was transported through the system but was unable to settle and remain on the seabed for long durations, possibly due to wave energy and current speeds. Macduff et al. (2012) found increased algal growth in the bay to cause sediment accumulation. Additionally, Wolanksi et al. (2009) found high sediment concentrations from excess runoff lead to areas of stagnation and increased residence time in the bay. The trapping of
sediment by invasive algae coupled with the slow flushing of sediment create muddy sand banks, which further degrade habitat conditions for coral reefs.

These findings demonstrate the need for further research that examines how water quality degradation impacts ecosystem services within Maunalua Bay. We will use existing data, along with our own, to draw connections between nutrient loads, sedimentation, and turbidity, and ecosystem functions.

**Reflection on Map Revision Process**

As we learned more about what causes poor marine water quality and the system of Maunalua Bay, we revisited the CMAP and made revisions accordingly. Changes to the CMAP system framework reflected the process of acquiring new knowledge about water quality, developing connections between the causes and consequences underlying water quality in Maunalua Bay, and the emergence of big-picture foci that drive water quality decline in the bay.

The initial class whiteboard map was a rough conglomeration of ideas based on a single excursion to the bay. Ideas as diverse as channelization as a driver, creating lo‘i kalo as a response to increased channelization, and storm protection ecosystem services provided by intact reefs in the bay comprised this first draft of ideas. Some concepts were condensed (i.e. recreation as photography, diving, surfing, and potentially tourism), while others were expanded (water quality). Concepts were already demonstrably interconnected; erosion was linked to water quality, dead coral, deposition of sediment, and stream health.

Pulling out key concepts from this first brainstorm session, we derived a rough draft of the system behind water quality in Maunalua Bay. This map was simplified from the class whiteboard map, but we were then able to make more detailed connections between pressures
(runoff, pollution, and sediments), states (water quality and corals), and impacts (fish stocks and recreational use). Development had already emerged as a primary driver (increasing runoff, causing pollution, and contributing to the accumulation of sediments) of poor water quality at this stage, but was difficult to distinguish because of the map structure—we were still working strictly from the DPSIR framework, and the structure was still very “boxy” as a result. “Beach structures” ended up on the parking lot, to eventually be discarded as either a primary cause or consequence of poor water quality. Continual refining was carried out at this stage, as we tried to distill the causes and consequences of poor water quality down to core drivers and responses that could line up with scientifically testable research questions.

The next map was an organic framework that evolved out of specific research questions and hypotheses that we had decided were essential to investigate as components of poor water quality. This map was also relatively simple, but with more abstract links between concepts (“urbanization” increases erosion, resulting in “suspended sediments” causing poor water quality). Responses and impacts had been eliminated for simplicity in order to focus on research questions. Algal growth degrading coral health, pollutants entering the watershed, invasive ungulates adding disease and erosion to the bay fed by invasive plants, and suspended sediments were all key components. At this stage, we still recognized “urbanization” as a key driver increasing erosion, but had not yet linked it to each of the research questions.

The next map iteration reflected the evolved complexity of knowledge that we accumulated as we sought out previous research on the bay and other background information about marine water quality causes, indicators, and consequences. “Pollutants entering the watershed” was expanded to include a variety of nutrient loads that specifically impacted algal growth and phytoplankton-linked eutrophication, as well as estrogens, heavy metals, and other
chemicals. The same nutrient loading was linked to invasive algae growth, which was broken down into native and invasive components (which had very different effects on fish and coral). “Inland erosion” became a more specific unifying concept for the effects of invasive vertebrates and impermeable surface creation. “Suspended solids” was expanded to reflect its components of phytoplankton, sediment, etc. which also drives turbidity as an indicator. We went back and forth on including water quality indicators like chlorophyll-A as a measure of phytoplankton, mg/L as a measure of suspended solids, but eventually decided that these were probably too specific to include on the conceptual map. Impacts on human health, wildlife health, coral health, recreational opportunities, and fish stocks were decided as the consequential impacts of poor water quality and linked back to causes where possible. Ultimately, “urbanization” really emerged as a key driver here, being the root cause of most detrimental changes causing poor water quality from channelization to impermeable surface creation to the increased number of cesspools leaching to the increased use of fertilizers and chemicals in the watershed.

