HYDROLOGIC FEASIBILITY ASSESSMENT REPORT

MANA PLAIN RESTORATION PROJECT

Kauai, Hawaii

Prepared For:

Mana Plain
Wetland Restoration Partnership

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FLOW RATE RELATED CONVERSIONS

KNOWN	SYMBOL	MULTIPLIER	PRODUCT	SYMBOL
Feet per day	(ft/day)	0.5	Inches per hour	(in/hr)
Acre-feet	(AF)	325,851.0	Gallons	(gal)
Million gallons	(MG)	3.07	Acre-feet	(AF)
Million gallons per day	(MGD)	1.121	Acre-feet per year	(AF/yr)
Gallons per minute	(gpm)	1,440.0	Gallons per day	(gpd)
Cubic feet per second	(cfs)	448.8	Gallons per minute	(gpm)

1.0 INTRODUCTION

This report was prepared by Kamman Hydrology & Engineering, Inc. (KHE) and presents the results of a hydrologic feasibility assessment for the Mana Plain Wetland Restoration Project proposed by the State of Hawaii Department of Land and Natural Resources (DLNR), Division of Forestry and Wildlife (DOFAW). The study was completed under the direction of the Mana Plain Wetland Restoration Partnership[1] and pursuant to the scope of work presented in their December 18, 2009 Request for Proposals.

1.1 Description of Project Area

The Mana Plain is located on the west side of the island of Kauai, within the county of Kauai. Historically the “Mana Swamp” encompassed 1500–2000 acres of seasonally, semi-permanently, and permanently-flooded wetlands. It has been described as “a great swamp full of Nekes or bulrushes” (Knudsen, 1991) that supported thousands of waterbirds including endemic Hawaiian waterbirds and migratory ducks (Henry and Ryder, 2008). In the late 1800’s, portions of the Mana Plain wetlands were developed for rice production (Faye, 1997). Between 1910 and 1959 the “Mana Swamp” was drained for the production of sugarcane. The network of main drains, irrigation ditches, and pumping stations used to drain the Mana Swamp are still present today. This drainage network continues to keep water levels on the Mana Plain artificially low by pumping water to the ocean via two pumping stations. During the late 1990s, sugarcane production at the105 acre site was abandoned and the land was transferred to the State of Hawaii Division of Forestry and Wildlife for wetland restoration to aid in the recovery of four species of endemic Hawaiian waterbirds.

The Mana Plain Wetland Restoration Project site is approximately 105 acres of abandoned sugarcane fields dissected by two main drains and a series of abandoned field ditches. The site, owned and managed by the State of Hawaii Division of Forestry and Wildlife is located at 21° 0’ 59.1” N, 159° 46’ 34.7” W along the Kaumualii Highway (see Figure 1-1). The area is dominated by invasive vegetation that became established after sugarcane production ceased. The restoration site and low-lying surrounding lands are within several feet of a relatively shallow groundwater table and often flood during the wet season. Surrounding land uses include the Kawaiele Waterbird Sanctuary to the south, the Pacific Missile Range Facility to the west, and agricultural lands to the north and east.

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[1] The Mana Plain Wetland Restoration Partnership is a diverse multi-disciplinary partnership including federal and state agencies, non-profit organizations, and corporations. It includes individuals from: State of Hawaii Division of Forestry and Wildlife (DOFAW; owner/manager of proposed wetland); State of Hawaii Division of Aquatic Resources; U.S. Fish and Wildlife Service (Kauai NWR Complex, Bosque del Apache NWR, Pacific Islands FWO, and Region 1 Portland); PAHIO Development, Inc.; Hawaii Wetland Joint Venture, a branch of the Pacific Coast Joint Venture; Wetland Management and Educational Services, Inc.; Scaup & Willet LLC; and National Park Service River, Trails, and Conservation Assistance Program. Biological planning for the restoration project has been on-going and includes individuals from the Partnership team with expertise in wetland ecology, avian biology, plant ecology, and soil science. Individuals with expertise in community outreach, refuge water management, wetland construction and maintenance, and archeology have also provided technical assistance for this project.

1.2 Project Purpose and Study Objectives

The purpose of the Mana Plain Wetland Restoration Project is to maximize the area of constructed wetlands within the restoration site. Palustrine emergent wetlands within the project will create habitat for four species of endangered Hawaiian waterbirds. The Mana Plain is of vital importance for the recovery of endangered waterbirds species. This restoration project will provide important breeding and feeding wetland habitats on an island where; 1) wetlands have been severely degraded, and 2) mongoose, an introduced predator, have not been established. Constructed wetlands will provide habitats for the following target species:

- Hawaiian stilts (*Himantopus mexicanus knudseni*, Endangered);
- Hawaiian ducks (*Anas wyvilliana*, Endangered);
- Hawaiian coots (*Fulica alai*, Endangered);
- Hawaiian moorhen (*Gallinula galeata sandvicensis*, Endangered);
- Migratory waterfowl; and
- Migratory shorebirds

A Biological Plan (Henry and Ryder, 2008) detailing foraging and nesting requirements of the targeted species has been developed by Restoration Team Partners. This plan, along with input from DOFAW and other restoration partners, guided the Mana Plain Wetland Restoration objectives, which include the following:

- Restore breeding/nesting and foraging habitats to severely degraded wetlands for Hawaiian stilts, Hawaiian ducks, Hawaiian coots, Hawaiian moorhen and migratory waterfowl and shorebirds;

- Constructed wetlands will have a water delivery system designed to prevent establishment of non-native fish populations and allow for management of invasive vegetation.

- Constructed wetlands should be easily maintained and function on the principles of moist soil management.

- Water levels in constructed wetlands should have independent water control capability.

- Constructed wetlands should be able to drain to allow for habitat management, control of invasive species, and control of disease outbreaks, when necessary.

- Water delivery should allow a) filling of more than one constructed wetland at a time, and b) maintaining water flow through the constructed wetlands.

- Constructed wetlands should allow for water level management for temporarily, seasonally, and semi-permanently flooded wetlands.

- Microtopography should be used to enhance the diversity and interspersion of plant species and wetland habitats.

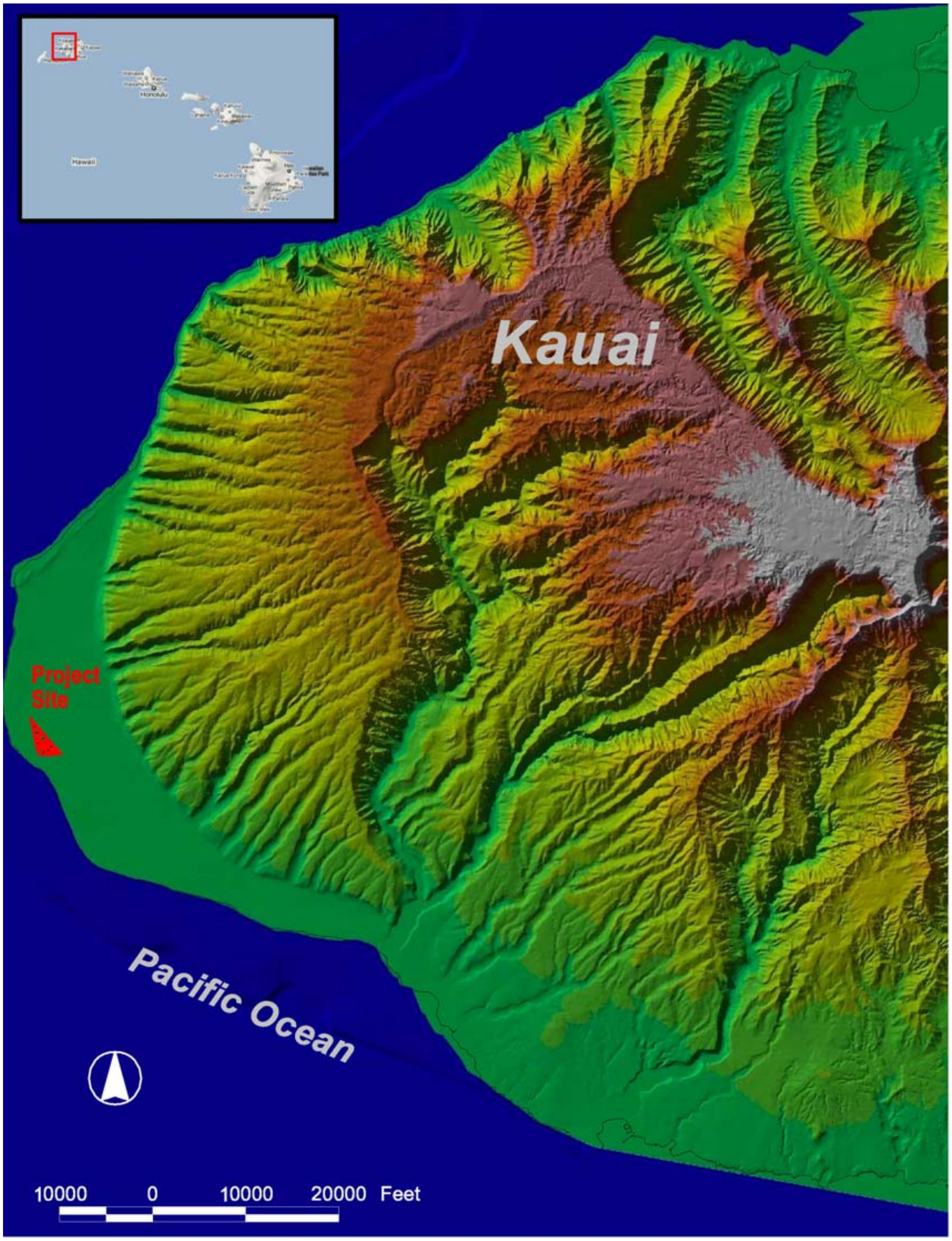

FIGURE 1-1. Site location map.

1.3 Report Organization

This report documents the approach and findings from KHE's assessments and describes the proposed restoration alternatives. The report consists of ten chapters. Chapter 1- (Introduction) summarizes the project site, project purpose and need for this study and report. Chapter 2 (Summary of Findings) presents summaries of key findings from this study. Based on available information, Chapters 3 through 6 present a synthesis of: the physical site setting (topography, geology, hydrogeology and soil); meteorology; surface water drainage and water quality; and groundwater conditions, respectively. Chapter 7 (Regional Conceptual Hydrologic Model), presents historic and recent water budgets to describe the characteristics and processes of surface water and groundwater movement into and through the project area. Chapters 8 (Water Source Analyses) presents the results of analyses completed to evaluate project feasibility, water supply alternatives and costs. Chapter 9 presents the results of a flood hazard impact assessment, completed to evaluate potential project benefits and impacts to local area flooding. Finally, Chapter 10 presents a list of references for studies cited in this report.

2.0 SUMMARY OF FINDINGS

The project site lies on the Kekaha-Mana Coastal Plain in the location of a former coastal marsh-lagoon system which has been drained by an expansive network of drainage canals in order to promote agricultural practices. Water levels are maintained in the drainage ditches as Kawaiele and Nohili pump stations discharge ditch water to the ocean. Annual rainfall totals to the site are approximately 21-inches/year. Evapotranspiration rates from irrigated lands are nearly 4-times higher at 83-inches/year. The project area only experiences standing water during extreme Kona-type storms that drop 5- to 10-inches of rainfall during a 24-hour period. The canal system effectively dewaters the upper approximately 8-feet of naturally saturated soil and drains floodwaters in about a weeks time. No change in flood hazards to surrounding lands or ditch pump operations would occur with construction of the project.

Site soils generally consist of surficial clay loam averaging 30 inches thick followed by an intermediate layer of sandy clay loam or silty loam and a basal layer of dense fine clay or silty clay loam. Local shallow sand lenses act to accelerate drainage of the shallow soils as they intersect and outfall to a number of on-site irrigation ditches and drainage canals.

Beneath the surficial soils, the site is underlain by approximately 200-feet of low permeability sedimentary deposits that rest on top of a basaltic lava aquifer. The low permeability surficial sediments are referred to as the caprock and the underlying lava deposits as the basal aquifer. Infiltration testing at the project site measured the lowest rates (0.03-feet/day) in the more clay-rich soil types. The caprock confines groundwater flow and aids in the creation of artesian conditions in wells completed in the basal aquifer. The basal aquifer is the primary freshwater aquifer on the Plain. Over-pumping and leakage from abandoned artesian wells during the sugarcane production era lead to the landward migration of a brackish-water zone in the basal aquifer that marks the boundary between fresh- and salt- groundwater beneath the island. Historical salt water intrusion from over-pumping during the peak groundwater withdrawal era lead to the abandonment of numerous wells, especially around Mana. With the closure of the sugarcane plantations, ground water pumping on the Kekaha-Mana Plain has decreased substantially since 1990, allowing the basal aquifer to recharge and ameliorate pumping-induced salt water intrusion.

Under natural conditions, the primary inflows to the project area consisted of rainfall, while primary outflows consisted of equal volumes of surface water drainage (to the Ocean) and evapotranspiration. In addition to groundwater development that started around 1880, imported water from Waimea River diversions is used to irrigate cropland on the Kekaha-Mana Coastal Plain and highlands to the east for sugarcane and more recently diversified agricultural crops. During the peak of sugarcane production, total inflow to the Coastal Plain and eastern highlands had doubled with the addition of surface water diversions and groundwater pumping. Similar to groundwater production, irrigation water inputs decreased significantly after sugarcane production ceased in the 1990’s.

Two primary water sources were investigated to supply the proposed project wetland basins - the main drainage canal and groundwater. Calculated project water demands are significantly affected by the assumed wetland basin infiltration rates. For example, total daily water demands for the project range from 1.5- to 3.2 million- gallons per day (GPD) under a high infiltration loss scenario, while rates range from 9,800- to 345,000-gallons per day (GPD) under a no infiltration loss scenario. Based on recent canal pumping records for the Kawaiele pump station, low canal water flows during the fall may limit the ability to use surface water as the sole wetland water supply during these times. Selected wetland basin salinities may reach marine (low infiltration losses) or hypersaline (no infiltration losses) concentrations if the drainage ditch water is used. Conversely, basin salinities will remain much lower with a groundwater supply, never exceeding approximately 3-ppt under any given infiltration loss scenario. Using a combination of drainage ditch water and groundwater would reduce basin salinities compared to using drainage ditch water as a sole source.

Based on comparison to average basal aquifer well yields on the Kekaha-Mana Plain to the daily wetland water demands, it appears that existing well yields are able to satisfy the daily water demands for the Low and No Infiltration Loss water budget scenarios, while the High Infiltration scenario demands are 2- to 3 –times higher than a single wells available yield. The Agribusiness Development Corporation (ADC) owns a well located one-mile east of the project site that historically produced around 1,000,000 gallons per day (gpd), or 700 gallons per minute (gpm), of fresh water and was used for irrigation of sugarcane. This well does not have a history of salt water intrusion and is being pursued for use as a project groundwater supply. If an on-site groundwater wells is pursued as the preferred project water supply, it is highly recommended that a test well be installed and an aquifer pump test implemented to evaluate if the necessary sustainable yields can be achieved. Salt water intrusion is a greater threat to an on-site well than the more distal ADC well discussed above. Capital costs for further aquifer investigation and well installation and operation are significant, with combined costs likely approaching $200,000. Annual average pumping costs will range between $2,500 to $33,300 depending on whether basins are engineered to reduce infiltration losses or not.

3.0 PHYSICAL SETTING

3.1 Project Site Description

The Mana Plain Wetland Restoration Project site is located on the Mana Plain on the western end of the Hawaiian Island of Kauai (see Figure 1-1). The site is approximately 105 acres in size and is dissected by two main drainage ditches and a series of abandoned internal field ditches. The site, owned and managed by the State of Hawaii Division of Forestry and Wildlife (DOFAW), is located less than 0.5-miles east of the Navy's Pacific Missile Range Facility (PMRF) and immediately north of the DOFAW Kawaiele Waterbird Sanctuary along the Kaumualii Highway.

Based on site topography and the local drainage ditch network, the project area has been divided into seven discrete wetland basins that could be managed independently. For purposes of this report, project wetland basin designations are indicated on Figure 3-1. The first letter of wetland basin name (N or S), indicates whether the wetland basin is located north or south of the main central east-west drainage ditch, followed by a number that indicates approximate wetland basin acreage. For example, the "N" in wetland basin N13's name indicates it is located north of main drainage ditch, while the "13" indicates it is approximately 13-acres in size.

