Keālia Pond and West Maui Mountains © Tony Temple

Chapter 3. Physical Environment

3.1 Refuge Introduction

Keālia Pond is adjacent to Māʻalaea Bay along the south-central part of the Island of Maui, Hawaiʻi. The Refuge is separated from the Bay on the south side by a narrow band of coastal dunes. Located within the isthmus bounded between the West Maui Mountains and Haleakalā, the Refuge is exposed to the regularly occurring trade-winds (trades) that come from the northeast and subject to the less frequent Kona (southerly) winds. Although the isthmus is less than 12 miles in length (north-south), the Refuge lies within a dry area compared to the wetter north shore.

The Refuge wetlands were formed by the combined natural action of the wind, waves, and erosion and act as a sump within the floodplain for the Waikapū watershed that drains approximately 56 square miles. This results in unique climatological and hydrological conditions that direct management capabilities.

Molokini is an eroded remnant of a tuff cone, arising from Haleakalā's southwest rift in the Alalākeiki Channel about 3 miles west of Puʻu Olaʻi on Maui's south shore. The islet reaches a maximum elevation of 165 feet. The outer sea cliffs are pockmarked with weathered holes and

shelves, and an average slope of about 73 degrees. The inner walls are not as steep with a 32-degree slope. The inner walls terminate in vertical sea cliffs above a wave cut terrace at the water's edge. The ridgeline distance between the islet's 2 northern points is nearly 3,200 linear feet and the total area is about 19 acres. Submerged remnants of the cone extend seaward in an arc from the northwest point.

3.2 Climate

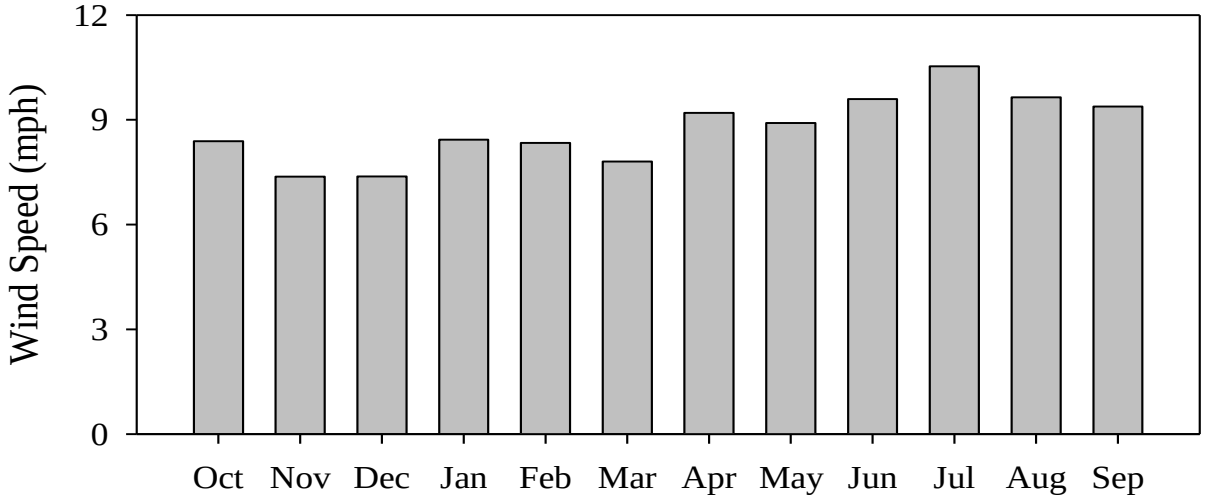
Located 2,400 miles southwest of the nearest continental landmass, the Hawaiian Islands are the most isolated archipelago in the world. The climate of Hawaiʻi is generally constant throughout the year, with only minor periods of diurnal and seasonal variability. During the summer season, temperatures are slightly warmer, conditions are drier, and trades originate from the northeast. The winter season is characterized by cooler temperatures, higher precipitation, and gustier winds. Native Hawaiians recognized only 2 seasons of 6-months each: a warm season with drier weather and more reliable trades and a cooler wetter season with more storms and fewer trades.

Modern analysis of climate records indicates the soundness of the Hawaiian system of seasons. The wet season is now considered to extend 7 months October-April and the dry season May-September. During the wet season, there may be two or as many as seven major storm events a year. Such storms typically bring heavy rains and large stream runoff into the Pond and are often accompanied by strong Kona winds that blow from the south. Rainfall and stream runoff are rare during the May-September dry season.

One of the most noticeable features in Hawaiʻi's climate is the persistent trades. The north Pacific anticyclone (high pressure area) moves south to north seasonally with the sun, and reaches its northernmost position at summer half-year. This position brings the center of the trades across Hawaiʻi during May-September. Trades are prevalent 80-95 percent of the time during this period. During October-April, the Pacific High moves south of the islands. Trades still blow across the island much of this period, but with less frequency (50-80 percent of the time in terms of monthly averages).

Maui's topography has a profound effect on wind. The funneling effect of Haleakalā and the West Maui Mountains tends to accelerate the normal trades through the isthmus of the island. Keālia Pond, being located at the south end of the isthmus, is exceptionally windy, even for Hawaiʻi, because of this effect. Data on wind speed and direction at Keālia Pond have been collected regularly since 2002, shown in Figure 3.1. Wind speeds are greatest in the summer months with July being the windiest. Wind is generally less consistent during the winter months, although there are some very windy days associated with Kona winds that blow from the south instead of the north. The timing and seasonality of winds at Keālia Pond have some important physical and biological implications that will be discussed later.

Figure 3.1. Average monthly wind speeds at Keālia Pond NWR, 2002-2006.

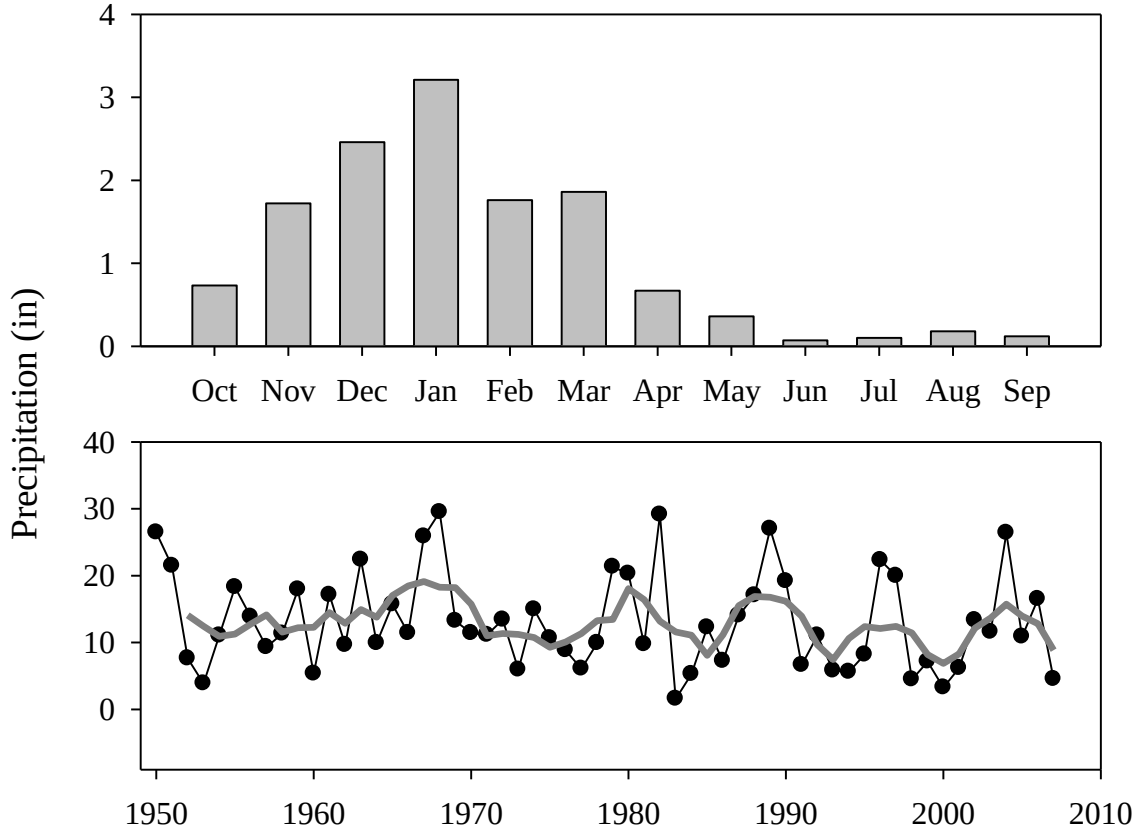


The Hawaiian Islands are broadly separated into two physiographic zones: windward and leeward, depending on the exposure to trades and associated precipitation. Keālia Pond is located in the leeward zone of the island. As a result of this and the rainshadow effect from Haleakalā, the area around Keālia Pond is arid. Tributary streams to Keālia Pond drain 56 square miles of the West Maui Mountains. Rainfall data at the Refuge has only been collected since 2000. However, there are four National Weather Service cooperative weather stations near the Refuge with rainfall data from 1950 to the present. Of the four stations, monthly rainfall at Kīhei (Station 514489) appears most similar to that measured at the Refuge, based on the period of overlapping records.

Approximately 92 percent of the total annual rainfall at the Kīhei station falls October-April. The period May-September is typically quite dry and windy in the area. Annual precipitation at the Kīhei station for the period 1950-2010 has averaged about 13 inches per year but has varied greatly from a minimum of 3 in/yr to a maximum of 30 in/yr. There has been slightly less precipitation and greater variability during the last half of the 57-year record. Figure 3.2 shows the average monthly precipitation at Kīhei from 1950-2010.

The climate is usually warm and pleasant year-round with average January daytime temperatures around 81° F and July/August averaging about 88° F. Evening lows in January average about 63° F with the summer evening lows averaging 69° F. While there is very little variation in annual temperature there appears to be an increase in the late 1970s which may correspond to the widely-recognized shift in the Pacific Decadal Oscillation (PDO) from negative to positive phase in 1977.

Figure 3.2. Annual cycle of average monthly precipitation (top) and total annual precipitation with 5-year moving average (bottom) at Kīhei, HI, 1950-2008.



3.2.1 Global Climate Changes and Projections

Global climate change is supported by a continuously growing body of unequivocal scientific evidence. The Intergovernmental Panel on Climate Change (IPCC) is a scientific intergovernmental body organized by the World Meteorological Organization and the United Nations Environment Programme in order to assess the causes, impacts, and response strategies to changes in climatic conditions. According to the Fourth Assessment Report by the IPCC, global temperatures on the Earth's surface have increased by 1.33° F over the last 100 years. This warming trend has accelerated within the last 50 years, increasing by 0.23° F each decade. Global ocean temperatures to a depth of almost 2,300-feet have also increased, rising by 0.18° F 1961-2003 (Solomon et al. 2007).

Global forecasting models offer a variety of predictions based on different emission scenarios. The U.S. Government agency Overseas Private Investment Corporation (OPIC) suggests that a further increase in greenhouse gas (GHG) emissions could double atmospheric concentrations of CO_2 by 2060 and subsequently increase temperatures by as much as 2-6.5° F over the next century. Recent model experiments by the IPCC show that if GHG and other emissions remain at 2000 levels, a further global average temperature warming of about 0.18° F per decade is expected. Sea level rise (SLR) is expected to accelerate by two to five times the current rates due to both ocean thermal

expansion and the melting of glaciers and polar ice caps. Recent modeling projects sea level to rise 0.59-1.93 feet by the end of the 21st century. These changes may lead to more severe weather, shifts in ocean circulation (currents, upwelling), as well as adverse impacts to economies and human health. The extent and ultimate impact these changes will have on Earth's environment remains under considerable debate (OPIC 2000, Buddemeier et al. 2004, Solomon et al. 2007, IPCC 2007).

3.2.2 Climate Change in Hawai‘i

Climate change impacts expected for Hawai‘i are warmer temperatures (air and ocean), more severe droughts and floods, and a rise in sea levels. Giambelluca et al. (2008) reported that air temperatures in Hawai‘i have increased at a rate of 0.3° F/decade since 1975, which is comparable to the rate of increase in global temperatures. Temperature observations at the Mauna Loa Observatory 1977-2006 indicate a warming trend of 0.4° F/decade. Rainfall intensity has increased 12 percent in Hawai‘i between 1958-2006 but total rainfall has decreased about 15 percent over the last 20 years. These changes have and will continue to affect biologic and water resources on Maui and the other islands (Mimura et al. 2007, Oki 2004, Chu and Chen 2005, Turcotte and Malamud 2009, Fletcher 2010).