“Invasive ungulates” and “invasive plants” undoubtedly contribute to poor water quality in the bay, and form their own reinforcing feedback loop (see Systems Animals). The direct effects of this feedback loop, however, would likely be difficult to distinguish from other sources of pollutants and sediments entering the bay. The “invasive plants” question was eventually displaced in importance by the potential ecologically disastrous impacts of excess nutrients on chlorophyll-a concentrations and eutrophication. As the effects of “invasive ungulates” became more and more diluted and difficult to distinguish because of their distance up the watershed, the research question evolved to include invasive vertebrates like cats, which added demonstrable levels of Toxoplasma gondii to watersheds, to the detriment of wildlife and people.
Revision to this very complex system was daunting. Everything was interconnected, and nothing seemed to particularly stand out as important. Upon discovering that multiple action arrows can be condensed together, we started to collapse causes and effects together, which helped reduce the multitude of arrow connections that held the map together. We started color-coding in order to track drivers and pressures, states and impacts. After initially discarding the framework and being able to add ideas and connections organically, reconfiguring the map using the DPSIR framework helped with organization and comprehensibility substantially. The subsequent revelation that we had eliminated responses somewhere along the way led to the re-addition of responses, linked to mitigation of driver and pressure components—rain gardens, for example, could reduce groundwater contamination and impermeable surface area which increases runoff. Ultimately, though, most of the responses we could come up with seem inadequate to address the core issue behind poor water quality—mitigating the impact of urbanization might prove to be an insurmountable challenge, which is perhaps what the take-home message of the current CMAP is.

The final CMAP indeed retains urbanization as a key driver of poor water quality. Most of our conceptual knowledge is well-formed at this point, and the map reflects this in relatively minor changes to wording and connection. The complexity of the issue is retained, but it is more comprehensible. Research question sectors are broken out into individual map components that are more easily explained. We focused in on the following: Impact of Feral Animals (driver), Total Suspended Solids (State), Phytoplankton Concentrations and Eutrophication (State), Non-Point Source Pollutants (Pressures), Algal Nutrient Uptake (Impact). We also outline these specific foci in smaller maps showing the nature of linkages, which is linked to the larger water quality map, which in turn is also linked to the larger map for Maunalua Bay, which addresses
the concerns of Malama Maunalua looking at the extent of livelihood dependence on the bay, how to address the poor water quality of the bay, how to better model the sedimentation of the bay, and to identify fisherman’s perspective on the removal of invasive algae on fish populations.

**Systems Animals**

Using Meadow’s (2008) systems framework, we identified two systems animals that can be found within our CMAP. The first animal to be addressed is the delays within our system. On a long-term scale, anthropogenic impacts on the nutrient load of the bay are based-off the perceived health of the bay. To describe this in more detail, runoff increases the nutrient content within Maunalua Bay creating degradation. Humans recognize this degradation and make efforts to decrease runoff, which thereby decreases nutrient content. This pattern is a balancing loop. Coinciding with this, the bats nutrient content leads to increase nutrient cycling thereby increasing the presence of algae. The increased presence of algae then decreases the nutrient contents of the bay creating a second balancing loop on the nutrient content of the bay. Having these two balancing loops beside one another creates a system with delays. These delays occur primarily because humans do not predictively respond to the nutrient load of the bay and its degradation but rather wait until the bay has already been inundated with nutrients to implement change.

A second systems animal found within our CMAP is the occurrence of shifting dominance paradigms. Shifting dominance occurs when a reinforcing loop and a balancing loop affect a single stock simultaneously. In our case, erosion leads to increased sediment loads in the bay, which leads to increased presence of algae. The increased presence of algae prevents coral
growth removing protection from shorelines leading to additional erosion. This combination of factors creates a reinforcing loop. On the opposite side of the loop, increased sediment presence causes more sediments to be exported. Once sediments are exported, more corals can grow, which traps sediments preventing corals from going. This creates a balancing loop of sediment presence in the bay. Because these reinforcing and balancing loops are in competition with one another, a shifting dominance paradigm occurs where one is more powerful than the other. Unfortunately, the recent trend in Maunalua Bay has been for the reinforcing loop of increased erosion leading to increased algal presence has been dominating causing degradation within the bay.

Exploring our CMAP further reveals several systems traps that Maunalua Bay and the residents within its watershed have also fallen into. Some examples of these traps include escalation, dependency, and rule beating. Escalation occurs when an increase in one issue leads to an increase in multiple issues. In our case, this can be seen when increased populations lead to increased urbanization leading to increased runoff causing increased sediment loads in Maunalua Bay resulting in increased degradation of the bay. Dependency occurs when one system’s growth requires change in another system. For us, this occurs when increased urbanization required increased channelization and increased presence of impermeable surfaces. These changes result in negative impacts in multiple systems due to the dependency amongst them. Finally, rule beating occurs when regulations are not adequately designed or enforced. In Maunalua Bay, this occurs when cesspools are not taken care of properly or serviced regularly leading to increased nutrient loads in downstream areas.


Browning CA. 2008. A preliminary examination of the effects of feral pigs (Sus scrofa) on water quality and soil loss within a Hawaiian watershed. University of Hawai’i at Manoa Press, Honolulu, HI.


McGowan MP. 2004. Submarine groundwater discharge: Freshwater and nutrient input into Hawai‘i’s coastal zone. University of Hawai‘i at Mānoa Press, Honolulu, HI.