3.2 Topography

The Mana Plain Wetland Restoration Project site is located on the Mana Plain on the western end of the Hawaiian Island of Kauai. The Mana Plain is a flat, low-lying feature bordering the Pacific Ocean for approximately 9 miles and extending inland an average of approximately 2 miles. Along the coast, elevations range from sea-level up to 15 feet along sand dunes west of the project site and then gradually decrease to 0 to 5 feet within the project site before gradually rising again to an elevation of 30 feet over one mile inland. Immediately east of the Mana Plain is a prominent wave-cut escarpment into the Na Pali region volcanic bedrock, with elevations rising quickly to over 800 feet within one-half mile from the eastern edge of the plain. Elevations then gradually rise to the east reaching 3000 to 3500 feet along the Makahoa Ridge, located approximately 5.5-miles east and paralleling the Mana Plain. Because of this rapid transition in topography, a wedge of coalescing alluvial fan deposits up to 80-feet high form along the east edge of the Mana Plain at the interface with the Na Pali Region.

Ground surface elevations at the project site range from 0 to 5 feet above mean sea level with the channel bed of the two main drainage ditches that bisect the site extending as much as 5 feet below sea level. The elevation of the road surface on Kaumaulii Highway is approximately 8 feet above sea level. Figure 2.2-1 includes the project site map with topographic contours surveyed by Ducks Unlimited in 2008.

3.3 Regional Geology and Hydrogeology

The majority of the Mana Plain is capped by 150- to 250-feet of sediment overlying a relatively flat buried erosional surface of lava deposits associated with the Napali formation of the Waimea Canyon volcanic series (MacDonald, et al., 1960). The entire Kekaha-Mana drainage area is underlain by the Napali formation (Burt, 1979). The Mana Plain consists of coralline and marly sedimentary rocks of marine, littoral and terrestrial origin (Burt, 1979). Some were deposited in lagoonal and estuarine environments and some are alluvium washed down from the eastern uplands. From east to west, the surficial deposits on the Plain consist of modern alluvial fans, a thin ribbon of lagoonal deposits, patches of older dune sand, and a coastal berm of modern beach deposits and dunes (Burt, 1979). The regional geology and schematic geologic section through the Mana Plain are provided in Figure 3-2.

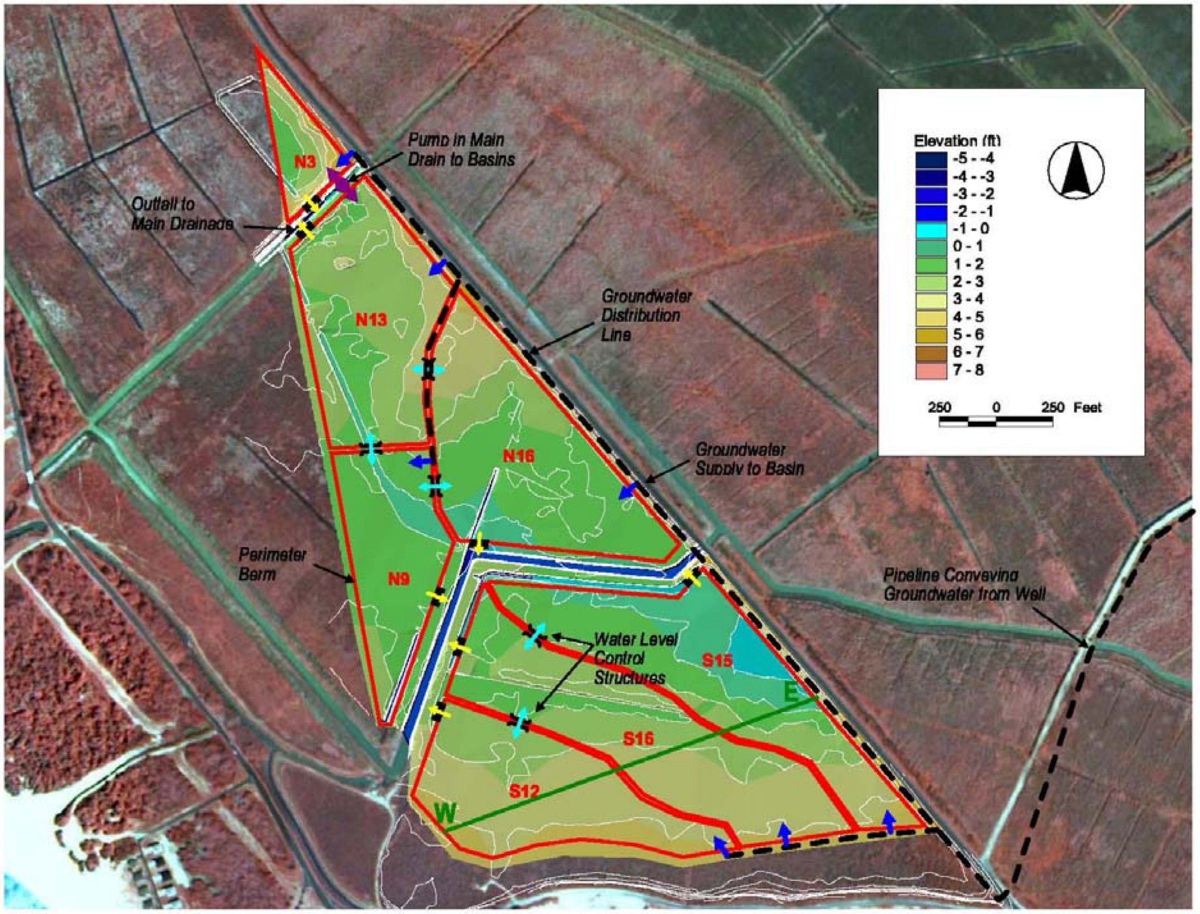

FIGURE 3-1. Shaded relief map of project site and internal wetland basins, prepared using topographic map prepared by Ducks Unlimited (2008).

The project site is underlain by lagoonal deposits, which are poorly consolidated sediments deposited in the shallow lagoon that once existed on the Mana Plain between Kekaha and Barking Sand. These lagoon deposits consist of calcareous sand and gravel, marl, and clay (MacDonald, et al., 1960). The thickness of the sedimentary deposits across the Plain range from zero feet on the inland edge of the plain to 400-feet or more along the edge of the Ocean (Burt, 1979). Well logs indicate that the thickness of deposits is about 160-feet within a half mile of the Ocean (Ibid).

Underlying the Mana Plain are two distinct aquifers, consisting of the basaltic lava aquifer and coastal plain sedimentary aquifer. According to MacDonald et al., (1960), the lagoonal deposits have a low permeability and yield brackish water to wells due to the high salt content in the sediments. In contrast, the underlying Napali formation lavas are highly permeable and contain fresher water and yield large quantities of water to wells and shafts. Water contained in the basaltic aquifer is called basal groundwater. The sedimentary complex is called the caprock because it overlies the basalt and confines the basaltic aquifer (Burt, 1979).

Burt (1979) and Oki et al. (1992) report that the principal basaltic aquifers have hydraulic conductivities[2] ranging from 400 ft/day to in excess of 1,000 ft/day. Because the Mana Plain sediments are much less permeable than the underlying lavas, they act as a confining layer (caprock) overlying the high permeability volcanic rocks. Burt (1979) reports caprock hydraulic conductivities at about 0.12-ft/day. Hydraulic continuity between the sedimentary and basal aquifers is poor. As a result, the caprock retards the seaward and upward discharge of the lava aquifer.

Most wells on the Mana Plain screened within the underlying lava are/were artesian when installed. MacDonald et al. (1960) report that water levels in these lava wells range from 8 to 12 feet above sea level. However, the beds of sand, gravel, and coral of the caprock can produce zones of relatively high permeability and leakage from the basal artesian lava aquifer into these sediments likely occurs wherever they are in contact. This upward leakage through the caprock probably maintained the marshy areas that once existed in parts of the Mana Plain which were drained and converted for sugarcane production (MacDonald et al., 1960).

On ocean islands such as Kauai, fresh groundwater beneath the island commonly occurs as a lenticular body of water called a freshwater lens that floats on saltwater and is separated from the saltwater by a transition zone of brackish water that is gradational in salinity. Figure 3-3 presents a schematic illustration of this relationship beneath the Mana Plain and includes two sections showing hypothetical potentiometric surfaces[3] and transition zone positions in the confined basaltic aquifer under pre- and post-development periods. Available data do not provide sufficient information to delineate the actual position of the transition zone in the project area. However the position of the transition zone is significantly affected by the degree of groundwater development, as discussed below. During peak groundwater use in the 1970's, the majority of wells and shafts completed on the Plain that were not abandoned due to salinity intrusion are located within a half-mile zone from the eastern bluffs, suggesting the transition zone was located a short distance to the east of these wells at that time (Burt, 1979).

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[2] Hydraulic conductivity (K) of an aquifer is the rate at which water can move through a permeable material.
[3] A potentiometric surface is the elevation to which water will rise in a well screened within a confined aquifer.

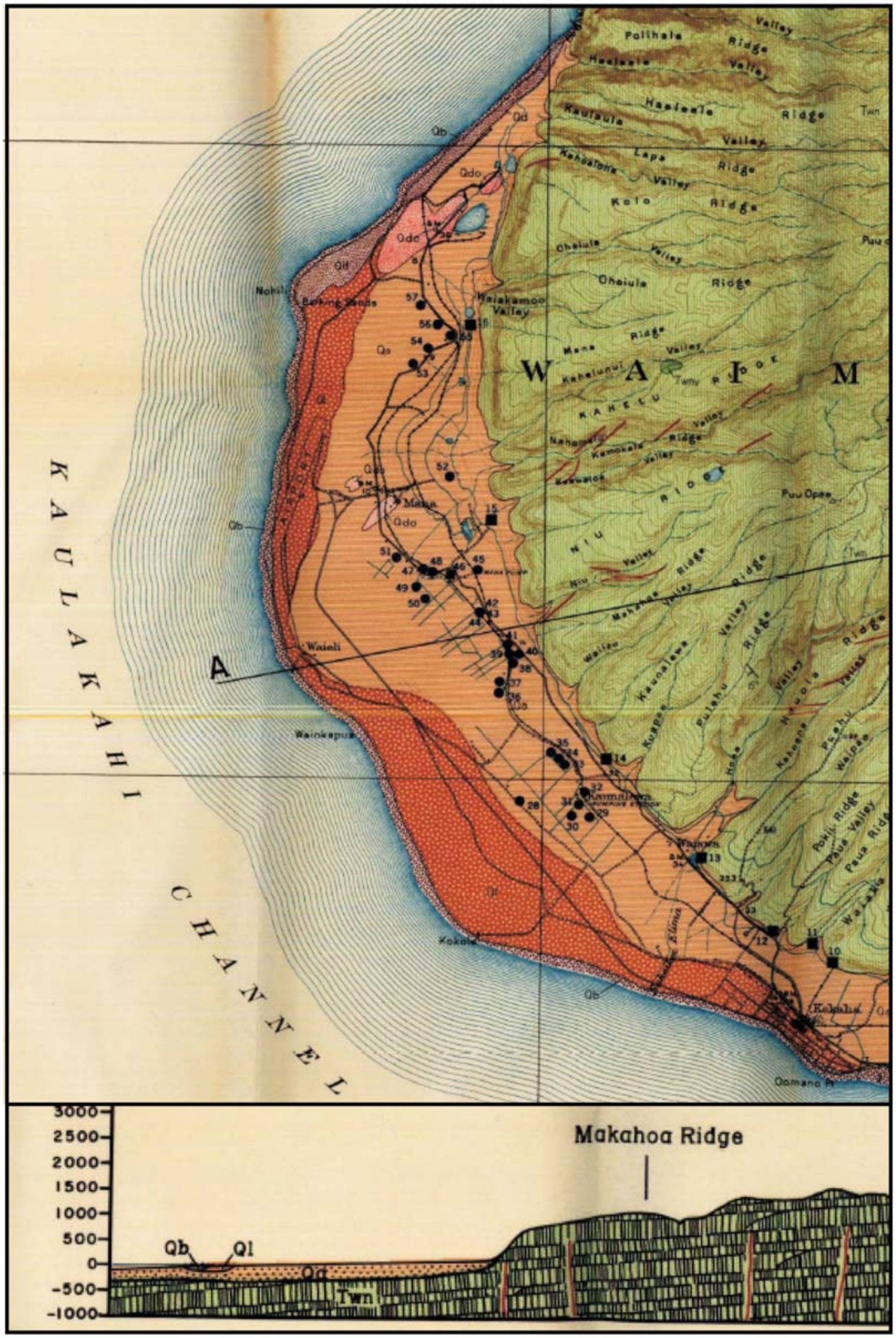

FIGURE 3-2. Regional geology. Twn= Napali formation lava; Ql = Mana Plain lagoon deposits; Qa = unconsolidated alluvium; Qdo = calcareous sand dunes; Qb = beach sand; Qd = dune sand; (from MacDonald et al., 1960).

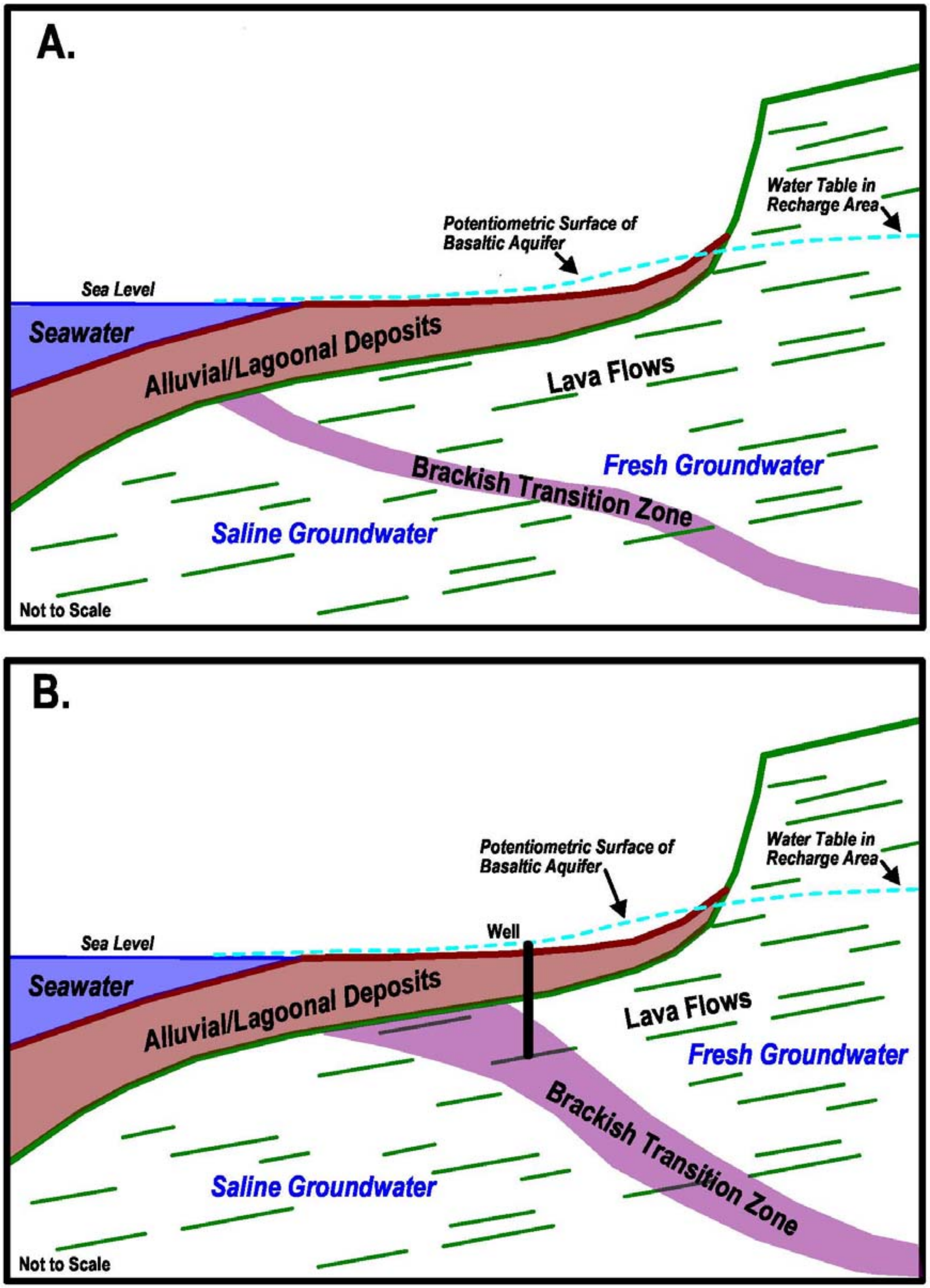

FIGURE 3-3. Schematic of groundwater conditions beneath the Mana Plain under predevelopment and post-1990s equilibrium conditions (A) and after development of wells for irrigation (B). Note hypothetical landward advancement of transition zone and salt water in response to increased groundwater pumping, especially during peak groundwater use period from 1940 through early 1990s. Modified after Burt, 1979.