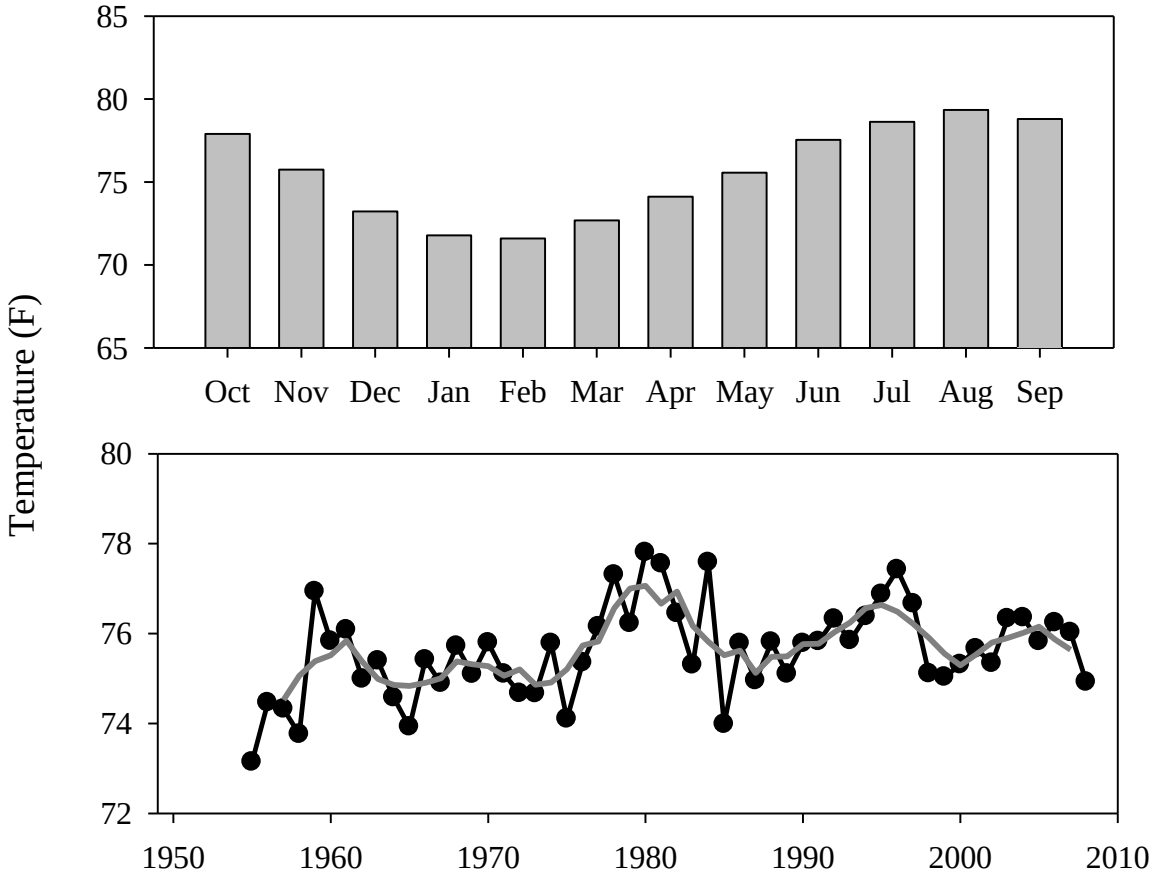
The Service is supporting the development of regional Landscape Conservation Cooperatives that will integrate local climate models with models of climate-change responses by species, habitats, and ecosystems. The local version of these Landscape Conservation Cooperatives is the Pacific Islands Climate Change Cooperative (PICCC), headquartered in Honolulu, but working across the Pacific. The PICCC was established in 2010 to assist those who manage native species, island ecosystems, and key cultural resources in adapting their management to climate change for the continuing benefit of the people of the Pacific Islands. The PICCC steering committee consists of more than 25 Federal, State, private, indigenous, and nongovernmental conservation organizations and academic institutions, forming a cooperative partnership that determines the overall organizational vision, mission, and goals.

Similar to the rest of the world, temperatures in Hawai‘i are rising. The EPA has estimated that the average surface temperature in Honolulu has increased by 4.4° F over the last century. In particular, nighttime temperatures are notably warmer, increasing by about 0.5° F per decade over the past 30 years. Recent studies have shown that this rising average night temperature is greater at high elevation sites than lower areas. Sea surface temperature near the islands has been increasing recently, showing a 0.72° F rise from 1957-1987. Sea level around the Hawaiian Islands is rising by 6-14 inches per century. Over the last 90 years, precipitation has also decreased approximately 20 percent (EPA 1998, Arakawa 2008, Giambelluca 2008).

Global and regional predictive climate simulations may not capture unique and important features of the Hawaiian climate. Existing large-scale models show large variability and uncertainty for the Hawaiian Islands; thus, applying these models to predict local conditions must be done with caution until more fine-scaled models are developed. Models from the IPCC and United Kingdom Hadley Centre's climate model suggested that by 2100 annual temperatures in Hawai‘i could increase by 3° F, with a slightly higher increase in fall. Other estimates predict a 5-9° F rise by the end of the 21st century. Future changes in precipitation are uncertain, dependent largely on shifts in El Niño/La Niña events. Some predictions forecast an additional rise of 17-25 inches by 2100, while others suggested decreased precipitation. The trend in precipitation at the Refuge, shown in Figure 3.3, has been

decreasing since 1950. The temperatures, as shown in Figure 3.3, have been on a slight rise since 1950 (TenBruggencate 2007, Timm 2008).

Figure 3.3. Annual cycle of average monthly temperature (top) and mean annual temperature with 5-year moving average (bottom) at Kahului airport, 1955 -2008.



Long-term climate change may be increasing temperature and reducing precipitation, groundwater recharge, and streamflow in Hawai‘i for extended periods. Oki (2004) looked at long-term trends in streamflow from 1913-2004 for seven streams in Hawai‘i, including three on Maui, that 1) had data available, 2) were free of upstream regulation or diversion, and 3) represented a variety of physical and climatological characteristics. He reported statistically significant declines in baseflow in all seven streams but a statistically significant decline in total annual flow in only one of the streams. These baseflow declines are consistent with a long-term downward trend in rainfall observed over much of the State during that same period and may reflect a decrease in groundwater storage and recharge. However, the author states that detection of the trends was dependent on the period of record considered. He says that the downward trends may just reflect higher than average baseflows from 1913 to the 1940s, followed by a period with little or no trend in baseflows.

3.2.3 Sea Level Rise

According to the IPCC, the oceans are now absorbing more than 80 percent of the heat added to the Earth's climate system. Since 1961, this absorption has caused average global ocean temperatures to increase and seawater to expand. Thermal expansion of the sea is the primary cause of global sea level changes. Melting ice-sheets, ice caps, and alpine glaciers also influence ocean levels. Worldwide, sea level changes have historically occurred on a small scale; however, scientific evidence suggests that the current, accelerated rate of global change began between the mid-1800s and 1900s. Similarly, sea levels in the Pacific have regularly changed over the centuries due to variations in solar radiation. Since 1800, sea levels in the Pacific region have been rising. During the last century, these levels have risen about 6 inches and this is likely to rapidly increase in the next century (Noye and Grzechnik 2001, GAO 2007).

Due to localized geographic and oceanographic variations, it is not possible to discuss SLR on a global scale. Near Pacific Island ecosystems, SLR is influenced by the rate and extent of global sea level rise, as well as changes in episodic events, such as the El Niño Southern Oscillation (ENSO) and storm-related conditions. Topography and exposure to normal and storm swell produce localized differences. Furthermore, it is important to note that shoreline sea levels are historically and currently influenced by isostatic tectonic changes as the islands move with the Pacific Plate, which are not due to global changes in sea level. Thus, sea level change in the Pacific is highly variable due to geologic uplift (Michener et al. 1997, Carter et al 2001).

Sea level rise is expected to exacerbate inundation, storm surge, erosion, and other coastal hazards. Currently, ocean waters only occasionally reach Main Pond during high tides with large waves. The frequency of these events will likely increase due to SLR. It is also likely that Mā‘alaea Beach may be more prone to erosion which may threaten habitat and infrastructure in the area.

In an effort to address the potential effects of sea level changes on national wildlife refuges, the Service contracted the application of the Sea Level Affects Marshes Model (SLAMM) 6 for several Pacific Region Refuges. This analysis is designed to assist in development of long-term management plans. The SLAMM model predictions for Keālia Pond NWR suggest that inland inundation within this Refuge will occur given SLR scenarios below 3 feet (eustatic). It is in the 3-feet scenario that rising waters begin to have an impact on the main part of the Refuge. The dry land (and beaches) between the Main Pond and the ocean, which acts as a natural impoundment against inundation, becomes heavily eroded in higher scenarios.

There is little or no tidal influence within the Refuge, however, after 3 feet of SLR salt water is predicted to move beyond the road barrier. Within this SLAMM application, a connectivity algorithm was used to determine when floodwaters are predicted to penetrate beyond the road resulting in more frequent flooding and salinity changes within the Refuge. Under the highest SLR scenarios, N. Kīhei Rd. is predicted to be regularly flooded and convert to ocean beach or open water if left as is without human intervention.

There is always uncertainty about how regularly flooded wetlands will respond to SLR. The most important effects of SLR at Main Pond and Mā‘alaea Flats are the gradual inundation and flooding of historic wetlands and dryland areas, as well as increases in the salinity of wetlands. Salinity alterations have the potential to shift aquatic plants and animal communities that do not tolerate high

salinity. Higher sea levels may inundate these low-lying land areas, potentially helping Refuge personnel to reclaim/restore former wetland areas for endangered waterbirds.

3.2.4 Ecological Responses to Climate Change

Evidence suggests that recent climatic changes have affected a broad range of individual species and populations in both the marine and terrestrial environment. Organisms have responded by changes in phenology (timing of seasonal activities) and physiology; range and distribution; community composition and interaction; and ecosystem structure and dynamics. The reproductive physiology and population dynamics of amphibians and reptiles are highly influenced by environmental conditions such as temperature and humidity. For example, sea turtle sex is determined by the temperature of the nest environment; thus, higher temperatures could result in a higher female to male ratio. In addition, increases in atmospheric temperatures during seabird nesting seasons will also have an effect on seabirds and waterbirds (Duffy 1993, Walther et al. 2002, Baker et al. 2006).

Changes in ocean temperature, circulation, and storm surge due to climate change will impact seabird breeding and foraging. The ENSO has been shown to cause seabirds to abandon habitats, nest sites, and foraging areas for colder/warmer waters. Studies have found that nesting success is reduced for some species during this climatic event. Oceanographic changes associated with ENSO may also increase or decrease food supply for seabirds and subsequently impact populations that forage offshore. Shifts in marine temperature, salinity, turbidity, currents, depth, and nutrients will have an impact on seabird and waterbird prey composition and availability. Although these potential changes may impact seabirds throughout the Hawaiian Islands, contrary evidence suggests that seabirds may have coped with and evolved around climatic changes in the past (Duffy 1993).

Warming has also caused species to shift toward the poles or higher altitudes and changes in climatic conditions can alter community composition. For example, increases in nitrogen (N) availability can favor those plant species that respond to N rises. Similarly, increases in CO_2 levels can impact plant photosynthetic rates, decrease nutrient levels, and lower herbivore weights. Although there is uncertainty regarding these trajectories, it is probable that there will be ecological consequences (Vitousek 1994, Walther et al. 2002, Ehleringer et al. 2002).

Climate change has the potential to influence two important ecological issues in the State of Hawai‘i: endangered species and pest species. The majority of U.S. endangered species are found in the State of Hawai‘i. Species declines have resulted from habitat loss, introduced diseases, and impacts from pest species. Changes in climate will add an additional threat to the survival of these species. For example, warmer night temperatures can increase the rate of respiration for native vegetation, resulting in greater competition from pest plants. Furthermore, climate change may enhance existing pest species issues because alterations in the environment may increase the dispersal ability of flora or fauna. Species response to climate change will depend on the life history, distribution, dispersal ability, and reproduction requirements of the species (DBEDT and DOH 1998, Middleton 2006, Giambelluca 2008).

3.2.5 Climate Change at at Keālia Pond NWR

Most of the anticipated climate change impacts at Keālia Pond NWR involve water supply and water quality. Tributary streams that flow into Main Pond originate in the West Maui Mountains, which is one of the wettest places in the world. Hydrologic conditions at Main Pond are largely dependent on streamflow inputs, which can be highly variable from year to year and are affected by climatic conditions and upstream regulation. Both short-term interannual climate variability and long-term decadal variability affect streamflows on Maui and the other islands. Many of the droughts in Hawai‘i are related to El Niño events, which are associated with drier than normal winters. The PDO also influences Hawaiian climate. The pattern of ocean-atmosphere variability associated with ENSO phenomenon occurs on a relatively short time scale of 1 to several years while the PDO is a longer term phenomenon occurring over 1 to several decades. Rainfall and streamflow tends to be low in winter during El Niño periods and high during La Niňa periods, especially during positive (warm) phases of the PDO. Temperature may be affected by PDO phases too. A number of studies suggest that climate change could be a major factor in accentuating the current climate regimes and the changes from normal that come with ENSO events (Mimura et al. 2007, Oki 2004).

It is difficult to assess the relative threat of long-term changes in rainfall and runoff to the Main Pond. Certainly declines in rainfall and runoff, including baseflow, would affect the water supply for the Pond. Warmer air temperatures may mean warmer water temperatures, decreased dissolved oxygen (DO), and greater evaporation. Nuisance issues of blowing dust and fish kills may also be expected to be more common. Presently, the water level record at Main Pond is not long enough to assess whether or not the frequency of dry conditions has already increased in response to warmer temperatures, increasing evaporation, and decreasing precipitation. However, any gradual, long-term changes in rainfall and stream inflow may be overshadowed by more immediate and direct changes in upstream regulation and diversion and land management practices. As will be discussed below, such changes have the potential to greatly modify Pond hydrology and ecology.