Groundwater pumping influences the relative position of the different groundwater zones, with the transition zone migrating inland during periods of high groundwater pumping and a return to a more ocean-ward equilibrium position during periods of lesser pumping When water is withdrawn from a freshwater lens, the freshwater lens shrinks and saltwater or brackish water will intrude upward and/or landward into parts of the aquifer that formerly contained freshwater. The degree of saltwater intrusion depends on several factors, including the hydraulic properties of the rocks, recharge rate, pumping rate, and well location. The effect of intrusion on a particular well depends on the vertical and lateral distance between the well and the transition zone. Wells completed in the freshwater lens near the coast are particularly likely to induce brackish water or saltwater movement into the well as pumping continues. Figures 3-3A and 3-3B depict the landward shift in salt/brackish water transition zone in response to large groundwater withdrawals during the peak groundwater use period from 1940 through the early 1990's. It is likely that the transition zone has recently shifted back towards a pre-development position since the end of the peak groundwater use period.

Because of the relatively impermeable and low storage capacity of the Mana Plain sedimentary caprock, recharge to the underlying basal volcanic rock aquifer occurs in the Napali region uplands to the east with groundwater flowing westward though the lavas, under the Mana Plain towards the Ocean. Recharge to these lavas comes primarily from infiltration of rainfall and irrigation water that is not lost to runoff or evapotranspiration. An average of 22 inches of rainfall occurs yearly at Mana, but up to 60 inches per year falls along the highly permeable basaltic mountains east of the site. Fog drip, which is cloud vapor that is intercepted by vegetation and subsequently drips to the ground, commonly occurs between altitudes of 2,000 and 6,000 ft (Gingerich and Whitehead, 1999). Recharge is reported at about 10 to 50 percent of the rainfall, fog drip, and irrigation water (Ibid). Runoff is directly related to factors including rainfall, topography, soil type, and land use. Burt (1979) reports that mean annual runoff from the eastern highlands onto the Coastal Plain is about 5-percent of the annual rainfall total.

In the early 1990s, there was a need to identify and describe aquifers for each island of the state of Hawaii to serve as a framework for the State of Hawaii's Department of Health groundwater protection strategy. In response, a system was initiated to classify and assign codes to the principal aquifers of the state as presented in a report by Mink and Lau (1992). The Aquifer Codes incorporate location and descriptive indices, while the Status codes indicate the developability, utility, quality, uniqueness, and vulnerability to contamination of the groundwater resources.

The project site lies within the Kekaha aquifer system of the Waimea aquifer sector. Pursuant to this classification scheme, the Mana Plain caprock sediments are considered an independent aquifer from the underlying Napali volcanics aquifer. The caprock sediment aquifer is an unconfined sedimentary aquifer that is classified as a potential drinking water source of water (as opposed to being an existing source of drinking water). Mink and Lau (1992) also indicate that it is ecologically important, contains moderate salinity (1000-5000 mg/l chloride)[4], and is classified as having a high vulnerability to contamination[5]. Burt (1979) reports that very few data are available concerning aquifer properties of the caprock but that it has a low potential for production of fresh/brackish water. He also states that wells pumping from the caprock induce recharge mainly from nearby ditches and drains.

The underlying volcanic aquifer is confined (by the overlying sediments) and compartmented by vertical dikes that cut through the lava bed aquifer. The basal volcanic aquifer beneath the Mana Plain is considered an existing drinking water source as it has low salinity (250-1000 mg/L chloride) and is also classified as having a low vulnerability to contamination.

3.4 Site Soil

3.4.1 Soil Types and Properties

Pursuant to the NRCS Soil Resource Report (USDA NRCS, 2010), the project site is underlain by four mapped soil types (see Figure 3-4). The majority of the northern wetland basins and western half of the southern wetland basins are underlain by the Kaloko clay loam (Kf). The southeastern portions of Wetland Basin N16 and eastern portions of all southern wetland basins are underlain by Kaloko clay (Kfa) which is very similar to the Kaloko clay loam. Both the Kaloko clay loam and the Kaloko clay are defined as poorly drained with a parent material from basic igneous rock alluvium. They have a very low (0.00 in/hr) to moderately high (0.20 in/hr) saturated hydraulic conductivity (Ksat)[6]. Depth to water is 12 to 24-inches and it is occasionally flooded. These soils are characterized as moderately to strongly saline (16.0 to 32.0 mmhos/cm) with a moderate water capacity[7] (about 7.8 inches). A typical profile in each consists of: 0 to 12 inches clay loam; 12 to 20 inches of clay; and 20 to 60 inches of silty clay[8]. A small area along the southwestern edge of Wetland basin N9 is underlain by fill (Fd) of unknown source and character.

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[4] Throughout preparation of this report, KHE did not encounter reports of any wells (irrigation or potable water) being constructed in the upper alluvial/lagoonal caprock deposits. The relatively higher hydraulic conductivity and lower salinity of the deeper basal aquifer make it the preferred target for well development on the Mana Plain. It is unlikely that the caprock deposits will be used for potable or irrigation water in the future.

[5] Mink and Lau (1992) characterize “vulnerability to contamination” in the following manner. In the Hawaiian Islands because of the geographical limits of the resources, interconnection among groundwater sources and the relatively rapid time of groundwater travel, aquifers can be described simply as being either vulnerable or not vulnerable to contamination. Most unconfined aquifers are vulnerable; confined aquifers may or may not be. A refinement in the degree of vulnerability may be instituted by using some modifiers or index. The one used in their classification (high, moderate, low, none) is based on familiarity with environmental conditions.

[6] “Ksat” refers to the fully saturated hydraulic conductivity of soil. Hydraulic conductivity (K) of soil is the rate at which water can move through a permeable material

[7] Water capacity of a soil is the amount of water that a soil can store that is available for use by plants.

[8] The NRCS soil profile descriptions are notably different from the soil profile descriptions completed during the project soil investigations. This may be because of the way the NRCS maps soil types. The NRCS completes their mapping based on a limited number of soil profiles. Acknowledging that individual soils on the landscape merge into one another as their characteristics gradually change and soil properties are highly variable within a given soil type area, the NRCS soil map units are more commonly based on geology, landforms, relief, climate and vegetation. Thus, soil profile descriptions for a certain soil type are only a typical representation and are not universally representative of a mapped soil unit.

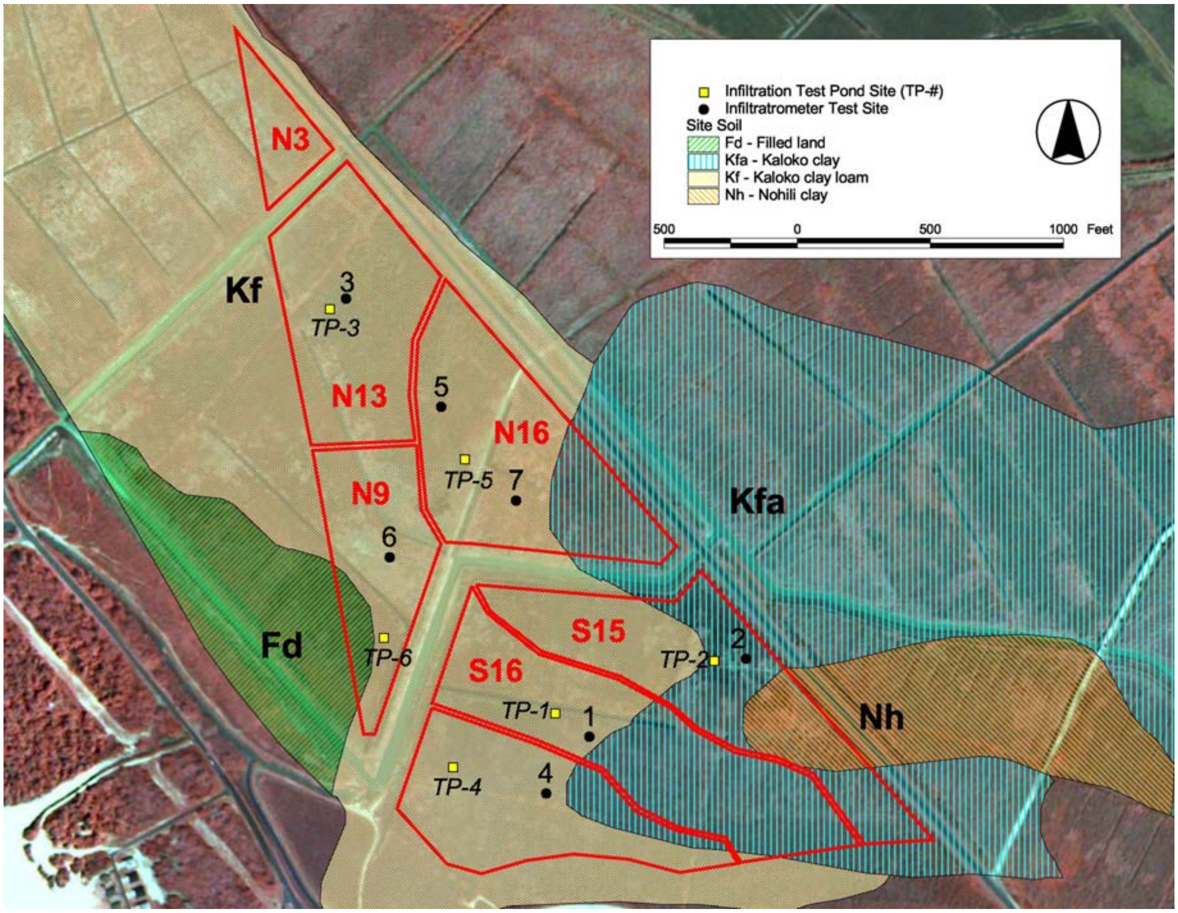

FIGURE 3-4. Map of NRCS soil types underlying the project site and infiltration test sites. Numbers indicate location of infiltrometer test sites while location numbers with "TP" precursor indicate location of test pond sites.

The central area of Wetland Basin S15 is underlain by Nohili clay (Nh). The Nohili clay is defined as poorly drained with a parent material from alluvium. It has a moderately low (0.06 in/hr) to moderately high (0.57 in/hr) saturated hydraulic conductivity (Ksat)[9]. Depth to water ranges from 18- to 36-inches and it is occasionally flooded. The soil is characterized with a moderate water capacity (about 8.3 inches). A typical profile consists of: 0 to 18 inches clay; 18 to 33 inches of clay; 33 to 43 inches of cemented material/clay; and 43 to 90 inches of clay.

A study by Yamamoto (1963) included sampling and physical testing of Nohili clay soils from the sugarcane fields of the Kekaha region of Kauai. Yamamoto (1963) characterized

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[9] Its important to note that the higher Ksat values for the Nohili clay versus the Kaloko clay and Kaloko clay loam are inconsistent with soil profile descriptions and field observations and measurements. Clays typically have lower Ksat values than loams and silty clays and one would expect the higher clay content of the Nohili would yield lower Ksat values than the Kaloko series. The project area underlain by Nohili clay is also observed to stay wet/ponded longer than areas underlain by the Kaloko series soil. Results of field infiltration tests also indicate lower infiltration rates occur in the Nohili clay than other site soil.

the upper 12-inches as clay, with about 65-percent pore space and soil moisture by volume, 2.2-percent organic matter content (by weight) and average grain-size distribution of 7-percent sand, 29-percent silt, and 64-percent clay. More importantly, Yamamoto (1963) classified the Nohili clay soil as a Gray Hydromorphic soil with a very high soil plasticity index[10]. Gill and Sherman (1952) completed a study of the physical properties of Gray Hydromorphic soils of the Hawaiian Islands, characterizing them as, "dark colored, poorly drained, sticky plastic clays." These soils owe their morphology to their hydromorphic condition produced by their naturally poor drainage. Gill and Sherman (1952) also determined that the clays were composed of montmorillonite type clay, which expand when wetted.

In June of 2009, the Mana Plain Restoration Partnership completed a site soil investigation that included sampling and describing soil at 60 locations throughout the project site. A complete description of this work is provided in the report prepared by Henry (2010). Within the proposed wetland restoration area, soil augers were used to collect soil profiles beginning at the soil surface. Successive soil samples were taken down through the soil until the water table was reached. Soil color and texture were described for each soil sample. The depth below the surface was recorded for each sample, including each change in soil color/texture, capillary fringe, and water table. Soil profiles were also collected along abandoned irrigation ditches to determine if ditches intersected sand or other course texture soil layers.

In general, the 2009 site investigation identified soils of a coarser-grained texture than those reported and mapped by the NRCS. According to field investigations (Henry, 2010) surface soil throughout the restoration area was characterized by clay loam averaging 30 inches (range 16–58 inches) below the ground surface. In general, this surface layer was followed by sandy clay loam or silty loam, followed by sandy loam and a basal layer of dense fine clay or silty clay loam. The depth to the shallow groundwater averaged 40 inches below the surface and ranged from 24 to 58 inches.

3.4.2 Infiltration Testing

In September of 2009, DOFAW completed single and dual ring infiltration tests across the project site followed by a series of infiltration tests at selected test (percolation) ponds in June-August 2011. The locations of infiltration tests are indicated on Figure 3-4.

Dual and single ring infiltrometer tests results are plotted on Figure 3-5. A total of eleven tests were completed using either a 6-inch and/or 12-inch diameter Infiltrometer. Most test results indicate the classic signature of decreasing infiltration rate with elapsed test time as soils become more and more saturated over the length of water application. Most test results did not reach a point in which infiltration rates leveled-off to a constant value as would be expected, and rates were higher than published estimates, so additional tests were done using test ponds (discussed below), which more accurately reflect site conditions. However,

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[10] The plasticity index (PI) is a measure of the plasticity or deformability of a soil. The plasticity index is the range of water content where the soil exhibits plastic properties. Soils with a high PI tend to be clay, those with a lower PI tend to be silt, and those with a PI of 0 (non-plastic) tend to have little or no silt or clay.

infiltrometer test results are informative in identifying the relative infiltration potential between the different proposed project wetland basins.

In general, final infiltrometer test rates were highest in the Kaloko clay loam, ranging from around 5.5- to 15-in/hr. As would be expected, infiltration rates were lowest (measured at 0.2- to 1.3- in/hr) at site 2, located in the more clay-rich Kaloko clay near the Nohili clay.

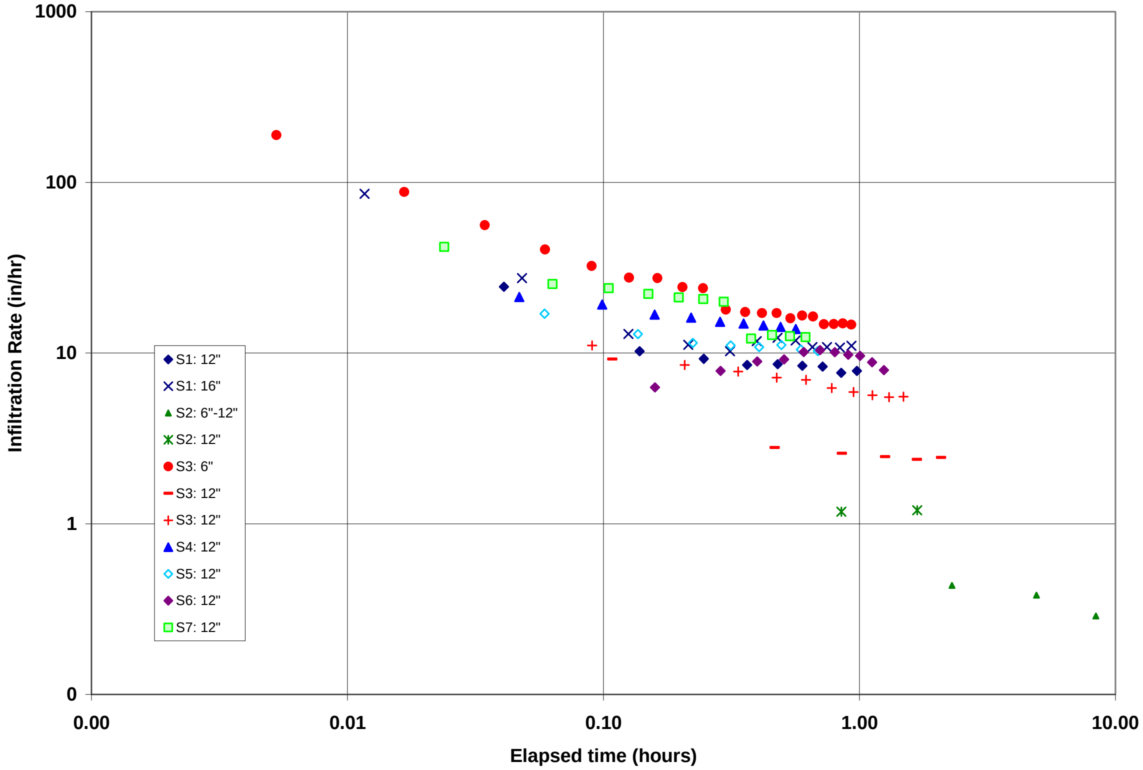

FIGURE 3-5. Plot of dual and single ring infiltrometer testing results, Mana Plain Wetland Restoration Project site.