More severe flooding would also affect the Main Pond in a number of ways. They may increase the frequency or severity of disturbance in the Pond and may also increase sediment loads reaching the Pond, which could affect water quality and Pond bathymetry. More severe flooding would also underscore the hydrologic function of the Main Pond with respect to ameliorating flooding and runoff to the ocean. The Main Pond is valuable for retaining storm water and reducing the velocity of flood waters. This wetland minimizes flooding of N. Kihei Rd., protecting the road as well as allowing through-traffic during most rain storms.

The Pond and surrounding area act as a buffer, capturing flood waters and holding them before they move into the ocean (either as surface flow or subsurface seepage). The wetland also protects the adjacent beach and offshore coral reef ecosystem from deleterious effects of erosion, sedimentation, and eutrophication associated with flood waters.

Most of the islands of the northwestern end of the Hawaiian archipelago are low sand and coral islands. A foot of SLR could inundate much of the dry land of the NWHI and high islets such as Molokini will have high value for seabirds in search of new protected nesting areas above water.

3.3 Geology and Soils

The Hawaiian Islands were formed by a series of volcanic eruptions that occurred at hotspots beneath the Earth's crust. As the tectonic plate slowly drifted, magma welled up from fixed spots creating a linear chain of islands. Iron-rich, quartz-poor rock flowed out of thousands of vents as highly fluid lava.

3.3.1 Keālia Pond

The Island of Maui formed from two shield volcanoes that were close enough that their lava flows overlapped, forming an isthmus between them. The oldest volcano, now forming the West Maui Mountains, is about 5,000 feet high. The younger volcano, Haleakalā, on the east side of the island is over 10,000 feet high. The isthmus that separates the two volcanic masses is formed from sandy erosional deposits and is the prominent topographic feature for which the island is known: "the Valley Isle."

A general soil survey for Maui County, including Keālia Pond, was completed by the Natural Resources Conservation Service (NRCS) in 1972. Soils at Keālia are all classified as Keālia silt loam. This soil series is found along coastal flats throughout the island and is associated with nearly level, poorly drained soils with high salt content. Ponding occurs in low areas after heavy rains, and salts accumulate on the surface with drying and evaporation. A representative soil profile consists of a dark reddish-brown silt loam about 3 inches thick with stratified layers of silt loam, loam, and fine sandy loam below this. A brackish water table occurs at a depth of 12-40 inches. The soil has a high concentration of salts and is moderately alkaline. It is highly erosive when dry and the surface becomes loose and fluffy.

Soils profiles described at several cores collected at Keālia Pond were generally silt loams and silty clays intermixed with layers of coarser sandy loams and fine sands at depth. The water table in the cores was consistently encountered at the depth of the sand layer or in the soil horizon just above it. This suggests that coarser textured sand layers may be acting as conduits or permeable horizons for groundwater movement into, out of, or underneath and around the Pond. Reportedly there is a hardpan underlying much of the bottom of the Pond itself, which probably acts to seal the Pond bottom and minimize groundwater/surface water exchange (Smith and Medeiros 1952, Nakai and Mayer 2001).

At two sites near the historic mouth of Waikapū Stream, the presence of the sands and rounded basalts indicated that at one time the stream channel flowed with enough energy to carry and deposit such material near the Pond. Presently, the stream lacks a defined channel near the Pond and does not appear to transport and deposit such material anymore. In cores located away from the Waikapū Stream channel, the sand layer still exists at depth but the sands are finer textured and there are no rounded basalts. The more permeable soils near the mouth of Waikapū Stream result in water levels that are much flashier and more variable than elsewhere, based on water level data from piezometers installed near the Pond. There is a much larger range of water levels here as compared to elsewhere around the Pond.

The presence of permeable sand layers and/or a hardpan has implications for management proposals to excavate the Pond or construct additional impoundments. If dredging or excavation is deep enough to intersect the sand layers, this may facilitate the flow of subsurface water into or out of the Pond or impoundment, depending on local head gradients. Groundwater in some of the shallow wells around the Refuge, especially on the north shore and to the southeast, is very saline (as much as 70 parts per thousand (ppt) or more). Intersecting a deeper, permeable layer with high salinity groundwater during dredging may cause saline groundwater to flow into the Pond and may alter Pond ecology. Additionally, the presence of a hardpan layer underlying the Pond would be important to consider as well. It is not known how thick this layer is or what is below this layer but removing this impediment to drainage and groundwater movement would undoubtedly affect Pond hydrology and water quality as well.

Chemical analysis of sediments in 2001 in the Pond found high salinity. The average conductivity of 1:1 soils to distilled water mix was approximately 4 ppt salinity. The high salinity of the sediments was apparently the reason Hawaiian Commercial & Sugar Company (HC&S) abandoned plans to drain the Pond and grow sugarcane in the early part of the 20th century. The high salinity of the sediments may also be part of the reason for a lack of rooted vegetation in the Pond. The only substantial area of emergent aquatic vegetation in the Pond is the area receiving freshwater from the wells. Sediments upgradient in the stream channels are not saline, suggesting that salts are accumulating in the Pond and not being transported to it (Smith and Medeiros 1952).

All the soils and sediments are very high in phosphorus (P) (total, extractable, and water soluble) and ammonia-N but fairly low in nitrate-N. Phosphorus is commonly the nutrient limiting primary productivity in aquatic systems but Keālia seems to be naturally rich.

3.3.2 Molokini

The tiny, crescent-shaped islet of Molokini lies 3 miles offshore of Maui. Molokini is a volcanic cone that rises about 500 feet from the submarine flank of Haleakalā to a summit only 162 feet above sea level. The cone is capped by a crater 1,770 feet in diameter, although the northern rim is below sea level and the crater is flooded by the sea. It was active about 230,000 years according to an age measured from lava fragments contained in the cone. Molokini is completely exposed to trades through the Maui isthmus on its north side and easterly winds wrapping around Maui to hit its south side. Wave action is continuously eroding the islet as evident by the undercutting along the sides (USGS 2008).

Hundreds of ancient cinder cones can be found all around Maui, but Molokini is unique because it is one of the few that rose all the way from the deep ocean floor and erupted above the water. When the islands were forming, molten lava flowed beneath the surface of the ocean through porous tubes. These tubes also trapped water within their rocky structure. When magma erupts explosively in shallow water, the liquid water heats, expands rapidly, and changes to steam, adding to the eruptive force. Rock and cinder were spewed into the sky and formed a crescent shape as they fell (USGS 2008).

Shallow marine eruptions have two consequences for the appearance of the resulting cone. The first is grain size, because the ripping power of these marine eruptions leads to finer-grained deposits than in cinder cones onshore. The second is the abundance of volcanic glass, because the lava fragments

are quickly cooled by water before crystals can form. Glass is a geologically unstable material. It alters rapidly to brownish-yellow clays, giving Molokini its earthy yellow color. In contrast, cinders erupted on land are reddish and black. The Molokini deposits are basanite, a type of basalt with fairly low amounts of silicon (Si) and high concentrations of sodium and potassium (USGS 2008).

3.4 Hydrology

The hydrologic processes that occur in the Hawaiian Islands are unique compared to continental landmasses or temperate zones. Drainage basins are typically small and streams are characterized by steep longitudinal profiles and numerous waterfalls. Due to its location, Keālia Pond has historically served as a settling/deflation basin for a 56-square mile watershed extending to the West Maui Mountains. There are three major streams that are tributary to the wetland: Pōhākea Stream, Paleʻaʻahu Stream, and Waikapū Stream. All three streams are unpredictable and intermittent, some of which is due to diversions for agriculture. Wilcox (1996) reports that most of Hawaiʻi's streams are flashy, with flow rates that rise and fall rapidly in response to precipitation. Several other streams occasionally flow into the wetland from the west side of Haleakalā during very high rainfall events. Historically, these streams may have flowed into the wetland more frequently.

Hydrologic conditions vary considerably seasonally and annually. During the wet season, the Main Pond usually maintains moderate to high water levels due to increased precipitation and streamflow with a maximum Pond depth of 3-4 feet. As summer progresses, precipitation decreases, less stream water flows into the Pond, and the water levels recede. Some years, inflows are sufficiently high to maintain water levels throughout the summer. Most years, the water level begins to recede by April or May, resulting in very low water or even dry conditions in the Pond by late summer or early fall.

3.4.1 Annual Hydrologic Cycle

The information presented next is based on Pond water level data collected at Keālia's Main Pond from 1996-2006. Since June 2000, Pond levels have been recorded hourly with a datalogger. Figures 3.4, 3.5, and 3.6 show the Pond levels and monthly precipitation for water years 1996-2007. The relationship between precipitation and water levels can be observed in the figures, with wetter years and wetter times of the year resulting in higher water levels.

In most years, the Main Pond fills quite abruptly (within days) due to a combination of rainfall and runoff following the first major storm in the fall or winter. Usually, this occurs in October or November, although it has happened later, as in 2000 and 2006. Rainfall directly on the Pond is a fairly minor component of the total inflow into the Pond. The majority of inflow is from runoff and streamflow. Inflow reaches the Pond in three forms: as direct streamflow from any of three major tributaries to the Pond; as runoff and diffuse surface flow from the surrounding lands; and as subsurface flow (groundwater seepage).

Of the three main streams flowing to the Pond, Waikapū Stream is the major contributor of inflow during the wet season. Although this stream is dry much of the time, the volume of water is considerable when it is flowing. Peak flow measurements were collected annually from 1963-1997 at USGS Station 16650500 Waikapū Stream, located just upstream of the Refuge at Lower Māʻalaea

Rd. The peak flows averaged 620 cubic feet per second (cfs) and ranged from 104-1,130 cfs. Flows greater than 1,000 cfs are not uncommon in the record. Weekly estimates of flow were collected at this same site by Refuge staff 2001-2006. The maximum estimated flow recorded was 450 cfs and the site was dry about 80 percent of the weekly visits. Historically, Waikapū Stream was believed to be perennial through its entire reach but the stream was fully diverted of all but peak flows many years ago for the purpose of sugarcane irrigation (Maciolek 1971). There is presently a reservoir upstream of the Refuge on Waikapū Stream that may affect inflows to the Pond. Within the past 5 years, water rights issues have come to the forefront between environmental groups, agricultural companies, and user groups that include the Waikapū Stream. However, to date, the State's decision to return water to some of the West Maui streams has not included the Waikapū Stream.

The other two streams, Pōhākea and Paleʻaʻahu, make up a smaller fraction of the streamflow to the Pond. Weekly flow estimates of these two streams were collected by Refuge staff 2001-2006 as well. These two streams are still intermittent but flow more consistently than Waikapū Stream. Pōhākea Stream was dry an average of 50 percent and Paleʻaʻahu Stream was dry an average of 20 percent of the weekly visits. The maximum estimated flow was 94 cfs in Pōhākea Stream and 25 cfs in Paleʻaʻahu Stream. Flows in Pōhākea Stream have been greatly reduced since 2004, based on Refuge staff observations. From 2001-2004, Pōhākea Stream was observed to be dry 23 percent of the weekly visits to the stream. In 2005 and 2006, the stream was dry 92 percent of the weekly visits. The decrease is likely due to some upstream change in water or land management. Pōhākea Stream is not a major contributor of inflow to the Pond. The major effect of this change is that the area around the outlet channel of this tributary has become slightly drier.

Groundwater levels are quite dynamic and generally follow the same seasonal patterns as surface water levels in the Pond. There is large temporal and spatial variability in water table levels and groundwater salinity. However, the groundwater system appears to be only weakly connected to the surfacewater system and groundwater seepage to the Pond is a minor component of total inflow. Groundwater does not seem to influence the Pond in terms of quantity or quality, although groundwater storage adjacent to the Pond may buffer the Pond water levels to some extent.

During the wet season, inflows from rainfall and streamflow usually exceed outflows, maintaining high Pond water levels through this season. As precipitation and runoff decrease in the late spring and summer, Pond levels begin a slow, steady decline. This decline usually begins in April or May and continues unabated throughout the dry season until the fall rains begin. Water is lost from the Pond through three processes: 1) surface flows to the ocean; 2) groundwater seepage losses; and 3) evapotranspiration losses. Based on the physical constraints to surface outflow discussed below and the consistency of salinity measurements as the Pond recedes (discussed later), the primary water loss from the Pond appears to be through evaporation.

Figure 3.4. Water level depths and monthly precipitation at Keālia Pond NWR, water years (WY) 1996-1999.

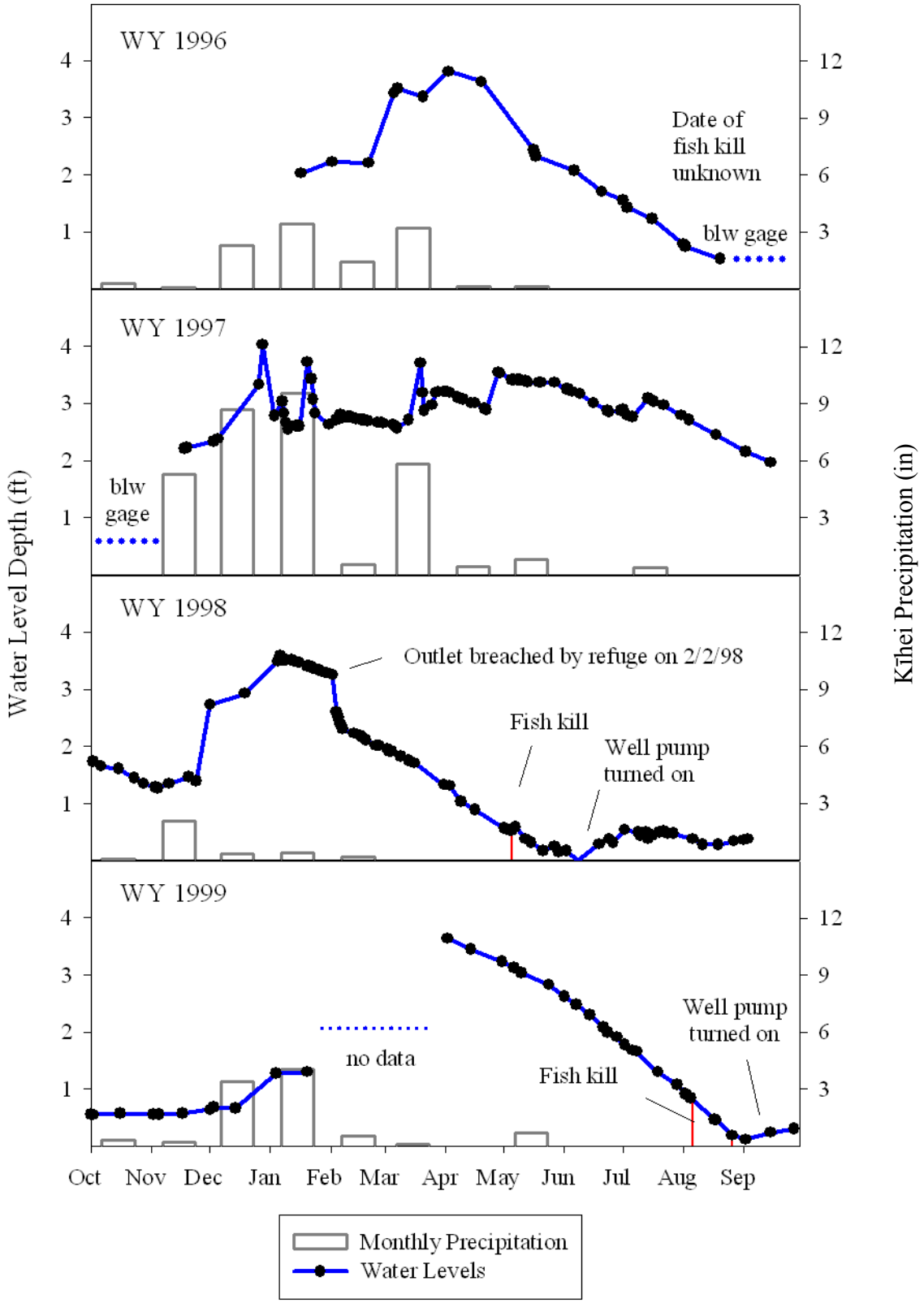


Figure 3.5. Water level depths and monthly precipitation at Keālia Pond NWR, 2000-2003.

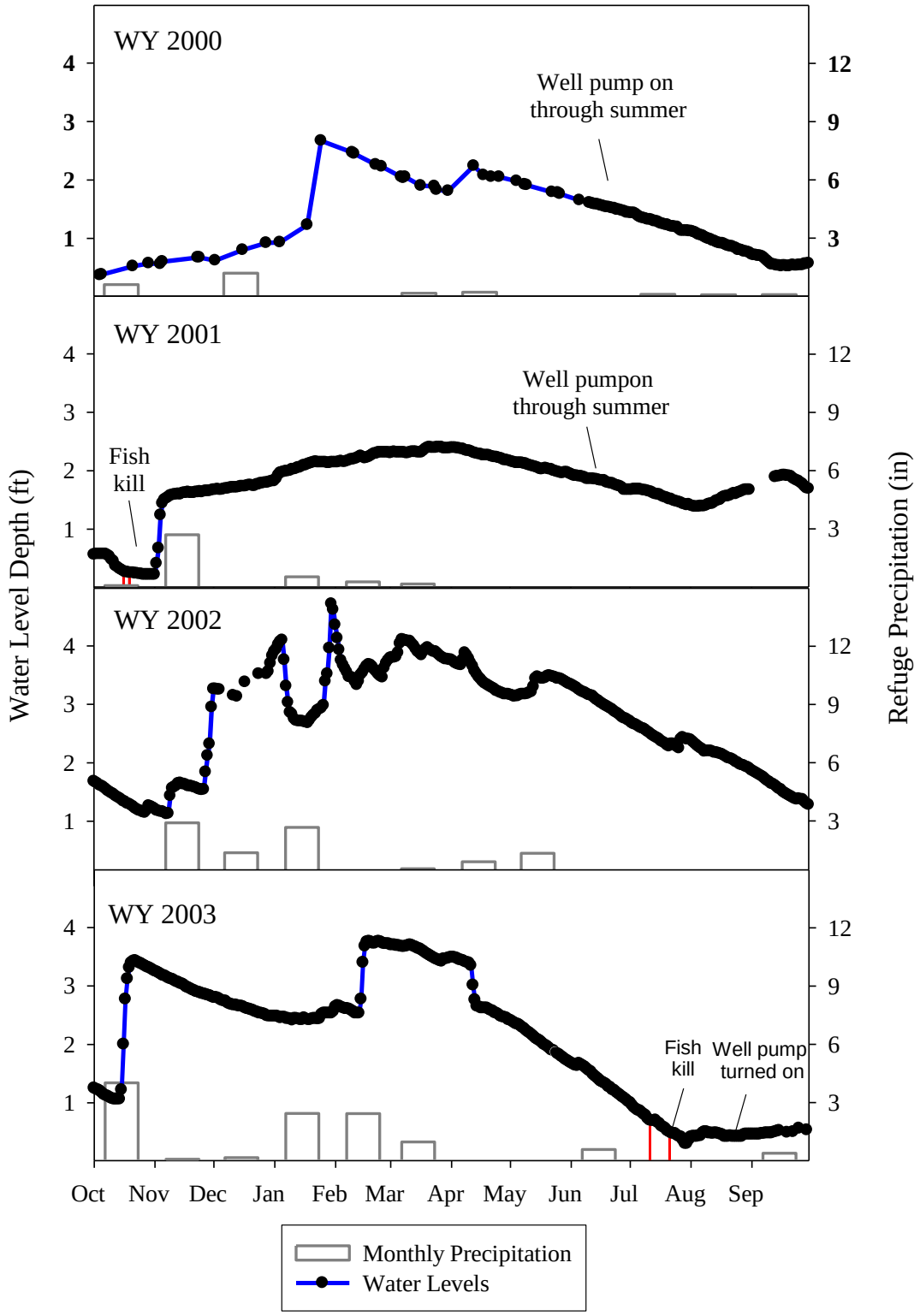
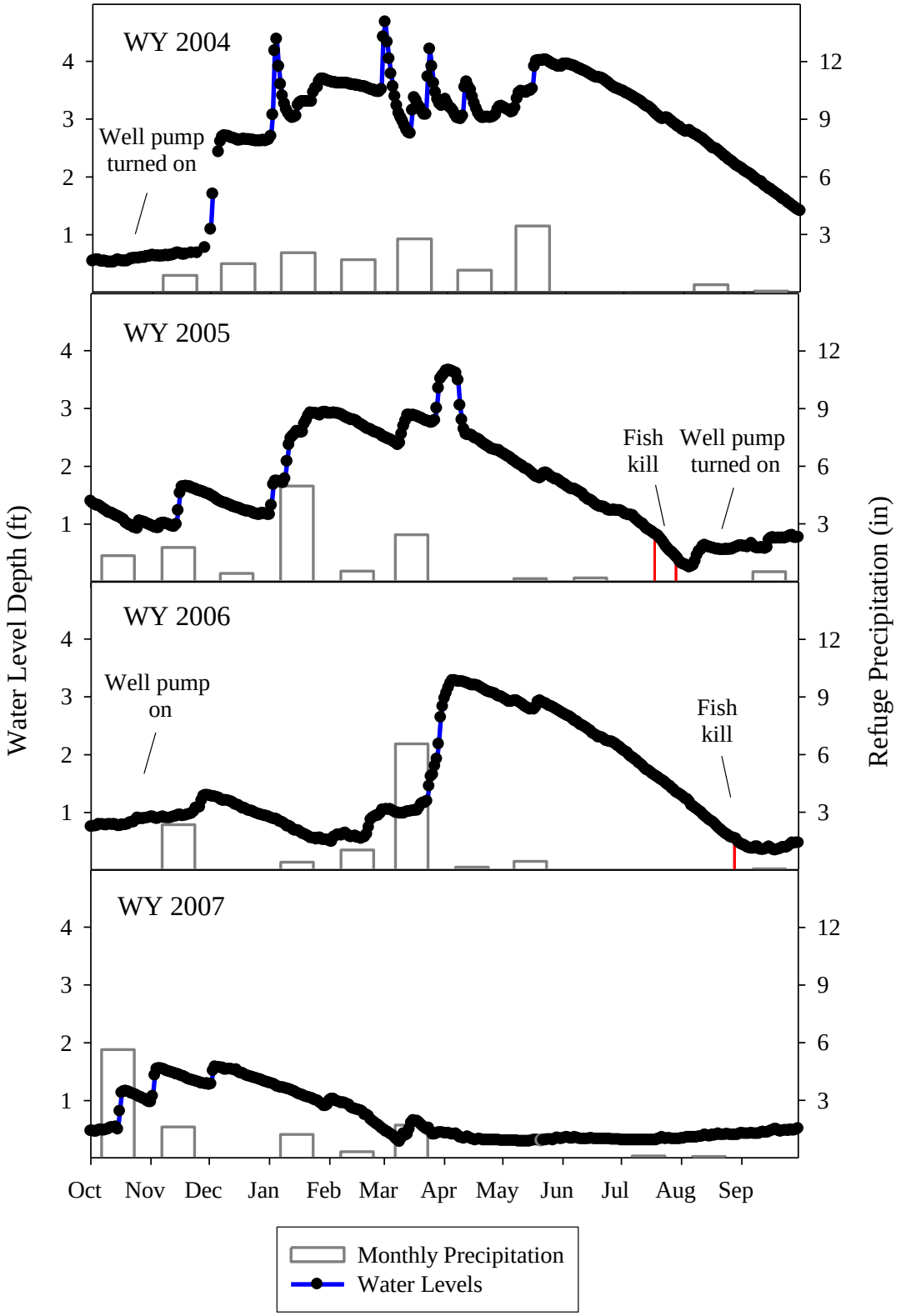


Figure 3.6. Water level depths and monthly precipitation at Keālia Pond NWR, 2004-2007.



Surface outflows to the ocean occur only occasionally in the winter at high Pond levels which are greater than 4 feet mean lower low water (MLLW). The outlet channel from the bridge to the ocean is usually blocked by a sandplug formed naturally by ocean currents and tidal action. This sandplug and the berm separating the Pond from the ocean cause water to Pond. Large rain events will raise the Pond level enough to breach the sandplug temporarily, allowing surface outflow to the ocean and resulting in a rapid drop in Pond levels. The sandplug typically rebuilds within several days. Although the water that outflows to the ocean contains some suspended sediment and organic matter, Maciolek (1971) believed that, at the time of the report, this turbidity was not severe enough to harm the Mā‘alaea coral reef community living at or to the west of the discharge point.

There appears to be a small amount of subsurface seepage through the sand beach berm and plug from the Pond to the ocean. Water can be observed to be flowing out under the bridge on N. Kīhei Rd. even when the sandplug is in place and there is no surface outflow to the ocean. This indicates the existence of subsurface seepage through the beach berm separating the Pond and the ocean. The sand substrate of the beach berm is probably more permeable than the silts and clays underlying the remainder of the Pond. The subsurface seepage outflow is estimated to be as high as 2 cfs or 4 acre-feet/day, depending on the Pond elevation. Subsurface seepage losses will be head-dependent, meaning the higher the Pond level, the greater the subsurface seepage outflow.

The elevation of the bottom of the box culvert under the bridge is 2.54 feet MLLW. As the water level recedes below this elevation, the box culvert blocks any outflow under the bridge, isolating the Pond from the area of seepage outflow. Seepage losses in other areas of the Pond are very small and, it appears that Pond outflows at water surface elevations less than about 2.5 feet MLLW are solely through evaporation. The Pond essentially acts as a closed basin as water levels recede below the elevation of the box culvert at the bridge. This has important chemical and biological implications since evaporation concentrates salts, nutrients, and other solutes, as will be discussed later.