In order to expand on the infiltrometer test results, DOFAW staff implemented a series of larger-scale and more long-term infiltration tests at selected site locations in June and August of 2011. In general, the test methods included filling previously excavated shallow (flat-bottomed) pond sites (dimensions of approximately 30-feet by 60-feet) and measuring the rate of infiltration in terms of the rate of fall in the test pond water level. A key objective of these tests was to maintain constant ponded conditions by periodically refilling the ponds – this was typically achieved by refilling no more than once a day[11]. Surface water from the main drains was used to fill test ponds.

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[11] Due to scheduling requirements and other job responsibilities, DOFAW personnel were only able to visit and maintain the tests once a day to collect water level measurements and refill test ponds with water.

Two infiltration tests were completed at TP-1 and TP-5 between June 14 and June 25-, while tests were completed at TP-2 and TP-6between August 9 and August 18, 2011. Successful tests were completed at all sites except TP-6, where high infiltration rates drained the test pond at a rate that would necessitate refilling the pond at a rate higher than once a day[12]. Test results for the remaining test pond sites are plotted on Figure 3-6. Raw test results uncorrected for evaporation losses are plotted as the solid symbols. In order to account for test pond water losses to evaporation, KHE estimated hourly evaporation losses for the duration of each test based on proportioning a daily average evaporation rate (calculated by dividing the average monthly evaporation rate by the number of days per test month) using 10-minute solar radiation rates available from near-by weather stations in Kekaha. Adjusted infiltration test results that account for evaporation looses are plotted as the hollow symbols on Figure 3-6.

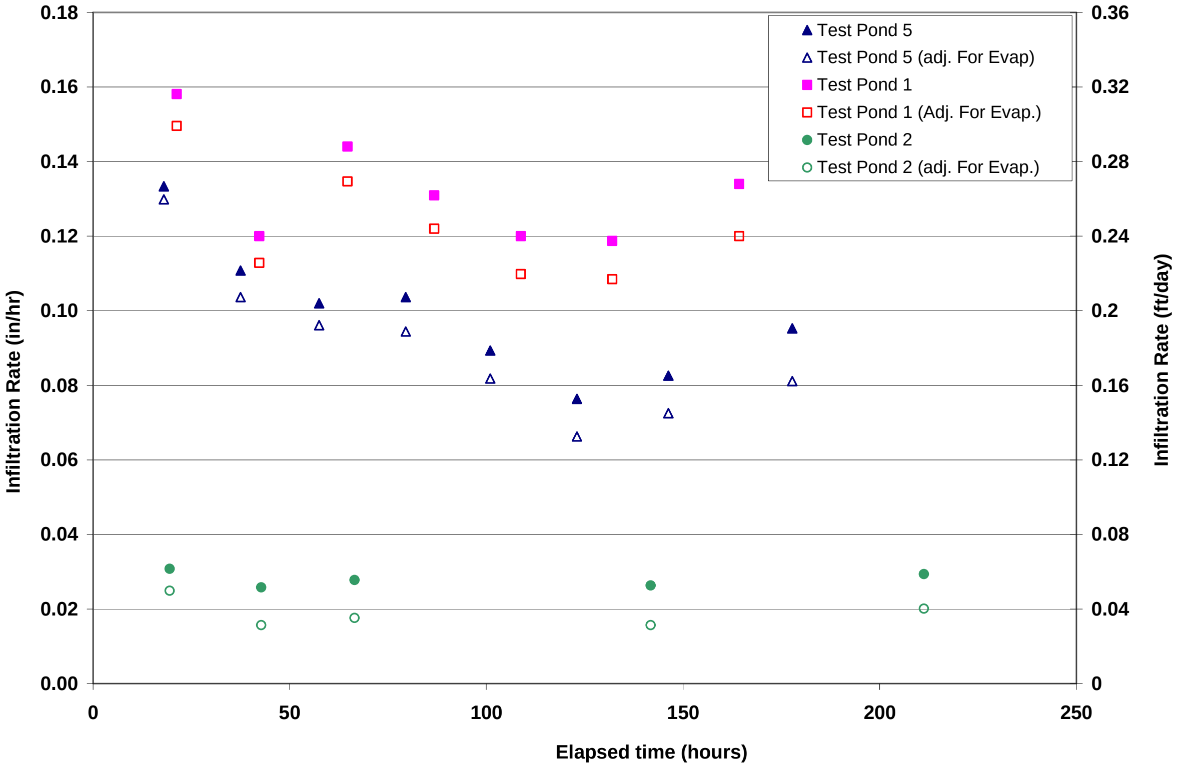

FIGURE 3-6. Plot of test pond infiltration test results, Mana Plain Wetland Restoration Project site.

Infiltration pond test results indicate that, again, the lowest infiltration rate occurs at TP-2, located in the most clay-rich soil unit, while Test Ponds located in the coarser-grained Kaloko clay loam have higher infiltration rates. Test results plotted in Figure 3-6 also

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[12] It is believed there is high permeability (coarser grained) material filling a historic drainage ditch at this location that acts like a French drain and accelerates subsurface drainage away from this area.

indicate that infiltration rates rise slightly from minimum values that occur roughly 125-hours into each test. This suggests that fully saturated conditions were achieved as rates appear to have leveled off – it is not known why rates rise after reaching a minimum value but perhaps micro-climatic conditions that effect evaporation (esp. wind or changes in humidity) may account for the variations in data. Regardless, test pond infiltration rates are over an order of magnitude lower than infiltrometer test results with infiltration rates reaching between 0.07- to 0.11-in/hr in the Kaloko clay loam (TP-1 and TP-5) and just under 0.02-in/hr at TP-2 in the Kaloko clay near the Nohili clay.

4.0 METEOROLOGY

4.1 Climate

The annual average temperature within the project area (as measured at Mana) is 74-degrees Fahrenheit, with a relatively narrow range in average monthly temperature from a low of 70-degrees in January to high of 78.1 in August (MacDonald et. al., 1960). Humidity in the area is generally within the 60 to 80 percent range (R.M. Towill, 1990).

Kauai lies in the belt of northeast trade winds, which dominates island weather for April through September. During this time, the trade winds deliver a mild but moist tropical weather pattern, with rains being introduced to the windward side of the island and dry conditions to the leeward side, including the Mana Plain. The moist northeast trade winds passing over the mountainous interior of Kauai are the primary source of rainfall. Kauai displays the steep isohyet gradient; as trade winds move over the mountains, the air expands and cools forming clouds, which leads to an increasing rate of rainfall with elevation. Mt. Waialeale, with a mean annual rainfall of 465 inches, is only 15 miles away from the semi-arid west coast (Chang, 1962). The Mana Plain, on the leeward side of Kauai, is in the rain shadow of Mt. Waialeale and receives much lower amounts of precipitation, averaging just over 20 inches/year. During the winter months (October through March) tropical storms, generally from the south (Kona storms), may bring heavy rains to the entire island.

4.2 Rainfall

Daily rainfall data from climate stations near the project site has been recorded since 1905 (WRCC, 2010). Data was obtained and reviewed for the Kekaha, Mana, Barking Sands, and Waimea climate stations for the period of record indicated in Table 4-1.

Station Name	Start Date	End Date
Kekaha 944 514272	Jan. 01, 1905	Nov. 01, 2000
Mana 1026 516082	Jan. 01, 1905	Nov. 01, 2000
Barking Sands 510197	Sept. 07, 2004	Jan. 10, 2011
Waimea 947 519629	Oct. 01, 1949	Nov. 21, 2010

Table 4-1. Climate stations near project site and period of record for rainfall data.

The Barking Sands data set has a relatively short duration with numerous time gaps and data patterns that did not follow the same trends as demonstrated by the Kekaha, Mana, and Waimea data sets. Based on these observations, the Barking Sands data were omitted from further evaluation. Since Kekaha, Mana, and Waimea monthly average data sets displayed similar patterns, linear correlations were derived for Waimea vs. Kekaha daily data and Waimea vs. Mana daily data for the overlapping time period of 1949 through 2000. The linear correlation allowed for reasonable estimates and extension of the Kekaha and Mana data sets for the period 2000 through 2010. Average annual and monthly rainfall totals for the time period 1949 – 2010 are presented in Table 4-2 for the three climate stations. Long-term average monthly rainfall totals for Mana are presented on Figure 4-1.

Month	Waimea (inches)	Kekaha (inches)	Mana (inches)
January	3.76	3.58	3.68
February	2.27	2.02	2.16
March	2.46	2.38	2.54
April	1.24	1.11	1.14
May	1.04	0.92	0.98
June	0.38	0.31	0.43
July	0.47	0.44	0.62
August	0.67	0.66	0.64
September	0.83	0.76	1.01
October	2.22	2.04	2.24
November	2.59	2.52	2.53
December	3.94	3.78	3.78
Average Monthly Annual Sum	21.88	20.53	21.73

Table 4-2. Average monthly and average monthly annual summation of rainfall data for climate stations near the project site[13].

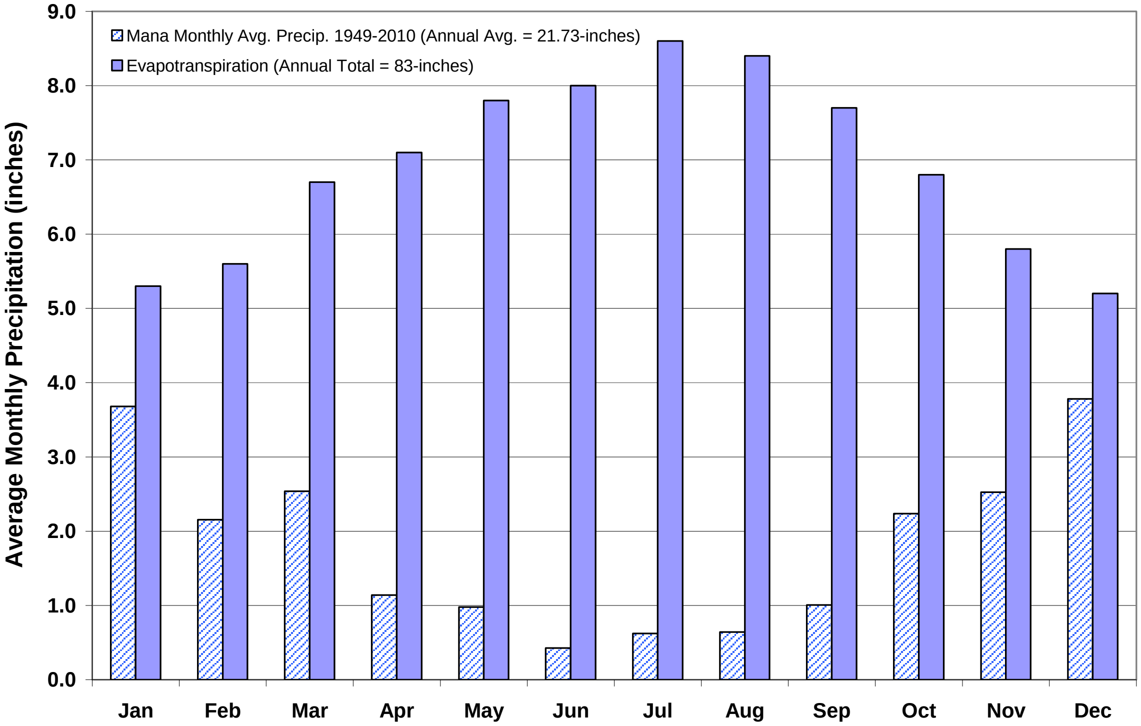

FIGURE 4-1. Average monthly precipitation totals (at Mana) versus average monthly pan evaporation rates (project site).

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[13] Waimea data is from 1949 – 2010. Kekaha and Mana data is from 1949 – 2000. A linear correlation was made between the Waimea data and the Kekaha and Mana data sets so as to extend Kekaha and Mana data through 2010.

Long-term climatic conditions for the study area are illustrated by a plot of annual precipitation totals for Mana from 1949 to 2009 (Figure 4-2). The time series plot indicates that annual precipitation amounts range widely, from 18- to 254-percent of the average annual precipitation total of 21.3 inches (the long term minimum and maximum derived annual totals for Mana are 3.75 and 54.14 inches, respectively). In order to identify and characterize long-term wet and dry periods, the cumulative departure from the mean annual precipitation was tabulated[14] for the long-term rainfall record. Figure 4-3 presents the results of this analysis and identifies multi-year drought periods.

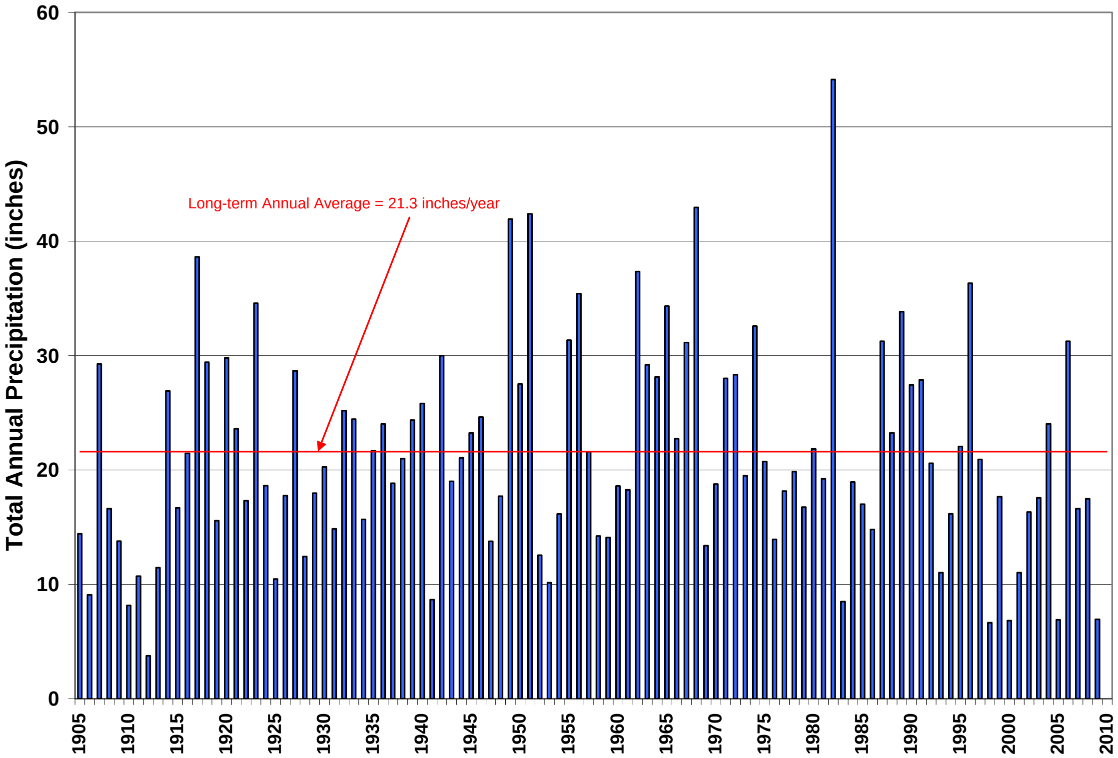

FIGURE 4-2. Annual rainfall totals for Mana, 1905 through 2009.