One of the characteristics of evaporative losses at Pond levels less than 2.5 MLLW is that they are quite predictable. The rate of evaporation varies seasonally but is consistent from year to year in the absence of any significant inflows. The dry season rate of decline, without any pumping of well water into the Pond, has averaged 0.023 feet/day (0.65 feet/month), with a range from 0.020 feet/day, in 2002, to 0.026 feet/day, in 1999 and 2008 (Table 3.1). Variability in the rate of decline during the dry season appears to be related mainly to fluctuations in evaporation rates and to occasional stream inflows during the period of decline. Pumping groundwater into the Pond slows the rate of decline considerably. In 2000, the rate was 0.01 feet/day and in 2001, it was 0.008 feet/day. In both years, pumps were running fairly consistently throughout the spring and summer during the period of declining water levels. The rate of water level decline is slightly slower in the cooler wet season. In the absence of any groundwater pumping or inflows, it averages about 0.013 feet/day during the winter months and about 0.18 feet/day during spring/fall months, based on data from 2007-2008.

At the previous well capacity of approximately 700 gallons per minute (gpm), groundwater pumping slowed the rate of decline and stabilized the Pond elevation at about 1.00-1.30 feet MLLW (about 0.4-0.5 feet average Pond depth) in the summer. This elevation range represents about 50-60 percent water coverage. Above this elevation, the evaporative losses are too great and the existing well capacity cannot meet the demand.

Table 3.1. Rates of Water Level Decline for Periods with No Significant Inflow to Pond.

Water Year	Period with No Significant Inflow	Season	Rate of Pond Level Decline (ft./day)
1998	2/24-5/21/98	Winter/Spring	0.021
1999	6/23-8/26/99	Summer	0.026
2000	4/17-9/5/00	Spring/Summer	0.010*
2001	4/1-8/1/01	Spring/Summer	0.008*
2002	8/24-10/11/02	Summer/Fall	0.020
2003	5/17-7/24/03	Spring/Summer	0.023
2004	9/5-24/04	Summer/Fall	0.022
2005	5/26-8/1/05	Summer	0.022
2006	7/4-9/5/06	Summer	0.026
2007	2/3-3/12/07	Winter	0.017
2008	2/22-4/30/08	Winter/Spring	0.018
Summer Average			0.023

* Wells were pumping continuously during the summer period during 2000 and 2001. These years were not included in the summer average rate of decline calculation.

There is about 2 feet of difference between winter maximum water levels and summer minimum water levels. Maximum water levels typically occur in winter months of February -April, with mean depths of about 3 feet. Even during the dry winter in 2006, the Pond was full by April. June, July, and August levels have been quite variable, but are usually quite low in dry years. October and November have consistently been the months of minimum water elevations. Early fall storms are responsible for the higher elevations observed during October and November in some years.

3.4.2 Water Quality of the Main Pond

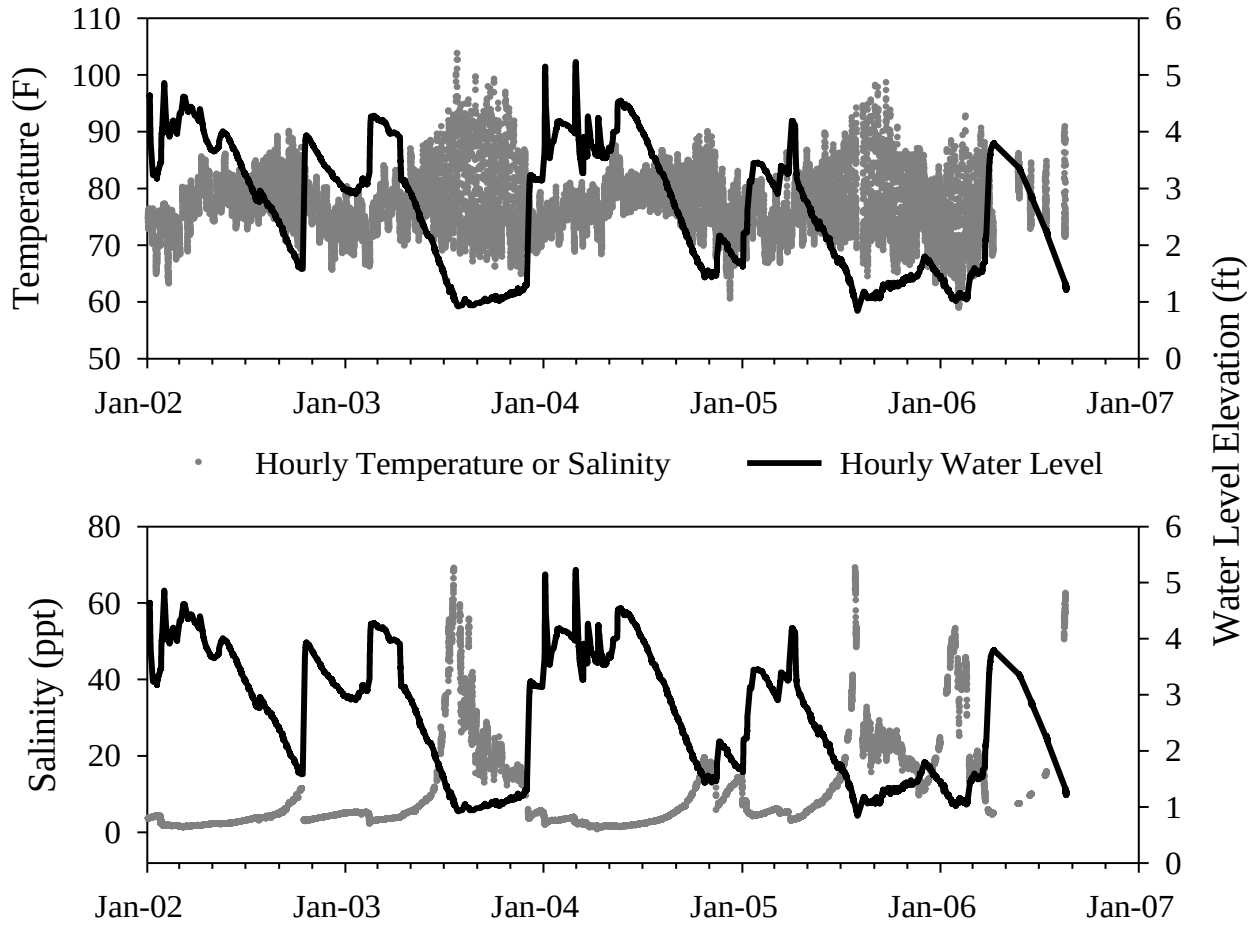
The water quality and algae information presented here is based on 5 years of monitoring at the Main Pond from 2001-2006. In general, the Pond is extremely productive and hypereutrophic, meaning chlorophyll-a concentrations greater than 100 parts per billion (ppb) as classified by the Organization for Economic Cooperation and Development. Chlorophyll-a had a median concentration of 125 ppb for the period but concentrations were greater than 1000 ppb on several occasions. Water temperatures, salinity, turbidity, macronutrient concentrations, chlorophyll- a concentrations, and algal biomass were usually greater in summer and fall at lower water levels. The Pond has a very low relative depth (ratio of depth to surface area) and flat bathymetry, and is polymictic (mixed continuously) due to the shallow depth and strong local winds. There is little spatial variability in water quality conditions in the Pond because it is so well-mixed. Water quality is strongly related to Pond water levels; this is the single most important factor affecting water quality. Pond depths and water quality are strong controls of its biota as well (OECD 1982).

Temperature

Mean annual water temperature at Keālia is 76.6° F and ranges from an average of about 73° F in winter (December-March) to 79° F in summer (June-September). This is very close to the annual average of 75.2° F predicted for water bodies at this latitude. A time series plot of hourly water

temperature and water level elevation is shown in Figure 3.7. Water temperature is strongly dependent on time of day, season, and water level depth.

Figure 3.7. Water Temperature and Salinity, 2002-2007.



Temperatures are higher and fluctuate more with shallow water depths. Daily maximums were as high as 102 °F in July 2003 and 95 °F in September 2005, when water levels were around 1.0 MLLW or less. The diurnal difference in daily minimum and maximum temperatures often exceeds the seasonal variation between winter and summer temperatures and can be as great 50 °F or more at very low water levels (Lewis 1987).

Salinity

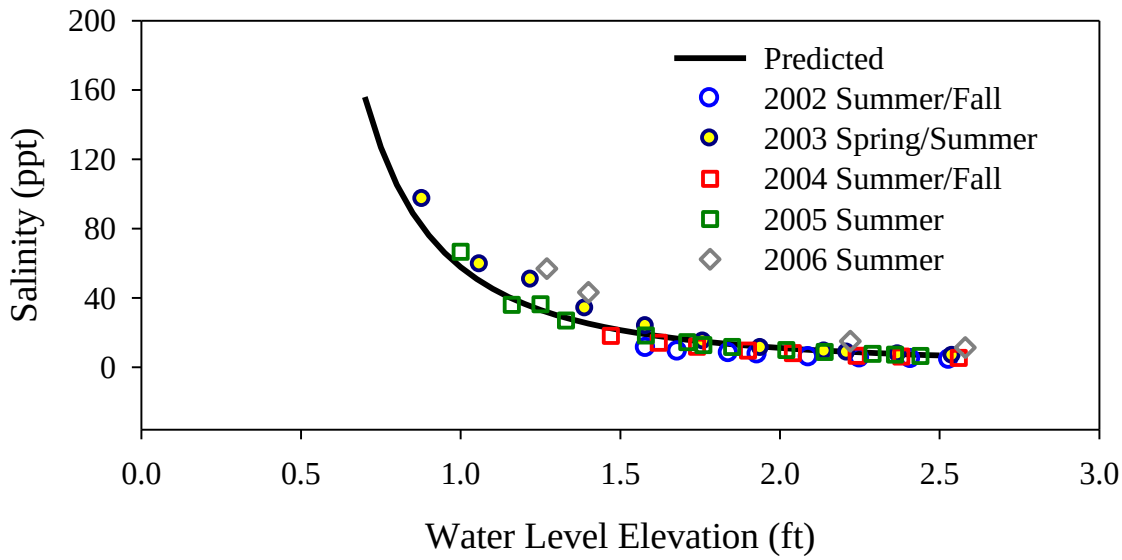
Salinity varies seasonally and interannually in the Pond, from fresh to brackish levels in winter to hypersaline levels in summer and fall. A time series plot of hourly salinity and water level elevation is shown in Figure 3.8. The range in salinity over a single season is large, from values less than 1 ppt to values of 70 ppt or more. The maximum salinities observed represent values twice as saline as sea water. This must be an extreme physiological stress on organisms living in the Pond. Given the seasonal fluctuations in salinity, it is almost certainly a strong environmental control of biota in the Pond.

The strong seasonal changes in salinity are driven by evaporation and surface inflows. Streams flowing into the Pond are characterized by very low salinity waters (about 1 ppt). With the initial fall flooding of the Pond, low salinity stream waters are mixed with residual Pond waters, usually of high salinity, to produce an initial salinity of 1-6 ppt. Salinity usually remains below 6 ppt throughout winter and spring until water levels drop to about 2.5 feet MLLW. Below this elevation, there are no longer any surface or subsurface outflows, only evaporative losses. As water levels drop below this elevation, salinity starts to increase rapidly and predictably, due to evaporative concentration of salts.

The predicted and observed salinity as a function of elevation below 2.5 feet MLLW is shown in Figure 3.7. The observed salinities were measured during the periods of no significant inflows. Most of the measured points fall close to the line of predicted values, indicating good agreement. Well water from the 2 production wells at Keālia is fresh (less than 1 ppt) so pumping groundwater into the Pond can reduce the salinity, depending on the ratio of Pond water to well water.

There is a very strong and consistent relationship between water levels and salinity in the Pond. The fact that the observations closely align with the predicted salinity assuming evaporative concentration of salts points to evaporation as being the single major outflow from the Pond at levels below 2.5 feet MLLW. Since evaporative losses from the Pond are predictable, it is possible to predict salinity in the short term as well, in the absence of any significant inflows.

Figure 3.8. Predicted and observed salinity concentration as a function of water level elevation.



Dissolved Oxygen

Like other field water quality parameters, DO varies diurnally and seasonally in relation to a number of factors. The DO concentration in the Pond results from a combination of photosynthesis, decomposition, algae biomass or organic matter concentration, temperature, water level, and mixing in the Pond. Photosynthesis of algae produces DO while respiration of algae and decomposition of organic matter consumes it. The higher the algal biomass, the greater the amount of photosynthesis, generally speaking, leading to more DO production, at least during the day. On the other hand, higher concentrations of organic matter will lead to more decomposition and consumption of DO. The diurnal cycle of DO is largely a result of the balance between photosynthesis and respiration.

A time series plots of hourly DO concentrations and water level elevation is shown in Figure 3.8. Conditions in Keālia Pond are very productive, causing very large swings in DO on a daily basis, with supersaturated DO concentrations during the day (meaning DO concentrations are much greater than equilibrium concentrations with atmospheric O) and undersaturated conditions at night (meaning DO concentrations are much lower than equilibrium concentrations with atmospheric O). Dissolved O, expressed as percent saturation, commonly exceeds 300 percent during the day and drops to near 0 at night, particularly at low water levels. The DO concentrations reached 20 ppm, the maximum measurable with our instrumentation, on numerous occasions. As with salinity, the large fluctuations in DO means that it is almost certainly a strong environmental control of biota in the Pond.