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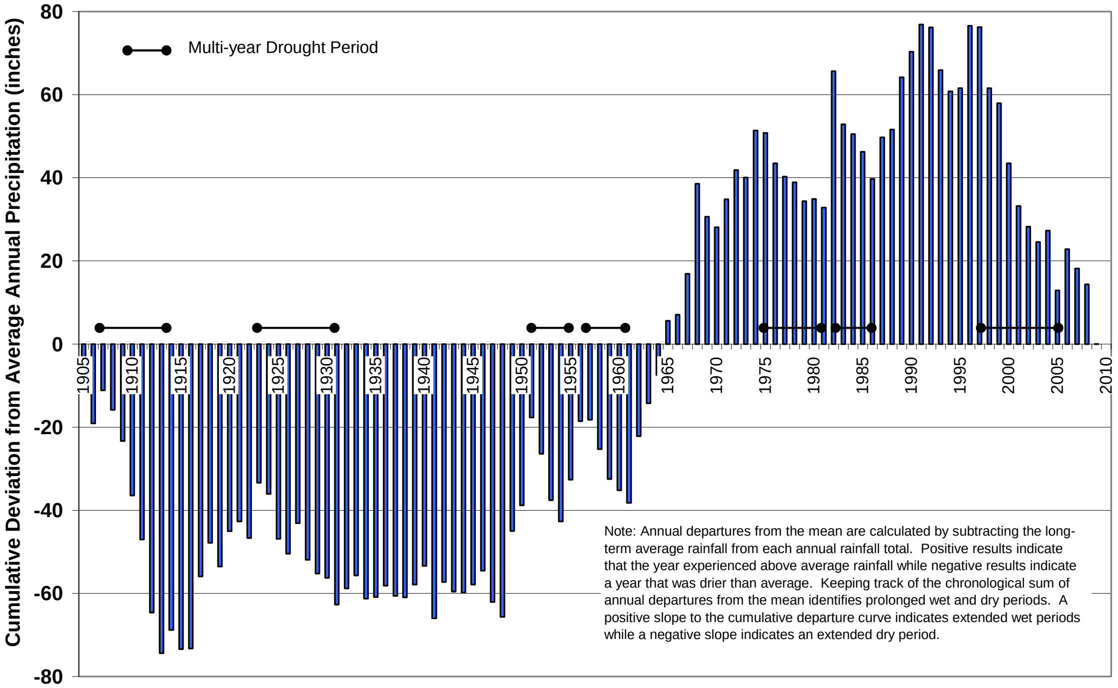
[14] Annual departures from the mean are calculated by subtracting the long-term average rainfall from each annual rainfall total. Positive results indicate that the year experienced above average rainfall while negative results indicate a year that was drier than average. Keeping track of the chronological sum of annual departures from the mean identifies prolonged wet and dry periods. A positive slope to the cumulative departure curve indicates extended wet periods while a negative slope indicates an extended dry period.



Note: Annual departures from the mean are calculated by subtracting the long-term average rainfall from each annual rainfall total. Positive results indicate that the year experienced above average rainfall while negative results indicate a year that was drier than average. Keeping track of the chronological sum of annual departures from the mean identifies prolonged wet and dry periods. A positive slope to the cumulative departure curve indicates extended wet periods while a negative slope indicates an extended dry period.

FIGURE 4-3. Cumulative departure from average annual precipitation for Mana.

The State of Hawaii, Department of Agriculture's Agricultural Water Use and Development Plan (Water Resources Associates, 2004) states the following with respect to past, current and future drought trends in Hawaii.

> *"Drought in Hawaii occurs infrequently, but during the last decade has become more persistent due to El Nino and La Nina weather conditions. These weather conditions affect the ocean temperatures which govern weather fronts and pressure systems and in turn result in failure of the trade winds and development of winter storms. In the dry leeward agricultural areas, lack of winter storms can result in severe droughts. For the water-rich windward areas, the interruption of trade winds diminishes rainfall, stream flow and consequently the water supply of irrigation systems."*

4.3 Evapotranspiration

The quantity of water evaporated from soil and water surfaces and transpired by plants is termed actual evapotranspiration (AE). Estimated values of AE are quantified through pan-evaporation data from class-A evaporating pans. Twenty-five sugarcane production locations in Kauai have documented between ten and thirty years of pan evaporation data (Shade, 1995). Using these data, Shade (1995) prepared a map of mean annual pan evaporation contours for Kauai. These data indicate that Pan evaporation reaches more than 90 inches/year in the hot and dry leeward lowlands and declines to 20 inches/year in the uplands due to decreasing temperatures and persistent cloud cover. The mean annual pan-evaporation rate for the project site is 83 inches per year (derived from Figure 8 of Shade, 1995). To obtain mean monthly pan evaporation rates at the project site, the mean annual value of 83 inches was multiplied by the monthly-to-annual pan evaporation ratios derived from all stations (presented on Table 3 of Shade, 1995). Calculated average annual and average monthly pan evaporation values for the project site are shown in Table 4-3 and also plotted against average monthly rainfall totals on Figure 4-1.

Figure 4-4 illustrates the deficit between average monthly rainfall and pan evaporation at the project site. Assuming no water is lost to groundwater, an annual input of 61.3 inches is required to maintain an unchanging water surface within the wetland. This value is calculated by subtracting average monthly rainfall (for Mana) from monthly pan evaporation and summing the difference.

Month	Pan Evaporation (inches)
January	5.3
February	5.6
March	6.7
April	7.1
May	7.8
June	8.0
July	8.6
August	8.4
September	7.7
October	6.8
November	5.8
December	5.2
Average Annual	**83.0**

Table 4-3. Average annual and monthly pan evaporation values for the project site.

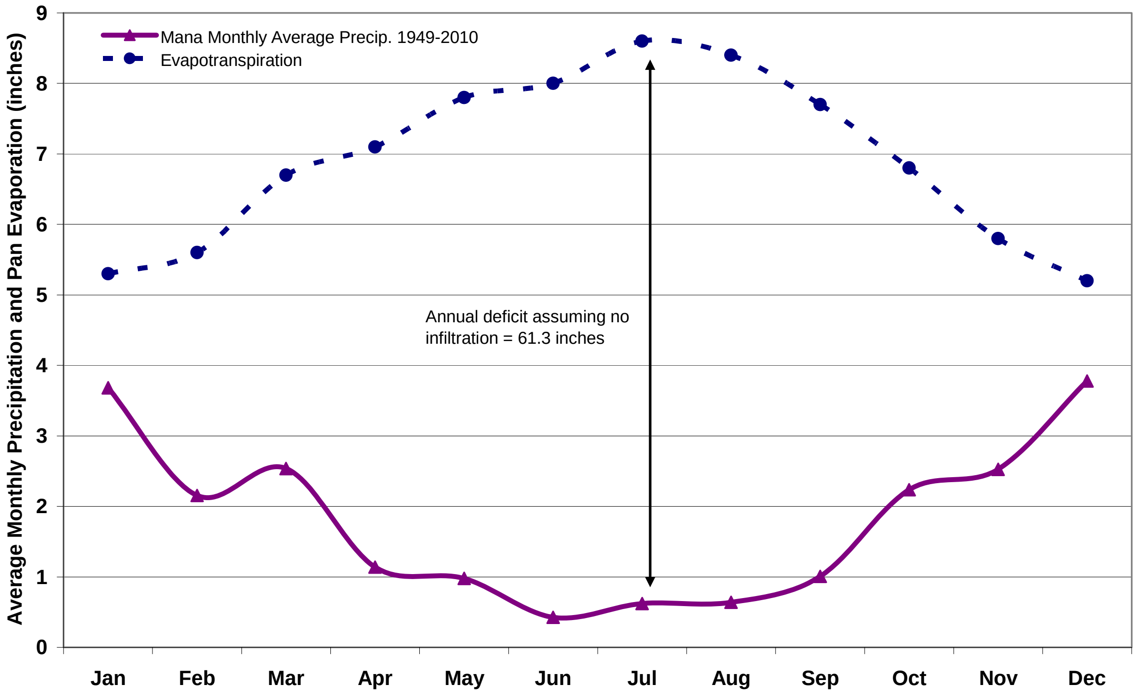


FIGURE 4-4. Comparison of average monthly precipitation against average monthly evapotranspiration for project site.

5.0 SURFACE WATER, DRAINAGE AND WATER QUALITY

5.1 Surface Water Development

The sugar industry started in the 1870s on the Mana Plain, but most of the plantation irrigation systems were developed around the turn of the twentieth century (Water Resource Associates, 2004). As part of this development, large quantities of surface water from the Waimea River were diverted into miles of transmission ditches and tunnels of the Kekaha Ditch Irrigation System (KEDIS) by the Kekaha Sugar Company (see Figure 5-1). This was done to move water to the abundant dry, fertile lands of the Mana Plain that required irrigation to grow sugarcane. The KEDIS, also known as the Waimea and Waimea-Kekaha Ditch, was started in 1906, with 16 miles of ditches, tunnels, flumes, and siphons in Waimea Canyon and four miles in the Kekaha bluffs. In 1907, the Ditch is reported to have provided an average flow of 30 MGD with a capacity of 40 MGD. Later, the ditch was extended another 8-miles northward to Polihale and supplied water to the Kekaha Plantation and others such as Kikiaola Land Company and Knudsen Land Company. By the 1920s the KEDIS had an average flow of 35 MGD and capacity of 50 MGD (Ibid). Today, the KEDIS consists of approximately 27 miles of ditches, tunnels, steel siphons, wooden flumes and two hydropower plants. The 2004 system capacities were reported to be an average flow of 56 MGD and transmission capacity of 104 MGD, with 95 MG of storage, an estimated water use of 9.2 MGD and a service area of 3,695 acres (Water Resource Associates, 2004). As of December 2011, Landis Ignacio of the ADC has stated that the KEDIS deliveries have decreased to 30 to 40 MGD (personal communication, December 2011). Figure 6-1 in Section 6.1 of this report plots the historic trend in diversion rates conveyed by the Kekaha Ditch. Interestingly, the increase in water delivery after the early 1990s is accompanied by a decrease in crop water demand or increase in water use efficiency. Water Resource Associates (2004) report that sugarcane historically required large volumes of water to grow (10,000 gallons per day per acre), while the more recent diversified crop operations require smaller unit volumes (4,000 gpd/acre).

Historically, the irrigation components of the KEDIS and the former Kekaha Plantation’s entire infrastructure operations, including drainage, hydropower and road systems were operated and maintained by an informal agricultural coalition under an interim agreement with the State of Hawaii DLNR. During 2004, the State (DLNR) transferred management of the KEDIS to the Agribusiness Development Corporation (ADC) (Water Resource Associates 2004). The ADC has statutory authority to set, enforce, and collect water rates and fees; further it has all the power of the State’s executive department in accordance with Hawaii Revised Statutes (HRS) Chapter 163D, (Water Resource Associates 2004). The KEDIS is also critical to the safety of the Pacific Missile Range Facility because it maintains the drainage system that prevents flooding of the low-lying agricultural lands surrounding the base.

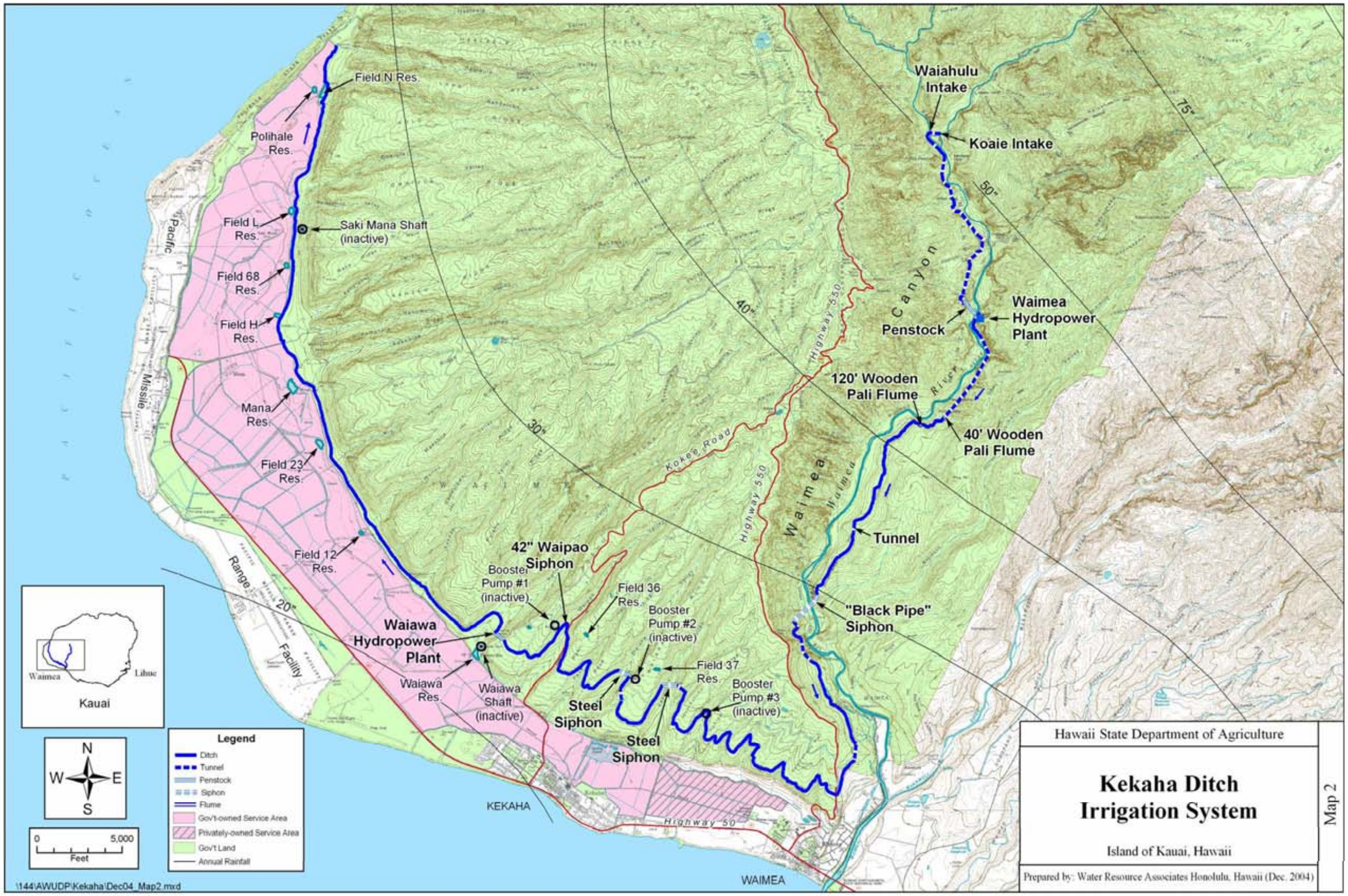


FIGURE 5-1: Kekaha Ditch Irritation System circa 2004. (Source: Water Resource Associates, 2004).

5.2 Runoff

Surface water runoff from the uplands east of the project site is intermittent and appears to occur in direct response to rainfall during the winter months. Records of runoff to/within the Mana Plain are limited to one USGS flow monitoring gauge in the Nahomalu Valley near Mana (station 16130000 indicated on Figure 5-2), which was operated for the period July 1, 1963 through September 30, 1971. Figure 5-3 is a plot of the average daily flow rates at the Nahomalu Valley gauging station. The gauge, located at an elevation of 236-feet, represents a 3.79-square mile drainage area. Based on the plot of the cumulative departure from average annual precipitation for Mana (Figure 4-3), this gauge operated over a relatively wet-period, experiencing above average runoff conditions. However, given this is the only surface water runoff record within the project area, it is considered representative of runoff from the Napali uplands lying east of the project site.

The flow hydrograph in Figure 5-3 indicates that flow from Napali upland drainages to the east of the project site are not perennial due to the rain-shadowing effects on the west end of Kauai and lack of groundwater/spring contributions. Flow from the eastern uplands occurs almost exclusively during the winter months in response to Kona storms. The magnitude of runoff per square mile of drainage area is also very low, likely due to the high porosity and rapid infiltration rates of the lavas that make up the eastern uplands. Burt (1979) estimated that the annual runoff from the Nahomalu Valley equals about 4.5-percent of the equivalent mean annual rainfall. Therefore, from a water resource standpoint, surface water runoff to the project area is not as significant a resource as groundwater even during multi-year wet periods.

5.3 Flooding

The entire project area lies within FEMA Flood Zone A and is subject to inundation by the one percent chance annual flood event (100 year rainfall event) (see Figure 5-4). FEMA determines Zone A areas using approximate methodologies, and since detailed hydraulic analyses have not been performed, no base flood elevations (BFEs) or flood depths are available (FEMA, 2010) for the project area.

Historic flooding within the project area is associated with Kona storms during the winter months of the year. Konas are preceded by strong and persistent southerly winds, and are generally produced by advance of extra tropical cyclones over the North Pacific (Chun, 1952). The direction of the Kona storm is generally from southwest, with greatest precipitation being recorded on the lee side of the mountain ranges (ibid).

In December of 2010, KHE staff experienced a Kona storm at the project site, where approximately 5-inches of rain fell over a 12-hour period on December 8 and 9. Considerable ponding occurred within the project site area, due to direct rainfall as well as overtopping from drainage ditches passing across the site. Similar conditions at the site were observed during March 2006 (Henry, 2010). In both cases, ponding persisted for several days, also in part to complete saturation of site soils in response to shallow groundwater that rose to the ground surface. During dry periods, depth to groundwater is generally between 20- to 40-inches below the ground surface. However, during both the

March 2006 and early December 2010 Kona events, all site soil was completely saturated until the downstream Kawaiele and Nohili pumps could draw down water levels in the main ditch system, allowing shallow surficial site soils to drain.

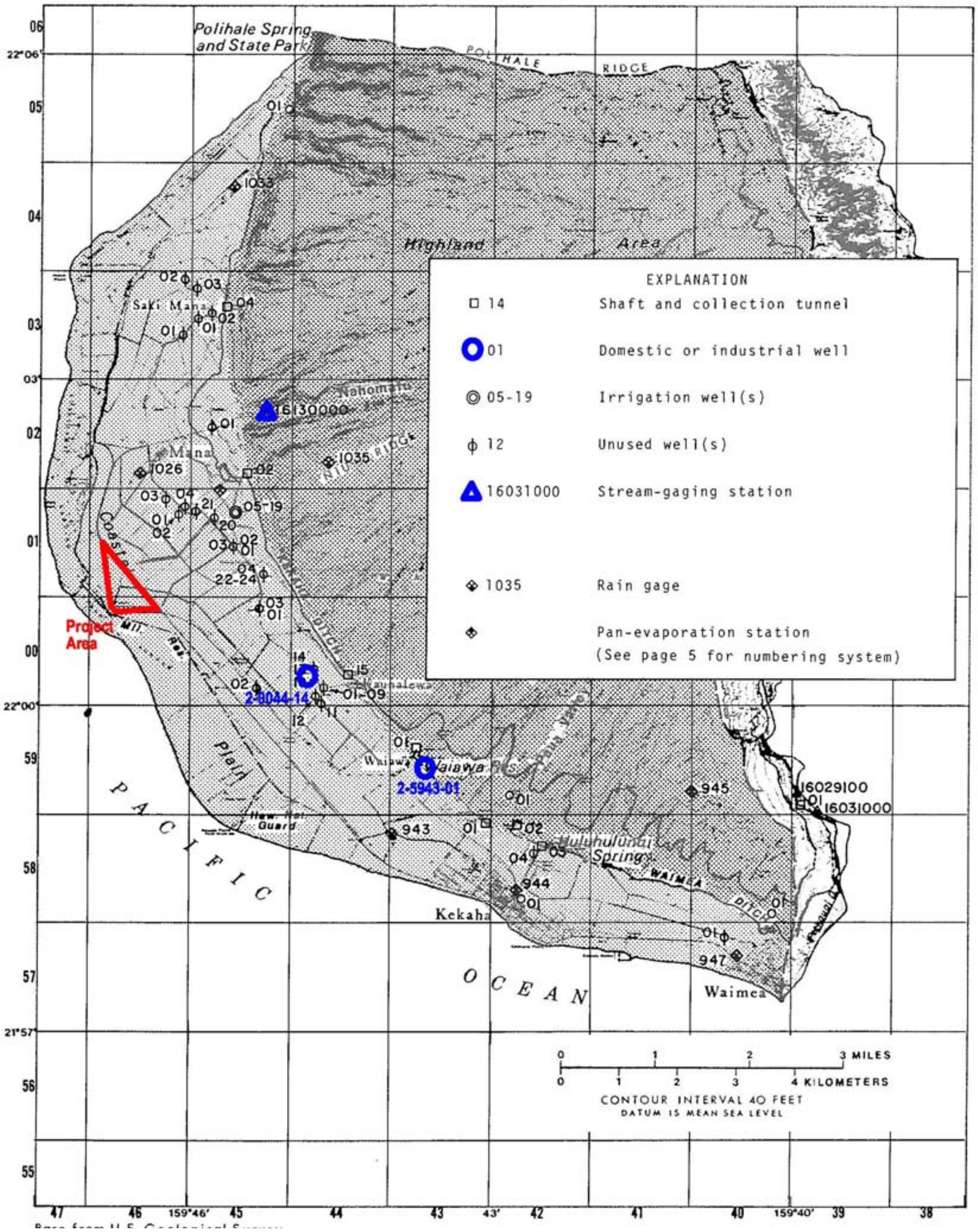


FIGURE 5-2. Surface water monitoring and groundwater well locations. Modified from Burt (1979).

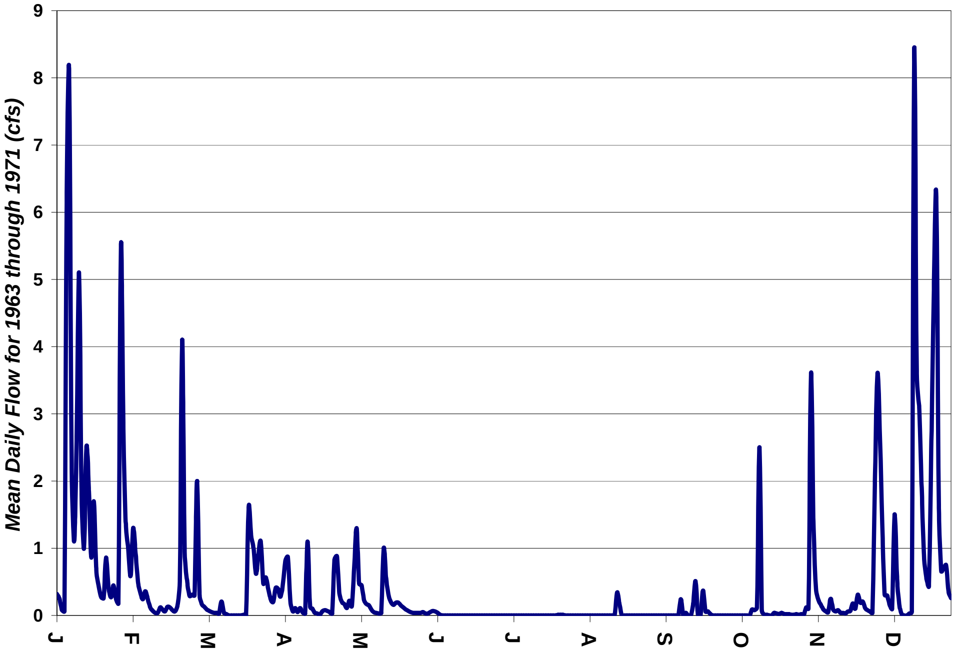


FIGURE 5-3: Plot of mean daily flow rates for the USGS flow monitoring gauge in Nahomalu Valley near Mana for the period July 1, 1963 through September 30, 1971.

FIGURE 5-4: Mapped 100-year flood zone and project area. Source: 2010 FEMA Flood Insurance Rate Map.

5.4 Surface Water Drainage

Surface water runoff within and across the Mana Plain and project site is controlled by a network of drainage ditches installed as part of historic land development focused on sugarcane production. Historically, great ponds and swamps existed on the Mana Plain (Faye, 1997). The "Mana Swamp" encompassed 1500 to 2000 acres of seasonally, semi-permanently, and permanently-flooded wetlands. The USGS 1910 topographic map clearly indicates the extent of the Mana Plain wetlands and shows some ditches already constructed, likely to drain wet areas (see Figure 5-5). In the 1860s, rice farming began in the Waimea River valley and quickly spread to the wetlands of the Mana Plain (Faye, 1997). Probably the first sugarcane pioneer, Valdemar Knudsen, a native of Norway, arrived in Kekaha in 1856. He acquired a 30-year lease on crown lands in the Waimea district where he established a ranch. Using an old Hawaiian ditch at "Waiele", he drained and reclaimed about 50 acres on which he planted sugarcane in 1878 (Hawaiian Sugar Planters' Association, 2004). Faye (1997) reports that, "Early sugar planters harmoniously used the dry land while the rice farmers used the swamp for their cultivation (see Figure 5-6; Faye, 1997)." The advent of large-scale rice farming in California in the 1920s overtook the market for Hawaiian rice and the Hawaiian rice industry collapsed at that time (Faye, 1997).

Beginning in 1922 with the Kekaha Sugar Plantation, low lying "swamp lands" on the Mana Plain were systematically drained (and in some instances filled) to expand sugarcane production (Faye, 1997). Cox et. al., (1970) report that in 1910, at the time of the first topographic survey of Kauai, there was a dredged channel from the original coastal-plain to the ocean at "Waieli" (sic). They state it was probable that the only original natural discharge from the swamps to the ocean was by ground-water seepage. By 1931, between 2,000 and 3,225 acres were reclaimed using ditches and planting a salt tolerant type of cane (Hawaiian Sugar Planters' Association, 2004)

The primary mechanism for "reclaiming" the Mana Plain swamp land was the construction of ditches that would eliminate ponding by drainage of surface waters as well as dewater adjacent soils and lower the shallow water table to a depth below the sugarcane rooting depth. The resulting drainage ditch network within the project vicinity is depicted on Figure 5-7, which indicates 2 main drainage canals bisecting the project site and several abandoned field ditches. Currently, the drainage ditch network includes excess irrigation water (irrigation returns), waste artesian well water, natural groundwater seepage, and surface water storm runoff from the eastern upland creeks local runoff (Cox et. al., 1970). Ditch discharges are directed to the Pacific Ocean via the Nohili and Kawaiele pump stations.

The pump stations and a drainage canal system adjacent to the project site are operated and maintained by the State of Hawaii Agribusiness Development Corporation (ADC) under NPDES Permit No. 000086. The Kawaiele and Nohili Pump Stations are operational 24 hours per day through cyclical pumping of drainage water from the main canals and releasing it to adjacent canals draining to the Pacific Ocean. Greater than 5 inches of rain in a 24 hour period or loss of power to the pump stations results in flooding of agricultural properties upstream of the pump stations.

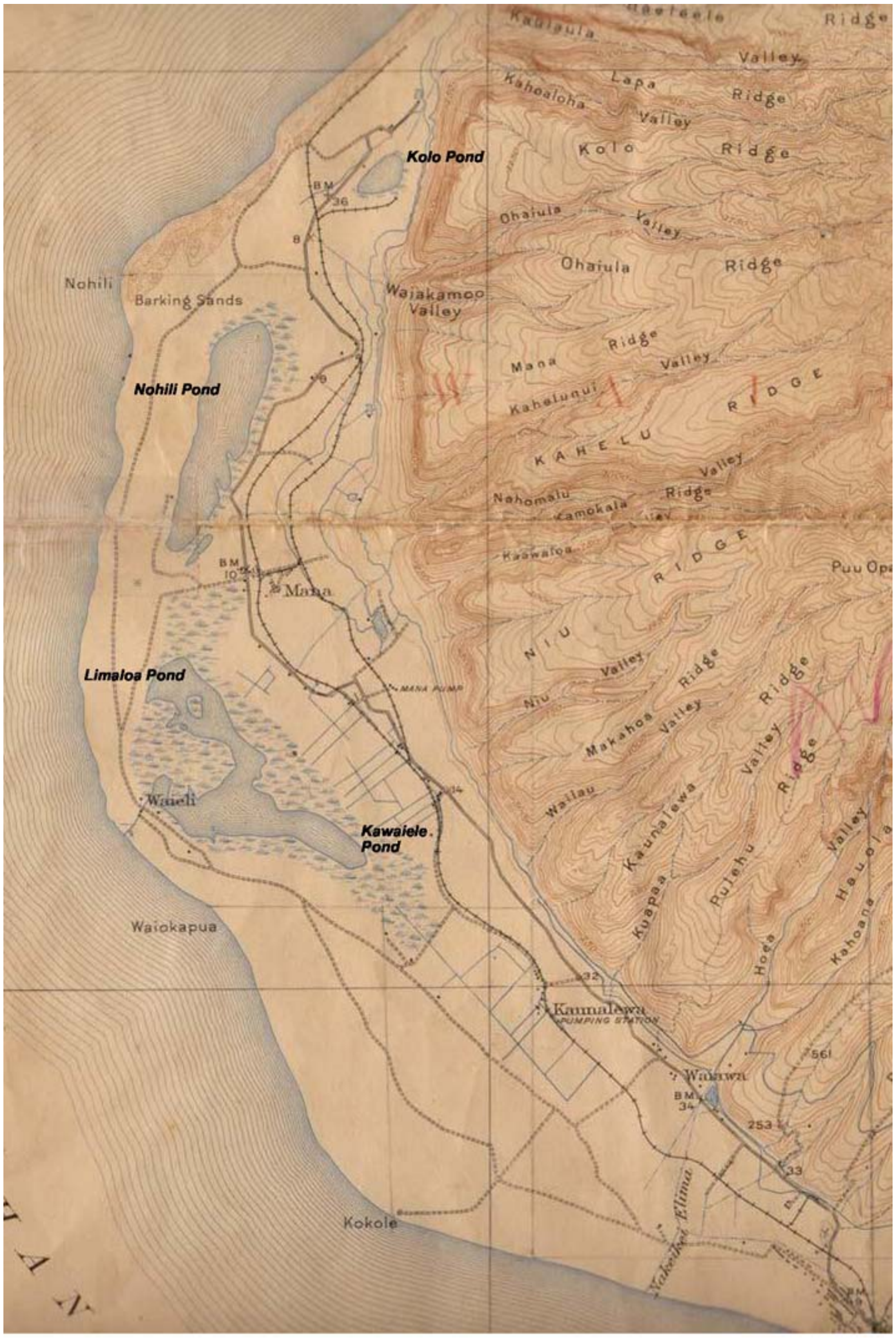


FIGURE 5-5. Annotated 1910 USGS topographic map of Mana Plain. Map taken from Henry and Ryder (2008) with pond names from Faye (1997).

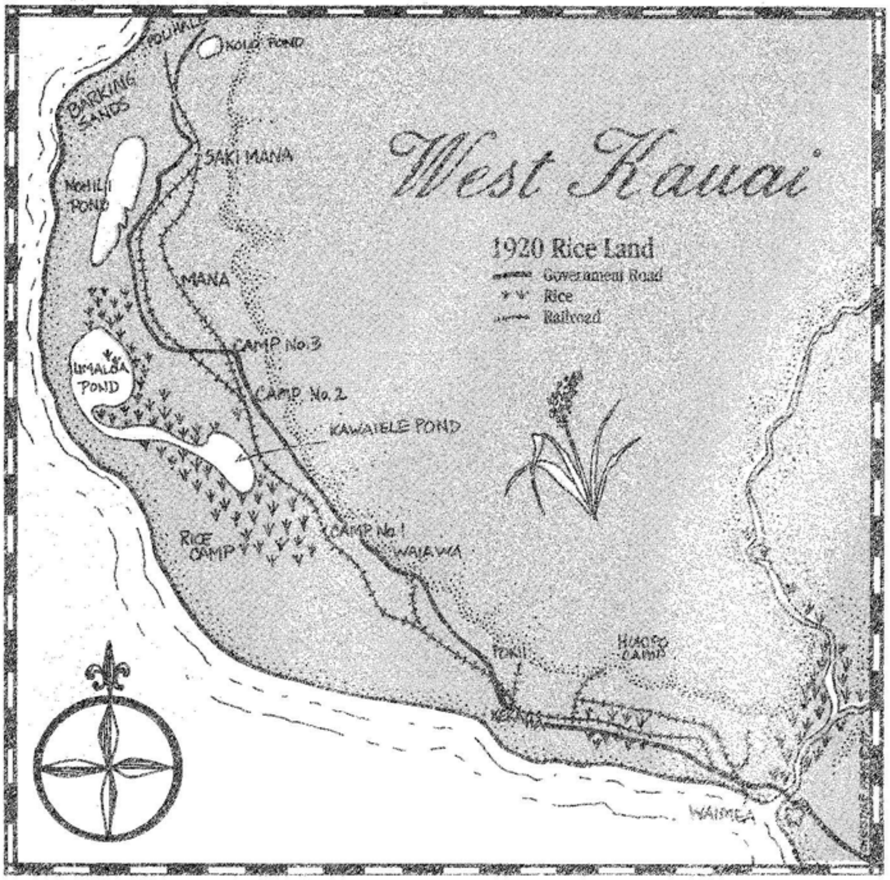


FIGURE 5-6. Extent of rice cultivation on Mana Plain circa 1920 (from Faye, 1997).