The solubility of DO is also strongly temperature-dependent, with declining equilibrium DO concentrations at warmer temperatures. Photosynthesis and decomposition are temperature-dependent, too. This means diurnal and seasonal temperature variability contributes to DO variability. At greater water depths (3 feet or more) and cooler temperatures, the range of DO is more moderate and less likely to become extremely supersaturated or undersaturated. Lower water levels have warmer temperatures, increased photosynthesis and decomposition, and greater chlorophyll- a and algal biomass, which produce a wider range of DO conditions.

Potential of Hydrogen (pH)

Like DO, pH shows diurnal and seasonal variability in response to many of the same factors. Dissolved CO_2 is the principal constituent controlling pH in the water column. The CO_2 acts as an acid in water and lowers the pH. Photosynthesis consumes CO_2 and causes pH to increase during the day, because of the removal of an acid. Respiration and decomposition produces CO_2 and causes pH to decline at night, because of the addition of an acid. Seasonal effects on temperatures and water levels will affect pH in the same way as DO, through the effects on photosynthesis and decomposition. Buffering in the Pond may moderate some of the pH swings.

The range of pH in the Pond is generally 8.0-9.5, with greater diurnal fluctuation and lower minimums (closer to 7.5) at lower water levels (about 2.0 feet or less) (Figure 3.9). The maximum daily pH is usually between about 9.0-9.5 but at lower water levels, pH exceeded 9.5 on several occasions. At very high water levels, the range of diurnal pH becomes smaller.

Turbidity

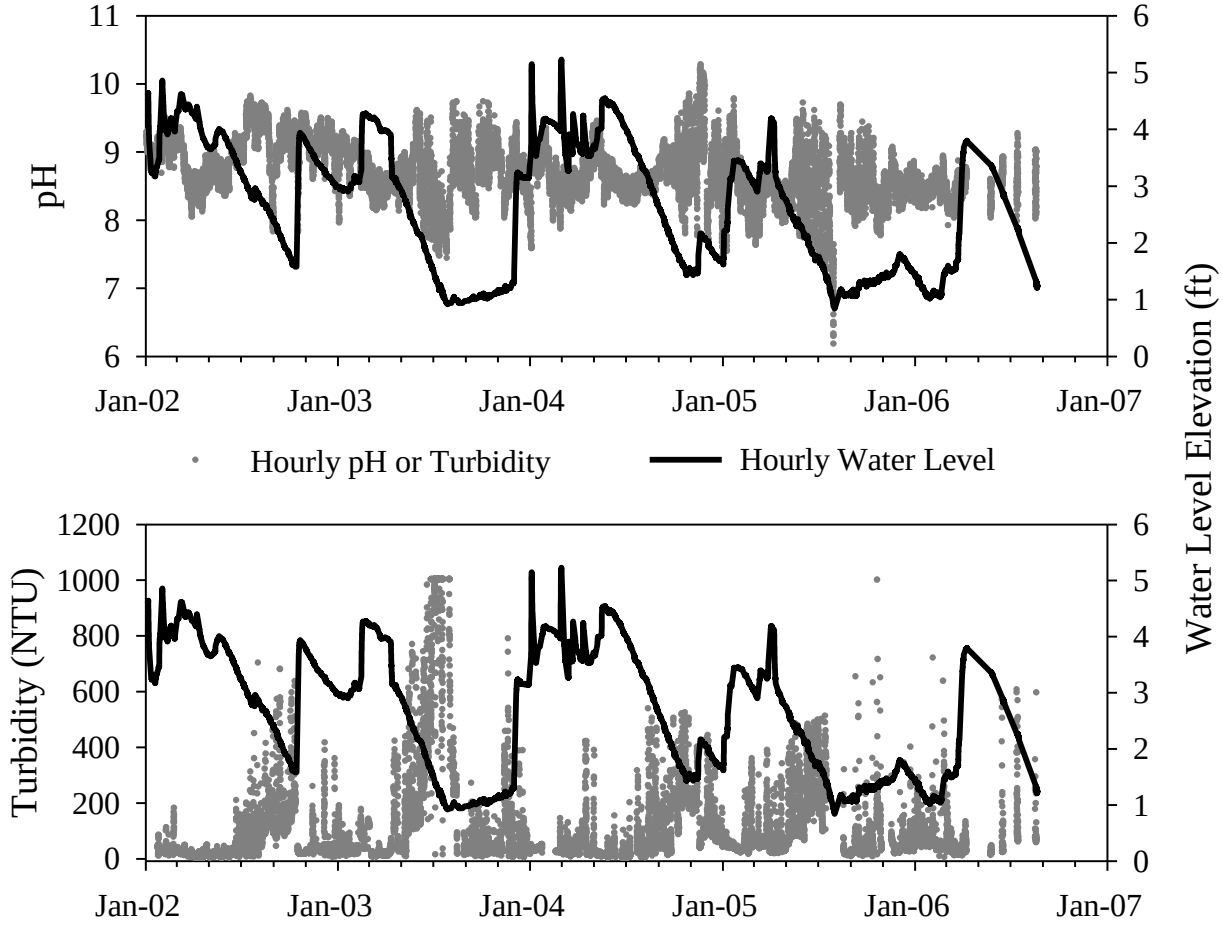
Turbidity is a measure of the amount of light scattered by suspended solids in the water column. Suspended solids have a tremendous effect on the light environment of the Pond, thereby affecting photosynthesis and primary productivity. The higher the turbidity or the concentration of suspended solids, the less light will penetrate into the water column. There is an inverse relationship between turbidity and Secchi depth (a measure of water clarity as determined by lowering a black and white disk into the water).

Turbidity in the Pond is quite variable and ranges from 0 to greater than 1000 nephelometric turbidity units (NTU), which is the maximum reading on the hydro-measuring device (Figure 3.9). Turbidity is very strongly related to water depth and wind speed. At shallow depths, algal productivity is great, increasing the biomass and solids concentrations in the Pond. Mixing depths likely extend all the way to the sediment in shallow water, which means that any particle or material that has settled can be resuspended by wind mixing. Algal biomass and total organic carbon are also important to

turbidity since these are primary sources of suspended material. As pointed out above, algal biomass increases with decreasing water levels. All of these factors mean that turbidity increases with decreasing water levels. Daily fluctuations in turbidity are correlated with the daily fluctuations in wind speed. Seasonally, mixing of settled material is more likely to occur during the dry season because of more consistent trades and lower water levels.

There are questions as to the origin and cause of turbidity and suspended solids in the Pond. Initially, we believed that suspended material was being brought into the Pond from upland areas through tributary streams. While this probably occurred in the past, it does not appear to be now. Even substantial surface storm runoff to the Main Pond rarely causes any measureable increase in turbidity or total suspended solids (TSS). There is rarely any turbidity increase associated with major inflow or abrupt water level increase in the Main Pond. This may be because the large expanse of flat, vegetated area upstream slows stream-flow and traps sediment. Conversion from flood irrigation to drip irrigation in the agricultural lands upstream in the 1970s probably reduced runoff and erosion from these areas as well. Most of the suspended material in the Main Pond now is autochthonous organic matter, meaning it is synthesized in the Pond rather than brought to it from the surrounding drainage.

Figure 3.9. Hourly pH, turbidity, and water level data at Keālia Pond, 2002-2006.



Secchi Depths

The Secchi is a small circular disk used to measure water transparency. The disk is mounted on a line and lowered into the water until it is no longer visible. The depth at which this occurs is the Secchi depth. Secchi depth measurements were made weekly or bi-weekly at the Pond from January 2004-April 2006. Secchi depths ranged from 0.05-1.4 feet and averaged 0.57 feet. Secchi depth is negatively correlated with turbidity, TSS, volatile suspended sediments, total organic carbon, and chlorophyll-a and positively correlated with water level depth, with increasing transparency and Secchi depths at higher water levels. As such, it varies with water depths , wind speeds, and algal biomass as a result of the same factors responsible for decreasing turbidity, TSS, organic carbon, and chlorophyll-a .

Macronutrients

The macronutrients P and N are both essential for algal growth and both will often control algal productivity in the aquatic environment. Total P (TP) and total N (TN) concentrations are high in the Pond (median concentrations 0.502 ppb and 4.91 ppb, respectively) but bioavailable forms (soluble reactive P, dissolved inorganic N) are very low. The median soluble reactive P (SRP) concentration in the Pond is 0.007 ppb. The median dissolved inorganic N concentration (DIN) is 0.028 ppb. Almost all of the nutrients are in particulate form, most likely associated with algae and organic matter. This is not unusual in highly productive systems where the demand for bioavailable nutrient forms is great. Concentrations of SRP and DIN do spike periodically and these spikes are almost always associated with inflow to the Pond, suggesting the surface and/or subsurface inflows are sources for bioavailable nutrient forms. The stream and piezometer sampling indicates that median concentrations of SRP and DIN are higher than the Main Pond, although median concentrations of total P and total N are lower. Surface and subsurface inflows may be important sources of bioavailable nutrients for algae.

Concentrations of TP and TN are significantly greater in the summer than in the winter. The median July-October summer concentration is 0.79 TP ppb and 7.1 TN ppb and the median January-April winter concentration is 0.37 TP ppb and 3.1 TN ppb, respectively. The higher concentrations in the summer are likely due to several factors including evaporative concentration (the same process that concentrates salts in the summer). They may also indicate a source of internal nutrient loading from the sediments or a nutrient contribution from groundwater seepage inflow. Most of the algae in the Pond are not cyanobacteria so they are not obtaining N through the atmosphere. At low water levels, total nutrient concentrations can become extremely high. Total P concentrations reached peaks of 11.2 ppb in July 2003 and 9.5 ppb in August 2005. Total N concentrations reached 45.0 ppb and 60.8 ppb during the same months. These high concentrations corresponded to the minimum water levels for the respective years.

Chlorophyll-a

Chlorophyll-a is the green pigment found in plants that allows them to convert sunlight to energy. Chlorophyll-a measurements indicate the biomass (weight) of phytoplankton in the Main Pond and its primary productivity. Keālia Pond is quite productive, with chlorophyll-a concentrations greater than 8,000 ppb observed in July 2003 and greater than 3,000 ppb in July 2005. These are extremely high concentrations and they coincide with the timing of nutrient peaks described above. Chlorophyll-a and algal biomass affect many other things in the Pond: turbidity, DO levels, pH, organic carbon, nutrient cycling, light attenuation, and possibly food resources for invertebrates and higher biota such as fish and waterbirds.

Chlorophyll-a is inversely related to Pond elevation. Lower water elevations generally correspond to periods of higher algal biomass. Light may be a limiting factor for algal growth, especially at higher water levels. While turbidity, TSS, algal biomass, and total O content (TOC) decrease at high water levels, allowing more light penetration, there is still a significant amount of the water column that is without light. Under these conditions, winds could mix algae in and out of the photic zone and thereby limit the time they spend in the photic zone.

Chlorophyll-a concentrations appear to build during quiescent periods with little water level change, especially at the lower water surface elevations (less than about 2.0 feet). Chlorophyll-a concentrations typically reach their annual peak at minimum water elevations. The high concentrations observed in July 2003 corresponded to the minimum water elevation (0.82 feet) for the year. Annual maximums in fall 2001 and fall 2002 corresponded to about 1.6 feet MLLW in both years.

Dissolved Silicon

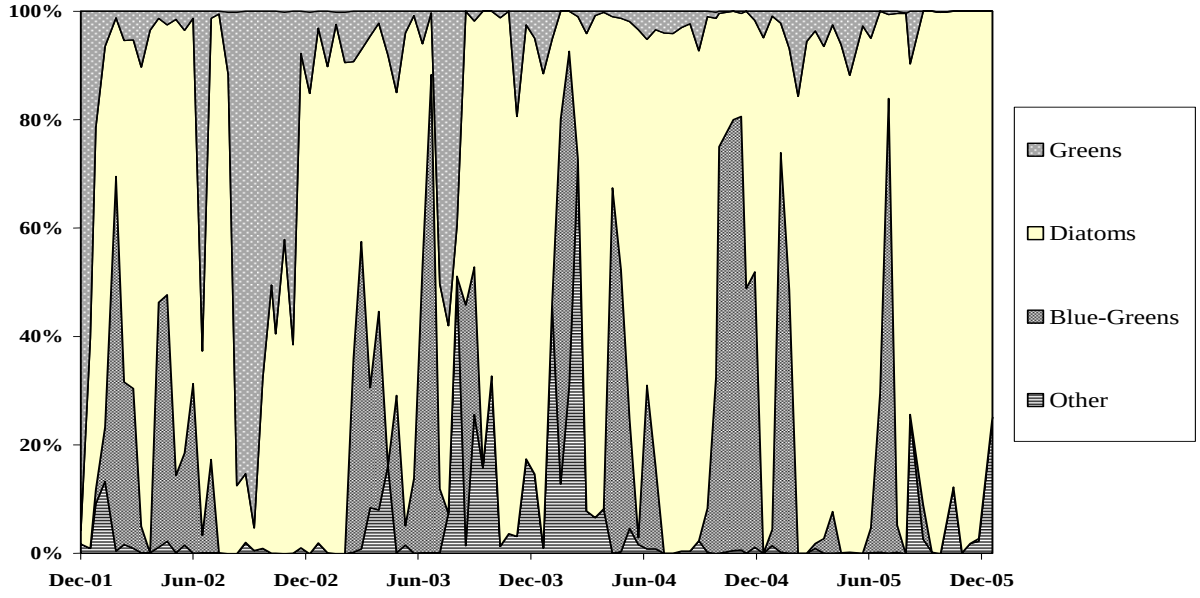
The soluble, bioavailable form of Si is soluble reactive Si (SRS). This element is an essential nutrient for diatoms, which represent two-thirds of the total biovolume of algae in the Pond. The concentration of SRS varied considerably in Keālia Pond, with a median concentration of 2.5 ppb and a range from less than 0.1-17.1 ppb. Approximately 10 percent of the water samples had concentrations below the detection limit of 0.1ppb. The concentration of SRS tended to be lower with greater diatom biovolume, but the relationship was not very strong. Other factors like water depth, light availability, macronutrient concentrations, and salinity may be controlling diatoms as well.