Average and maximum monthly pump rate data for both pump stations are available from 2001 through 2009. A plot of average and maximum monthly pumping rates for both stations is presented on Figure 5-8. The 2001-2009 average pumping rate at the Kawaiele station was 65.5 acre-feet per day (AF/day) while the average flow rate at the Nohili station was 24.8 AF/day. These flow rates equate to an average annual pumping volume of 23,900 and 9,040 AF or combined rate of 32,940 AF/year. Cox et. al. (1970) reports that average discharges at Kawaiele and Nohili in 1970 were 169 AF/day (55 million gallons per day [MGD]) and 43 AF/day (14 MGD), respectively. These rates reported by Cox et al. (1970) sum to 212 AF/day or 61,685 AF/year – nearly double the rates presented in the 2001-2009 ADC reports.

Records for the Kawaiele pump station indicate a constant decrease in the volume of water pumped between the 2002 and 2009 period, indicating a decrease in the amount of water available as wetland supply (the 2001 record is missing monthly pump values for January and February and is not included in this plot; see Figure 5-9). Review of pump records also indicates very low availability in some summer months (e.g., 62- and 47-AF during the months of October and November 2009) that may not be sufficient to meet wetland water demands. In comparison to the 2001-2009 values presented above, the average pumping rate at Kawaiele for the more recent 2005-2009 period drops to about 50 AF/day or 18,150 AF per year, while the Nohili station drops to about 20 AF/day or 7,350 AF per year.

Cox et al. (1970) go on to report that pump capacities would need to be increased two-fold for periods of one to two weeks during and after Kona storms to take care of the storm runoff. During a site visit on December 10, 2010, KHE staff noted the capacities on the three pumps that comprise the Kawaiele pump station; two at 28,000 gallons per minute (gpm; 62-cfs) and one at 14,000 gpm (31-cfs). This equates to a combined pumping rate of 70,000 gpm or 309 AF/day (155-cfs) if run continuously for an entire day. In actuality, actual pump rates are only 85% of these values, due to energy losses associated with piping, etc. (DOFAW, 2011).

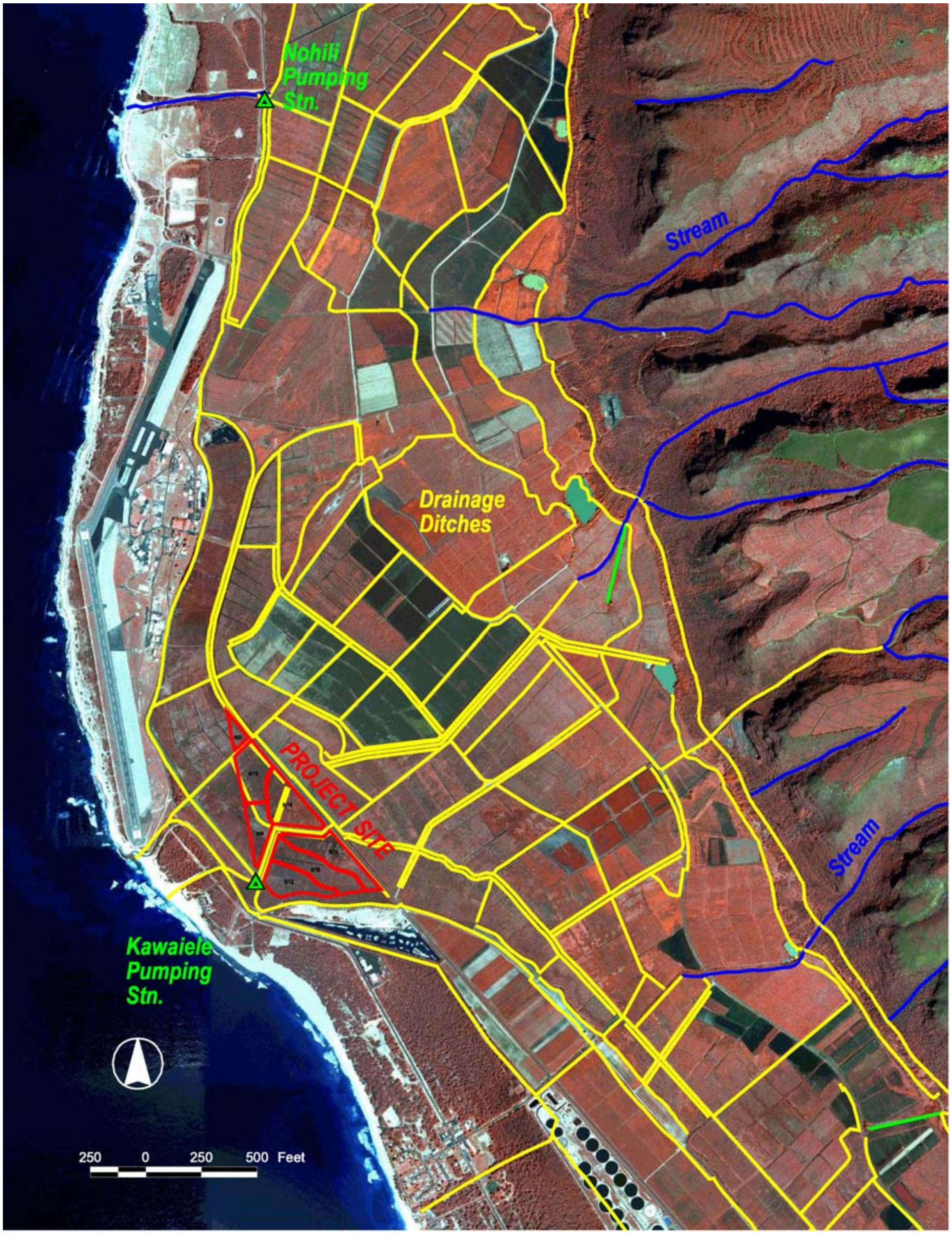


FIGURE 5-7: Local area surface water drainage system and pumping stations.

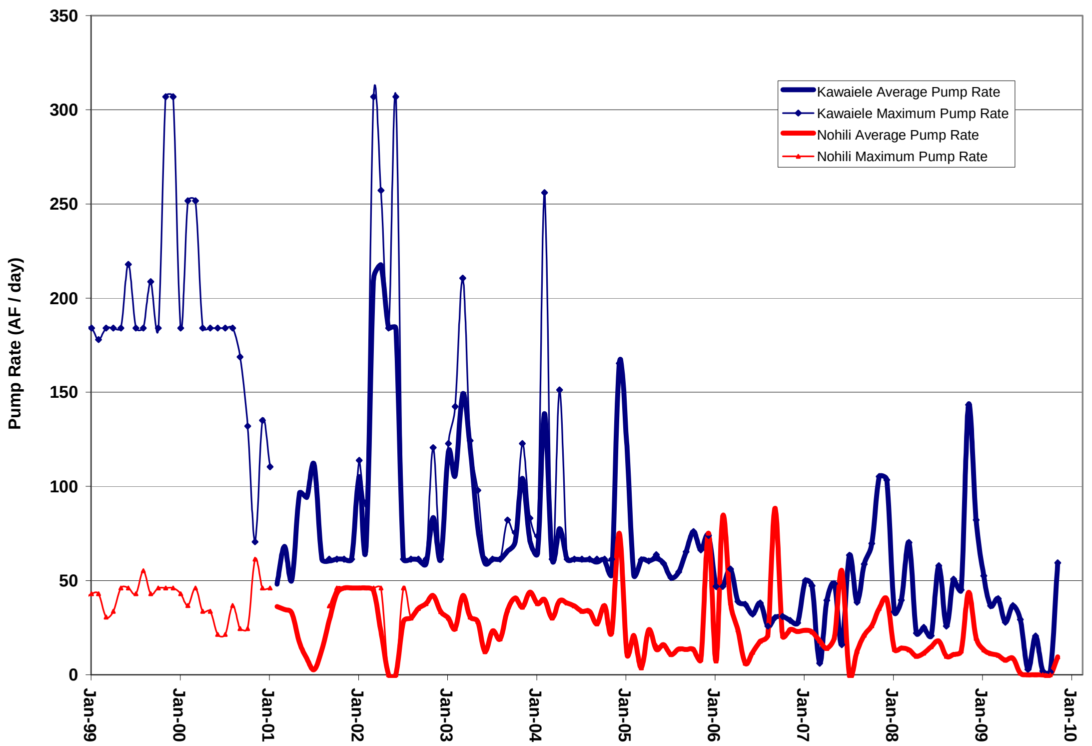


FIGURE 5-8: Average and maximum monthly pumping rates at Kawaiele and Nohili pump stations.

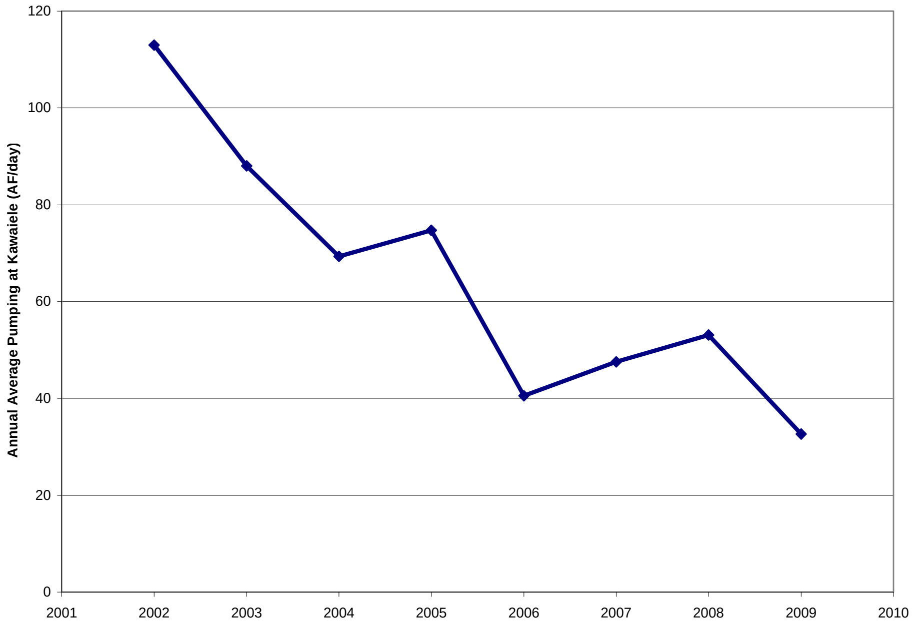


FIGURE 5-9: Measured average annual pump rates at the Kawaiele pump station from 2002 to 2009.

5.5 Drainage Water Quality

The surface water drainage through the project site may have an influence on the quality and sustainability of restored wetlands. Therefore, water quality data for the surface water drainages through the site was obtained and evaluated. Water quality data sources reviewed as part of this study included:

- Water quality measurements taken quarterly from 1999 through 2009 at the outfall of Kawaiele pump station (#002) as reported in the Agribusiness Development Corporation discharge monitoring reports (DMRs) submitted to the State of Hawaii Department of Health as a condition of the NPDES Permit No. 000086; and
- Refractometer salinity measurements by DOFAW in drainage canals and abandoned field ditches (see Figure 5-10).

A summary of quarterly average, maximum and minimum water quality concentrations at the Kawaiele pump station (#002), as reported in the DMRs obtained from the State of Hawaii Department of Health, is provided in Table 5-1 as it represents water quality in the main drainage canals that bisects the project site for the period 1999 through 2009. Analytical results for eight discrete water samples collected at the Kawaiele pump from 2005 through 2008 are also available from the DMRs and are summarized in Table 5-2.

5.5.1 Salinity

Based on ADC reports for the 1999 through 2006 period, the average salinity of water at Kawaiele pump station was 7.6 ppt and ranged from 0.6 ppt during December 2000 to 26.3 ppt during the summer of 2006 (Table 5-1). Discrete salinity measurements for the 2005-2008 period also fall within this range (Table 5-2) and have a similar average concentration (8.23 ppt) to the longer term quarterly average (7.6 ppt). Salts at the Kawaiele pump station are the result of seawater drawn inland by the KEDIS pump system (Hawaii Pacific Engineers and Tom Nance Water Resource Engineering 1994). They estimate that the water discharged by the Kawaiele pump station is 27% seawater and 73% surface water runoff from the uplands.

Monitoring of the main canals by DOFAW during January 2012 revealed that salinity decreases in the eastern direction from about 10 ppt in the north-south canal to the west of the project site, to an average concentration of about 4 ppt in the canals at Kaumaulii Highway. Decreasing salinity measurements observed by DOFAW in main drain surface waters when moving inland from the pump station is consistent with the conclusions of Hawaii Pacific Engineers and Tom Nance Water Resource Engineering (1994).

Measurements of salinity in abandoned irrigation field ditches exhibit increasing concentrations with distance away from the main drainage canals. Water within the abandoned irrigation field ditches experiences longer residence times, less freshwater mixing, long-term leaching of salts from onsite soils[15], and multiple years of irrigation water evaporation within agricultural fields. The soils at the project site are “moderately to strongly saline” (16.0- to 32-mmhos/cm) (USDA NRCS, 2006).

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[15] The weathered state of igneous basalts naturally contains large quantities of magnesium salts.

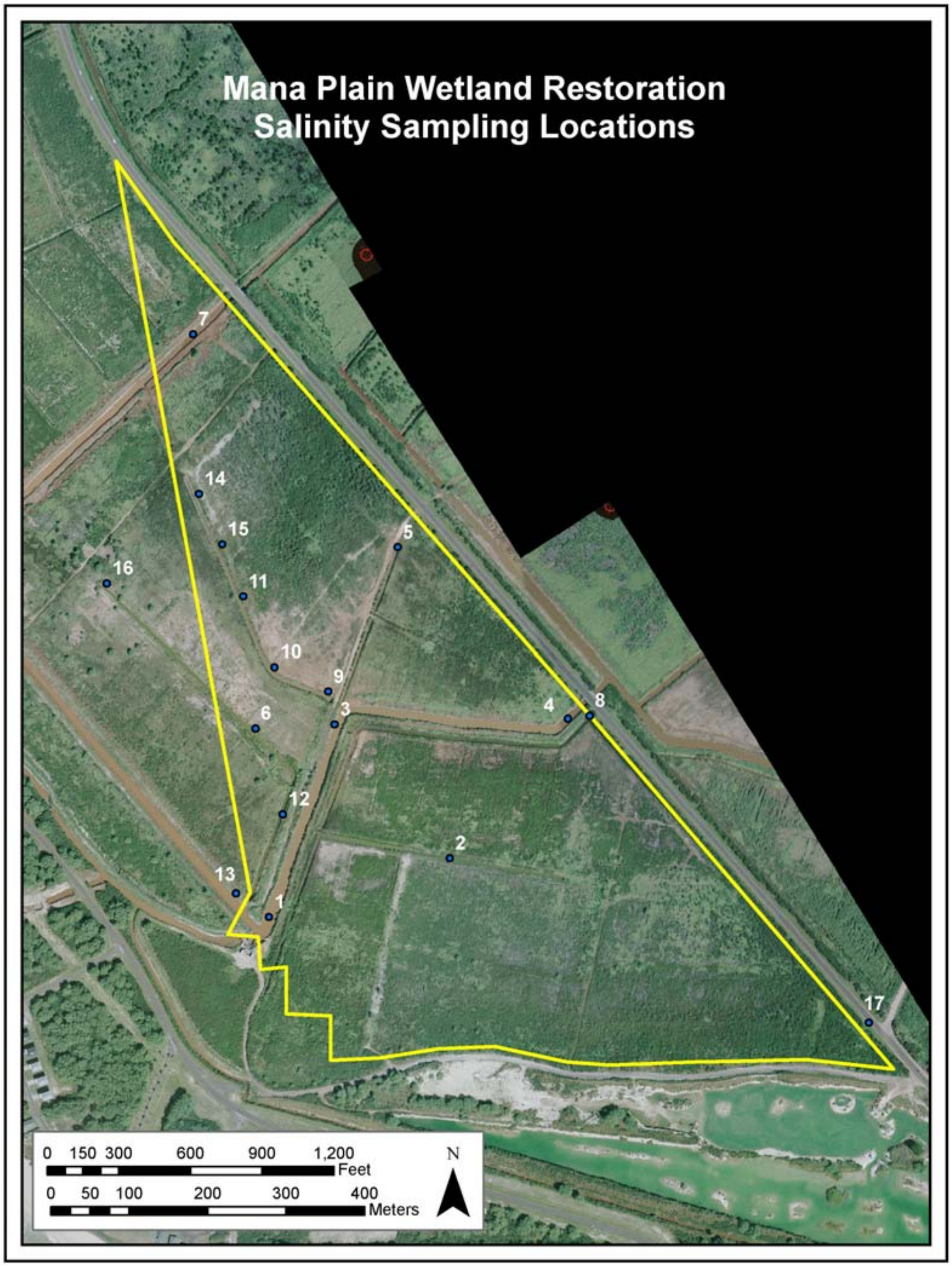

FIGURE 5-10: Water quality sampling sites at Mana Plain Wetland Restoration Project site (map provided by DOFAW).