Algae

High salinity, sediments, turbid waters, and wind-driven waves limit the growth of any rooted emergent or submergent vegetation and favor the growth of phytoplankton in the Main Pond. Algae are responsible for most of the primary productivity in the Pond and were monitored regularly at the Main Pond from 2002-2005. The following information is based on the results from this monitoring.

The species, densities, and biovolume of algae varied considerably seasonally and interannually (Figure 3.10). There was an average of 11 species of algae. Reynolds (1994) states that nutrient-rich environments will usually have fewer niches to exploit and therefore, fewer number of algae species. The three most common algal groups were diatoms, green algae, and blue-green algae or cyanobacteria, as is common in small, highly enriched water bodies. Diatoms were the dominant group, representing an average of 67 percent of the total biovolume of algae in the Pond. Green algae were the second most dominate algal group. Generally speaking, diatoms and green algae seem better adapted to fluctuating light conditions in well-mixed waters than cyanobacteria. Being non-motile and non-bouyant, they typically occur in well-mixed waters whereas positively bouyant algae, like planktonic cyanobacteria, persist in stable waters and still, windless conditions.

Figure 3.10. Algal group biovolume as a percent of total biovolume at Keālia Pond, 2002-2005.



All of the algae in the Main Pond are generally smaller-bodied, planktonic algae, with higher growth rates and lower sinking losses. They are generally tolerant of a wide range of salinities and light environments and typically found in nutrient-rich waters. Most were non-flagellate, most were small (geometric mean biovolume is 134 um^3 per cell), and many were osmotrophic. The dominance of diatoms and other small-bodied algae may be because the Pond is continually disturbed through wind-mixing, and runoff events, causing perennial "spring-like" conditions in this system. Very shallow lakes are often arrested in a single successional stage, which explains their greater simplicity and lower degree of seasonal variation in phytoplankton communities (Lewis 1996).

3.5 Topography/Bathymetry

The area around Keālia Pond has undergone substantial changes since the 1900s. Reportedly, Native Hawaiians used the Pond for an easy supply of ʻamaʻama and oʻopu and salt was mined from the northeast shore of the Pond by European visitors. During the 1920s and 1930s, accelerated erosion from agricultural development upstream of the area likely caused a great deal of sedimentation in the Pond. Combined with the diversion of inflows, the Main Pond depth and volume were reduced substantially. Since the 1930s, it has been intermittently dry, probably due to a combination of sedimentation from the surrounding agricultural development and alteration and diversion of surface flows to the Pond (Smith and Medeiros 1952).

The apparent decrease in Pond depth and capacity has generated a lot of interest and concern about sedimentation in the Pond. One of the factors driving this concern is the dust that blows from the exposed sediments of the Pond bottom during periods when it is dry. Dry periods during summer correspond with the season of maximum wind speeds and frequencies. The blowing dust may be viewed as a potential ecological threat to the coral reefs; however, Maciolek (1971) postulated the

dust had little impact on the reefs and is less detrimental than the sedimentation from the outlet stream when all sediments are discharged at once.

An obvious concern is that the reduced depth and capacity of the Pond has resulted in an increase in the frequency of dry conditions and exposed sediments in the Pond. Several earlier studies have been focused on the question of whether or not the Pond is filling in due to sedimentation and, if so, at what rate. In the 1970s, there were three elevation surveys of the Pond and the surrounding area to address this question. These were done by the U.S. Army Corps of Engineers (USACE) in 1970, NRCS in 1972, and the Service in 1976.

In addition to the survey capacity curve, the NRCS did a sedimentation study in conjunction with an environmental assessment of the area by Maui Electric Company (MEC) at the request of the Maui Planning Commission. Based on the survey and the sedimentation study, the NRCS estimated that the capacity in 1910 was about 450 acre-feet and that there was a 55 percent loss of capacity in the Pond from 1910-1972 due to sedimentation. The corresponding Pond elevation at 450 acre-feet capacity is not stated in the report, and it is hard to compare it to other more recent capacity estimates without knowing the assumed water level elevation. Applying the 55 percent capacity loss to the 1910 estimate of a 450 acre-feet Pond means that the 1972 Pond capacity was about 200 acre-feet.

Included in the 1972 sedimentation study was an estimated sediment budget for the Pond. In 1972, the Pond was estimated to be receiving 10.5 acre-feet of sediment annually with about 5 acre-feet of this accumulated sediment lost to wind erosion and another 2.3 acre-feet lost to the Bay, leaving a net addition of 3.2 acre-feet in the Pond. The sedimentation estimates emphasize the importance of dry conditions and deflation to the Pond. The Pond acts as a settling and deflation basin maintained by wind erosion of deposited silt. If the Pond were permanently inundated, this would preclude deflation and may actually tend to channelize drainage directly to the ocean. While the blowing dust is a nuisance issue to neighboring residents, Maciolek (1971) did not believe the blowing dust is harming coral reefs offshore, pointing out that much of the material is deposited further, beyond inshore Mā‘alaea waters.

A current elevation survey of the Pond was one of the most important information needs identified by a Service workshop in 2000. In October 2000, the Service completed an elevation survey of the Pond. The results of that survey are shown in Figure 3.11 and 3.12. It is not clear that the datums for the older surveys are accurate and comparable to the newer survey information. However, if the Pond has continued to accumulate 3.2 acre-feet of sediment per year as estimated in 1972, then an additional 100 acre-feet or more of capacity should have been lost by now. This would represent a 50 percent loss of the estimated capacity in 1972, which appears unrealistically high, based on observations by Refuge staff. The current maximum surface acreage is estimated at 197.

Figure 3.11 – Elevation & Contours

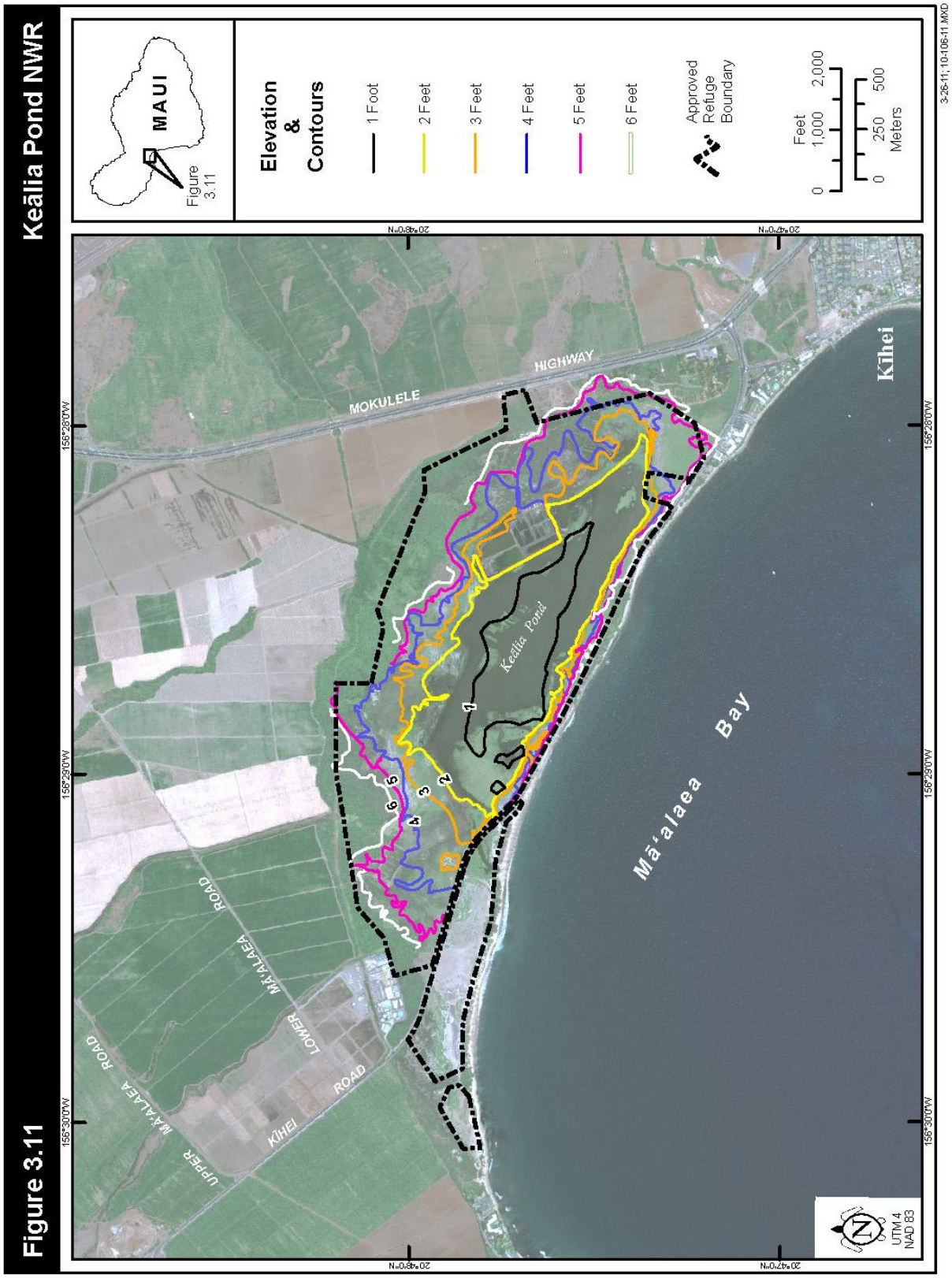


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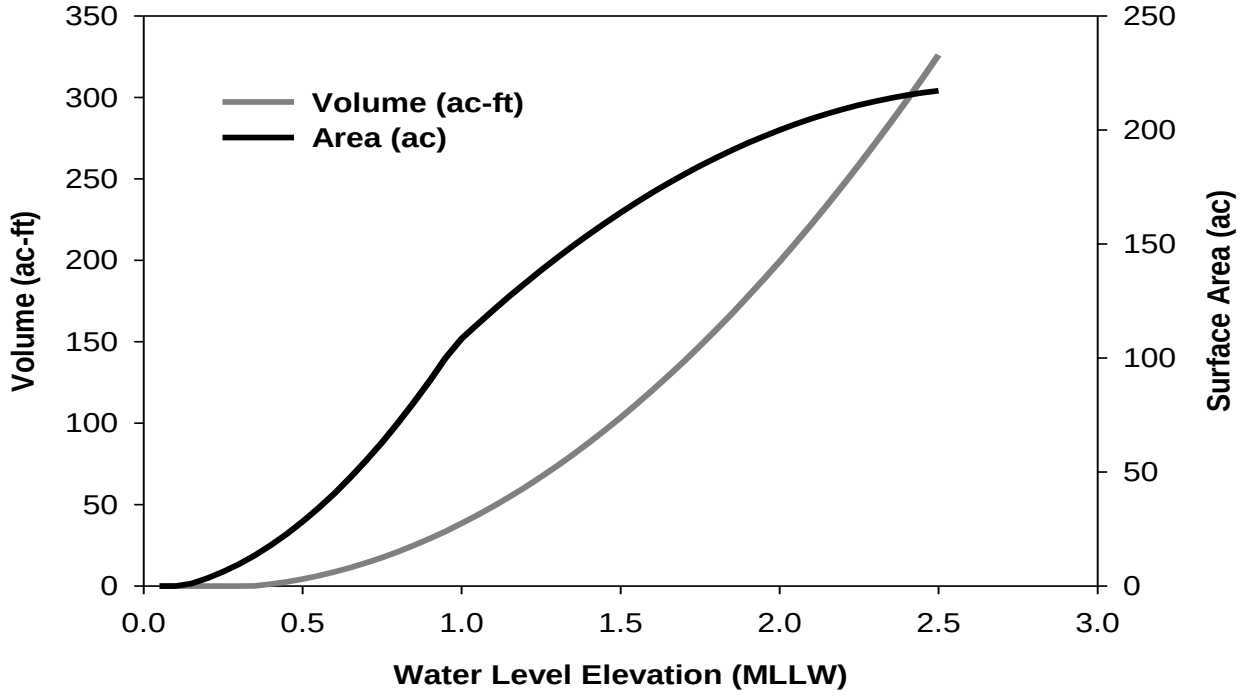
Figure 3.12. Pond volume and area as a function of water level elevation, USFWS 2000.



Changes in land use and water management upstream may have affected the sediment input to the Pond. Most of the sugarcane fields in the area were converted from furrow irrigation to drip irrigation in the 1970s. Engot and Vanna (2007) report that furrow-irrigation efficiency ranges from 0.3-0.7 while drip-irrigation efficiency ranges from 0.8-0.95. More efficient irrigation in recent years has likely reduced erosion and runoff into the Pond. Runoff through ditches from furrow irrigation may have contributed to small increase in sediment loads during non-rain events. However change in land use such cattle ranching in and adjacent to the Main Pond may have been the source of high sediment loads during rain events (Wilcox 1996).

3.6 Environmental Contaminants

A study of environmental contaminants at Keālia Pond NWR was completed in 1992, prior to its establishment as a Refuge. The purpose of the survey was to determine contaminant concentrations within and adjacent to the proposed acquisition boundary, specifically for pesticides, heavy metals, petroleum byproducts, and certain physical parameters (e.g., particle size of sediment). Given the history of the property and adjacent lands at the time, these analyses were essential in identifying the present and future quality of the wetland (USFWS 1992).

The chemical analyses for approximately 80 pesticides and related breakdown product residues were at levels below the analytical detection limits of the pesticide scan for samples within the Refuge boundary; therefore, no detectable levels of pesticides were reported for soil samples collected.

These results corroborate a 1986 contaminant survey of Keālia Pond which reported no detectable levels of pesticides, including lindane, heptachlor epoxide, heptachlor, aldrin, DDD, DDT, ametryn, and atrazine. These results suggest that soils at the Refuge are neither pervasively nor acutely contaminated with traditional persistent pesticides above analytical detection limits of the scan. These findings were unexpected given the long history of agriculture within the Waikapū watershed.

The study also included chemical analyses for 20 heavy metal compounds (mercury, lead, arsenic, cadmium, chromium, copper, nickel, selenium, and zinc) from soil samples. With the exceptions of cadmium, chromium, and nickel, the results did not indicate widespread or pervasive contamination by heavy metals within the Refuge. Detectable levels of these exceptions were thought to be due to the historical and then current use of the property by the military and aquaculture facilities (see Land Use section 3.7).

Site inspection screening was performed during this same period, concentrating in areas of historical use within and beyond the Refuge boundary, and areas used by the operational aquaculture facilities. Evidence of petroleum-based waste was observed; however, the sources were identifiable. These sites included areas around the old Maui airport at Mā‘alaea Flats along with over 40 abandoned vehicles, and household and industrial items. Many of these sites were beyond the final boundary delineation; however, they remain in the wetland within a much larger watershed and pose a potential risk to wildlife and habitat. Following the contaminants survey and prior to the acquisition, most of the potential contaminant sites had been remediated by the landowner (A&B) or their tenants.

The aquaculture facility was in operation in 1992 and was also evaluated for contaminants. Unlabeled bags, bottles of chemicals, and oil patches in and around the former laboratory were observed. These were cleaned up or removed by the County of Maui in accordance with their lease agreement with A&B. The MEC surveyed their pole-mounted electrical transformers within the Refuge and replaced one transformer that contained regulated levels of polychlorinated biphenyls (PCBs). Currently, all transformers within the Refuge contain non-PCB fluid.

The Refuge will always be subjected to activities occurring in the upper watershed, thus it is beneficial to periodically re-evaluate the soils. For this reason, a contaminants study was conducted in 2001 to determine contaminant levels in superficial sediments throughout the Pond and streams that supply runoff and assess potential hazards to aquatic biota. Of the 129 possible contaminants, 12 tests resulted in detectable levels of organic contaminants (polyaromatic hydrocarbons, acetone, and methyl chloride). Polyaromatic hydrocarbons result from emissions of gasoline engines and municipal incinerators; whereas volatile organics (acetone) result from domestic and industrial solvents as well as emissions of gasoline engines. Although organic contaminants were detected in sediment samples, none of these contained concentrations above effects levels (Kilbride 2002).

Endangered waterbird and migratory bird tissue is sampled only when dead birds are retrieved from the wetland and submitted to the USGS National Wildlife Health Center in Honolulu. Aside from testing for avian diseases, the tissue is analyzed for lead. To date, lead has not been detected in birds from the Refuge. A small sample (10) of live tilapia was collected from Keālia Pond in 1999 to test for organic contaminants. Results indicated no detectable levels in the tissue. The fish in the Pond have yet to be sampled for metals but will need to be prior to consideration of any public fishing program.

Changes in upstream land use and presence of agricultural fields since the early 1900s have resulted in deposition of sediments within the soil profile of the Pond. The potential for contaminants entering into the Refuge will continue to be a concern and requires periodic monitoring to prevent accumulation into the habitat and wildlife species.

3.6.1 Molokini Contaminants

The USACE has designated Molokini and 157 acres of the surrounding waters as Unexploded Ordnance Removal, Formerly Used Defence Site, and confirmed the site has munitions and explosives of concern originating from military activities. The Navy was tasked to conduct a surface survey of Molokini. Two site surveys conducted in December 2006 and March 2007 found three ordnance items that had to be disposed of prior to the turnover of islet: a 250-pound old-style bomb, a 105mm projectile, and a 5-inch rocket with 3.25-inch motor. These items were destroyed in place.

3.7 Land Use

A diversity of land uses occur in the vicinity of Keālia Pond NWR, a majority of which is agriculture. The towns of Kīhei and Māʻalaea are nearby the Refuge to the east and west, respectively. One of the two power plants operated by the MEC borders the Refuge to the west. The Waikapū watershed, beyond the Refuge boundary, has residential and commercial development.

Since the early 1900s, sugarcane has been the predominant crop cultivated within the lower sections of the watershed and the fields surrounding the inland margins of the Refuge boundary. The three channelized streams that feed into Keālia Pond from West Maui Mountains have been diverted to irrigate the sugarcane fields creating minor flow to the ocean. Agricultural activities over the years have drastically altered the landscape of the watershed through excessive vegetation clearing and subsequent downstream sedimentation (Maciolek 1971, USFWS 1978).

The HC&S operates the only sugarcane plantation in Maui County and Hawaiʻi as a whole. The HC&S owns the 34,900-acre plantation surrounding Keālia Pond and produces over 172,000 tons of raw sugar annually. In addition, HC&S employs over 900 Maui residents. Currently, the company is researching new commercial uses of sugarcane, including alternative fuel (Maui County 2009).

On the northwest side of the Refuge boundary is the MEC's Māʻalaea Power Plant. The company's high voltage electric transmission line runs from the Māʻalaea Power Plant east towards Kīhei, between the Refuge's north boundary and the sugarcane fields.

The Puanani o Kula nursery, operating since 1989, is adjacent to the Refuge's east boundary. This landscaping operation grows both native and exotic plants on land leased from A&B. The KNUI radio transmitting facility is also located on their property.

The closest town to the Refuge is Kīhei, with condominiums starting across the eastern side of the Refuge along Māʻalaea Bay. Occupants of these buildings include full- and part-time residents and vacationers. Constructed in the early 1970s, the largest condominium is Sugar Beach Resort with

more than 200 units. Continuing east, S. Kīhei Rd. follows the shoreline with commercial development (resorts, condominiums, businesses) and residential housing.

A couple of transportation corridors are adjacent to the Refuge. Mokulele Hwy. is 6.5 miles in length and situated north-south, connecting the towns of Kahului and Kīhei. The Refuge's entrance road is off this four-lane highway. The south boundary is bounded by N. Kīhei Rd. that bisects the Refuge from Mā‘alaea Bay. This two-lane highway separates Keālia Pond (open water Pond and flats) from Mā‘alaea Flats. The coastal property parallel with N. Kīhei Rd. is narrow, approximately 1.25 miles long, and owned by A&B from the road right-of-way to the high water line. This property continues westward to the Mā‘alaea community along the south boundary of the Refuge's Mā‘alaea Flats.

Land use beyond the Refuge's boundary includes the community of Mā‘alaea, located more than 3 miles west of the Refuge. This area is primarily condominiums adjacent to Mā‘alaea Harbor (developed in the 1950s) where numerous tour boats are docked. A new residential community at Mā‘alaea (Ohana Kai Village) is currently under construction and will include 1,100 single-family homes within 257 acres at the intersection of N. Kīhei Rd. and Honoapi‘ilani Hwy. and adjacent to Pōhākea Stream. A rock quarry and construction dump site is also located at this intersection on the southwest side of Pōhākea Stream.

The former Naval Air Station (NAS) Pu‘unēnē is less than 1 mile northeast of the Refuge and topographically directly upgradient. This area is currently used for drag racing and is behind the National Guard's training center off Mokulele Hwy. Further up the gradient within the Waikapū watershed, beyond the sugarcane fields, is the town of Waikapū consisting of residential and commercial development. Area above the town's housing is too steep for development.

3.7.1 Previous Land Uses

The first Maui airport was constructed at Mā‘alaea Flats in 1929. On November 11, 1929, the first scheduled air service from Honolulu to Maui was inaugurated. Planes used were eight-passenger Sikorsky S-38 Amphibians. Mā‘alaea Airport was a level dirt field and was unusable in wet weather. In 1935 the Inter-Island Airways began adding 16-passenger Sikorsky S-43s to its fleet; however, the field was too small and too close to the mountains to meet desired safety criteria. Due to these safety concerns, the airport was moved to Pu‘unēnē, a few miles north of the Refuge. Evidence of the paved runway from this former airport, now almost completely obscured by vegetation, can still be seen in the Mā‘alaea Flats, beyond the Refuge boundary. A number of small concrete pads or foundations are in the vicinity of the airport runway. Two large concrete foundations, approximately 100 feet square, are on the west of the former runway (USFWS 1992).

During World War II (WWII), the military used Mā‘alaea Flats for training activities. A concrete wall, approximately 100 feet long and 15 feet tall, oriented parallel to the shoreline with soil piled up to the top of the wall on the mauka side. The 1954 USGS Mā‘alaea Quadrangle refers to this structure as a "Sea Wall". Longtime local residents remember this structure as a gunnery range used by the Marines for military training. The Navy used Molokini for target bombing practice because its size and shape was somewhat similar to a battleship.

Anecdotal information implied a potential landfill was located in Keālia Pond; however, the County of Maui Department of Public Works, whose file information on landfills begins in the late 1960s, has no information on this possible landfill. In addition, this landfill could not be located during the preacquisition contaminants survey conducted in 1992. Mink (2000) mentions the use of the area as a rubbish dump between 1925 and 1930 but there is no official record of this use. It is probable that illegal dumping of residential and commercial waste did occur, however.

In 1970, Fish Farms Hawai‘i leased 25 acres of land on the northern boundary of the Main Pond to harvest Malaysian prawn (*Macrobrachium rosenbergii*). Pacific Aquaculture Corporation purchased this commercial operation in 1972 (Shallenberger 1977). Due to poor water quality, prawn aquaculture ceased and Pacific Aquaculture Corporation began generating approximately 100,000 pounds of catfish (*Ictalurus punctatus*) annually. Cultivation of a catfish species (*Clarias* sp.) began in 1984 after Pacific Aquaculture Corporation sold the facility to Maui County. When Keālia Pond NWR was established in 1992, the aquaculture facility was called Keālia Fish Farm, Inc. This facility stopped operations on September 30, 1995, and Keālia Fish Farm, Inc. officially closed on December 31, 1995. The Refuge still uses these ponds; however, they have been redesigned for waterbirds and access by the public. In 2005 the Refuge hired a contractor to redesign the old Keālia Fish Farm ponds for bird use and installed water distribution lines.

On the west side, near the Mā‘alaea Power Plant, Maui County funded a project in 1978 to provide an alternate source of baitfish for the aku fishery. The project raised Cuban molly along with ‘ama‘ama (striped mullet) and ‘awa (milkfish). Funding for the project ended in 1987. The ponds were partially restored 1990-1998 when a County-funded program used the area. These small ponds (still called the Baitfish Ponds) are within the Refuge and managed for endangered waterbirds. In 2007, the Refuge combined the original six small ponds into one wetland management unit and installed a pump on the existing sump to flood the Pond, as needed. Use of the area within the Refuge boundary for cattle is evident from kiawe posts, barbed wire in forested habitat, and water troughs but the period in time is unknown (DeLeon 1987).

Molokini navigation aid beacon
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3.7.2 Molokini Land Use

Molokini was withdrawn from lands ceded by the Republic of Hawai‘i to the United States of America and set aside by Territorial Governor W. F. Frear on September 13, 1910, to be administered by the USCG for lighthouse purposes. In 1911, a 16-foot-tall tower was erected on the southwest rim of the crater where it had a focal plane of 173 feet above the water. Rabbits were introduced some time around 1915 but apparently died out on their own by the 1960s.

In 1925, the Molokini light tower was replaced by another tower 187 feet above the water. This second light marked Molokini for 22 years until it was replaced in 1947 by another tower, which displayed an electric light powered by batteries stored in a shack built inside the base of the tower. In April of 1989, a powerful storm toppled the 1947 tower and sent it tumbling down the crater. The USCG erected a temporary beacon and later the metal pole and

solar-powered Aids to Navigation System light that they currently maintain on the islet (Dean 1991).

The marine environment surrounding Molokini, beginning from the high water mark at the islet shorelines to depths of 180 feet (30 fathoms), has been designated by the State of Hawai‘i as the Molokini Shoal Marine Life Conservation District, managed by DLNR and further included in NOAA’s Humpback Whale National Marine Sanctuary.