PARAMETER	AVERAGE	MAXIMUM	MINIMUM	COUNT
AVG TSS (kg/day)	4,112.3	26,501.0	57	104
MAX TSS (kg/day)	8,546.2	53,618.5	67	125
AVG TSS (mg/L)	53.6	251.5	3.3	71
MAX TSS (mg/L)	75.8	476.0	4.3	71
TOTAL N_2 (ug/L)	795.3	1,682.1	37.3	24
Ammonia N_2 (ug/L)	95.2	857.4	0.7	23
Nitrate + Nitrite NO_3+NO_2 (ug/L)	380.5	1,234.1	13.4	23
TEMP (^{o}F)	76.8	80.0	73.0	5
TEMP (^{o}C)	25.6	28.2	23.2	26
Salinity (ppt)	7.6	26.3	0.6	31
pH (min)	7.6	8	7	69
pH (max)	7.8	8.6	7.1	70
chlorophyll-a (ug/L)	3.3	23.5	0.5	29

Table 5-1. Water Quality at the Kawaiele pump station as reported in the Agribusiness Development Corporation Discharge Monitoring Reports (DMR) for the period January 1999 through December 2009.

Date	NO3 (ug/L)	NH4 (ug/L)	TP (ug/L)	TN (ug/L)	TURB (ntu)	SALT (o/oo)	Chl-a (ug/L)
6/22/2005	13.44	29.68	39.68	427.28	4.6	9.33	0.535
10/9/2005	807.52	30.24	68.20	1179.92	28.0	9.20	3.650
4/30/2006	623.84	857.36	86.80	1620.08	5.8	12.99	1.206
12/16/2006	953.68	104.72	45.88	1169.28	7.7	5.15	0.703
3/7/2007	418.32	63.28	38.44	814.80	9.1	8.07	0.986
9/29/2007	184.24	99.68	62.00	464.24	23.0	9.69	0.955
3/1/2008	525.56	65.22	78.40	5985.00	84.9	6.75	0.580
12/8/2008	389.76	76.16	42.16	515.76	1.3	4.69	0.535
Average	**490**	**166**	**58**	**1522**	**21**	**8.23**	**1.14**

Table 5-2. Summary of ditch water quality feeding the downstream Kawaiele Outfall pump #002 (2005-2008).

Salinity values observed in the central irrigation field ditch at locations 3, 9, 10, 11, 14, and 15 on February 14, 2010 were 2 ppt at the confluence with the main drainage ditch, then 3, 6, 8, 12, and 28 ppt measured in the upstream direction away from the irrigation ditch. Salinity as high as 67-ppt was measured in a plugged irrigation ditch located parallel to and approximately 80-feet west of the main drain. This higher salinity measurement results from concentrating salts as water evaporates with no or little inputs of fresh water.

Salinity and other water quality parameters were sampled within the Kawaiele Waterbird Sanctuary Wetland immediately south of the Mana Plain Wetland Restoration site. Water in these wetlands is supplied by local groundwater and exposed to evaporation, which tends to concentrate salinity and leads to higher salinity levels. Measurements in three locations were taken monthly over a one year period from December 2009 through December 2010. The average salinity for each area was 8 ppt, 11 ppt, 12 ppt.

5.5.2 TSS

Total Suspended Solids is measured quarterly at the outfalls of the Kawaiele and Nohili Pump Stations as a condition of NPDES Permit No. 000086 (ADC, 1999-2009). A summary of data is provided in Table 5-1. TSS data was recorded as an average and a maximum monthly value in kg/day, and as an average and maximum value in mg/L. TSS values at the Kawaiele station ranged from 3.3 to 476 mg/l and averaged 53.6 mg/l. Cox et al., (1970) state that the colloids that constitute the TSS in the drainage ditches, must originate in major part from erosion of agricultural lands. They also express concern about low concentrations of herbicide that seem likely to be present but have not been reported.

5.5.3 Nitrogen

Nitrogen, an essential nutrient for plants and animals, is present in the environment in several chemical forms. In excessive quantities, nitrogen reduces levels of dissolved oxygen in a waterway, leading to eutrophication and negative impacts on vegetation and organisms. Nitrogen was measured as total nitrogen (TN), nitrate- and nitrite-nitrogen combined (NO_3^--NO_2^-) and ammonia nitrogen (NH_4^+). TN, the total amount of nitrogen in a sample, is made up of bioavailable forms of nitrogen including NO_3^-–NO_2^- and NH_4^+ (16). Ammonia is a measure of the most reduced inorganic form of nitrogen in water and includes dissolved ammonia (NH3) and the ammonium ion (NH4+). Ammonium is typically the ammonia species present in most natural water environments (Hem, 1985).

Three forms of nitrogen are measured quarterly at the outfalls of the Kawaiele and Nohili Pump Stations as a condition of NPDES Permit No. 000086 (ADC, 1999-2009); total nitrogen, ammonia and Nitrate + Nitrite. Based on the 1999-2009 quarterly monitoring results (Table 5-1): total nitrogen averaged 0.795 mg/L; ammonia averaged 0.0952 mg/L; and nitrate+nitrite averaged 0.381 mg/L. Discrete sample results (Table 5-2) yield a higher

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[16] In contrast to TN**,** Total Kjeldahl nitrogen (TKN) is nitrogen unavailable for growth or nitrogen bound up in organic form. TKN was not measured as part of the Kawaiele pump station monitoring.

average total nitrogen concentration of 1.522 mg/L, but similar average ammonia (0.166 mg/L) and nitrate+nitrite[17] (0.490 mg/L) concentrations were recorded.

Nitrate is a measure of the most oxidized and stable form of nitrogen in a water body. Nitrate is the principle form of combined nitrogen found in natural waters. Without anthropogenic inputs, most surface waters have less than 0.3 mg/L of nitrate. The average nitrate concentrations of the canal water are slightly higher than this concentration, which likely results from drainage of the surrounding agricultural fields. Nitrate is the primary form of nitrogen used by plants as a nutrient to stimulate growth. Excessive amounts of nitrogen may result in phytoplankton or macrophyte proliferations.

Natural waters typically have ammonia concentrations less than 0.1 mg/L. Average ammonia concentrations of the canal water bracket this concentration with occasional spikes relatively higher. The elevated ammonia concentrations are likely associated with drainage from agricultural fields. Excess ammonia contributes to eutrophication of water bodies. This results in prolific algal growth that has deleterious impacts on aquatic life, drinking water supplies, and recreation. Ammonia comes in two forms, Ammonium (NH_4^+), which isn't toxic and ammonia (NH_3), which is toxic. The toxic ammonia occurs at higher proportions with higher pH and higher temperature. Ammonia levels that are toxic to aquatic organisms depend on the ammonia concentration, pH and temperature of the water (Hargreaves and Tucker, 2004).

5.5.4 Phosphorous

Phosphorous was only analyzed and reported for the discrete samples collected within the 2005 – 2008 period (Table 5-2). Total phosphorous (TP) concentrations ranged from 38.44 ug/L to 86.80 ug/L and averaged 58.00 ug/L. Hem (1985) reports that naturally occurring total dissolved phosphorous in river water should average about 25 ug/L. General sources of elevated TP and soluble reactive phosphorous (SRP)[18] include sewage treatment plant effluent, agriculture, urban developments (particularly from detergents), and industrial effluents. The elevated concentration of total phosphorous detected in project surface water is likely attributable to agricultural runoff.

5.5.5 pH

Quarterly measurements of pH are recorded at the outfalls of the Kawaiele and Nohili Pump Stations as a condition of NPDES Permit No. 000086 (ADC, 1999-2009). A summary of data provided within the report is provided in Table 5-1. Quarterly data was available from March 2005 through December 2009. Monthly maximum and minimum

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[17] Although not analyzed for separately but quantified as the sum of both nitrate + nitrite, nitrite is a measure of a form of nitrogen that occurs as an intermediate in the nitrogen cycle. It is an unstable form that is either rapidly oxidized to nitrate (nitrification) or reduced to nitrogen gas (de-nitrification). Thus, it is likely that the reported sum of nitrate+nitrite is dominated by nitrate. Hem (1985) also reports that nitrite is normally present in only minute quantities (i.e., is unstable) in surface waters (<0.001 mg/L). Nitrite and organic species of nitrogen are unstable in aerated water and are generally considered indicators of pollution through disposal of sewage or organic waste (Hem, 1985). Therefore, the nitrate (NO3) concentration reported for the discrete sample set from 2005-2008 is believed a reasonable representative concentration for nitrate+nitrite.

[18] Soluble reactive phosphorous (SRP) is a measure of orthophosphate, the fraction of phosphorous that is most available for plant uptake during photosynthesis.

pH was analyzed for 58 data samples. On average, pH ranges between 7.6 and 7.7. The maximum recorded pH was 8.1, and the minimum was 7.0.

5.5.6 Chlorophyll a

Chlorophyll a is the pigment that allows algae to convert sunlight into organic compounds (food) during photosynthesis. Chlorophyll a is the predominant type of chlorophyll found in living (respiring) algae. It is an indirect measure of algae level; elevated concentrations of chlorophyll a in water indicate nutrient pollution because nutrients fuel the growth of algae. Chlorophyll a concentrations in ditch water ranged from 0.5- to 23.5-ug/l and averaged 3.3-ug/l.

The concept of trophic status is based on the process where changes in nutrient levels (measured by total phosphorus) cause changes in algal biomass (measured by chlorophyll *a*) which in turn causes changes in water clarity. A trophic state index is a convenient way to quantify this relationship. One popular index used by the U.S. EPA is the Carlson's index, which uses a measure of algal biomass on a scale from 0 – 110 to rank the trophic state of a water body (U.S. EPA, 2007). The Carlson trophic state index is useful for comparing waters within a region and for assessing changes in trophic status over time. Concentrations of chlorophyll a and total phosphorous can be used to calculate the Carlson’s Trophic State Index.

Ranges in the Carlson’s Index values are often grouped into trophic state classifications. The range between 40 and 50 is usually associated with mesotrophic water bodies (moderate productivity), while index values greater than 50 are associated with eutrophic water bodies (high productivity), and values less than 40 are associated with oligotrophic water bodies (low productivity) (U.S. EPA, 2007).

Based on the 1999-2009 quarterly chlorophyll a water quality results presented above (Table 5-1), the canal drainage water has a Carlson’s Index ranging from 24 to 62 and average of 42. These values are an indirect measure of the algal biomass occurring in the canals. Total phosphorous results were also be used to estimate the potential trophic state from the standpoint of nutrient availability. Based on the 1999-2009 quarterly total phosphorous water quality results presented above (Table 5-1), the canal drainage water has a Carlson’s Index ranging from 57 to 69 and average of 63.

The Carlson Index values based on chlorophyll a are representative of a mesotrophic water body. Mesotrophic water bodies are waters with an intermediate level of productivity, and are commonly clear water lakes and ponds with beds of submerged aquatic plants and medium levels of nutrients. The Carlson Index values based on total phosphorous are representative of a eutrophic water body. An eutrophic body of water has high biological productivity due to excessive nutrients, especially nitrogen and phosphorus, and typically supports an abundance of aquatic plants and/or algae. Occasionally an excessive algae bloom will occur and significantly reduce dissolved oxygen levels, which can be detrimental to aquatic organisms. The process of eutrophication can occur naturally and by human impact on the environment. Although the chlorophyll a based index represents an algae-based trophic state, the total phosphorous concentrations suggest the potential to develop eutrophic conditions and project wetland basins should be observed and water quality monitored, if necessary, to evaluate future water quality and habitat conditions.

5.5.7 Compliance with Water Quality Standards

The main ditch water which feeds the Kawaiele Outfall pump #002 may be used as a water supply to the Mana Plain Wetland Restoration Project basins. Therefore, it is necessary to evaluate the ditch water quality against likely water quality standards that will apply to the project wetlands.

Based on review of Chapter 54 of Title 11, Hawaii Administrative Rules (HAR), titled "Water Quality Standards", available through the state Department of Health, it appears that the project wetlands would be classified as inland waters or more specifically “low wetlands,” or if brackish inland “coastal wetlands.” Chapter 54 of Title 11 defines “low wetlands” as follows.

> *"Low wetlands" means freshwater wetlands located below 100 m (330 ft) elevation that may be natural or artificial in origin and are usually found near coasts or in valley termini. Low wetlands are maintained by either stream, well, or ditch influent water, or by exposure of the natural water table. Low wetlands include, but are not limited to, natural lowland marshes, riparian wetlands, littoral zones of standing waters (including lakes, reservoirs, ponds and fishponds) and agricultural wetlands such as taro lo'i.*

Low wetland inland waters are subject only to the basic water quality criteria set forth in HAR Section 11-54-4. These criteria are summarized in Table 5-1. Comparison of the ditch water quality data summarized in Tables 5-1 and Table 5-2 to the water quality standards presented in Table 5-3 indicate that measured ditch water quality concentrations meet State water quality standards.

Basic water quality criteria applicable to all waters
All waters shall be free of substances attributable to domestic, industrial, or other controllable sources of pollutants, including: (1) Materials that will settle to form objectionable sludge or bottom deposits; (2) Floating debris, oil, grease, scum, or other floating materials; (3) Substances in amounts sufficient to produce taste in the water or detectable off-flavor in the flesh of fish, or in amounts sufficient to produce objectionable color, turbidity or other conditions in the receiving waters; (4) High or low temperatures; biocides; pathogenic organisms; toxic, radioactive, corrosive, or other deleterious substances at levels or in combinations sufficient to be toxic or harmful to human, animal, plant, or aquatic life, or in amounts sufficient to interfere with any beneficial use of the water; (5) Substances or conditions or combinations thereof in concentrations which produce undesirable aquatic life; and (6) Soil particles resulting from erosion on land involved in earthwork, such as the construction of public works; highways; subdivisions; recreational, commercial, or industrial developments; or the cultivation and management of agricultural lands.
To ensure compliance with paragraph (4) above, all state waters are subject to monitoring and to the following standards for acute and chronic toxicity and the protection of human health. (A) "Acute Toxicity" means the degree to which a pollutant, discharge, or water sample causes a rapid adverse impact to aquatic organisms. The acute toxicity of a discharge or receiving water is measured using the methods in section 11-54-10, unless other methods are specified by the director. (B) "Chronic Toxicity" means the degree to which a pollutant, discharge, or water sample causes a long-term adverse impact to aquatic organisms, such as a reduction in growth or reproduction. The chronic toxicity of a discharge or receiving water is measured using the methods in section 11-54-10, unless other methods are specified by the director. (C) "Dilution" means, for discharges through submerged outfalls, the average and minimum values calculated using the models in the EPA publication, Initial Mixing Characteristics of Municipal Ocean Discharges (EPA/600/3-85/073, November, 1985), or in the EPA publication, Expert System for Hydrodynamic Mixing Zone Analysis of Conventional and Toxic Submerged Single Port Discharges (Cormix 1) (EPA/600/3-90/073), February, 1990. (D) "No Observed Effect Concentration Observed Effect Concentration" (NOEC), means the highest per cent concentration of a discharge or water sample, in dilution water, which causes no observable adverse effect in a chronic toxicity test. For example, an NOEC of 100 percent indicates that an undiluted discharge or water sample causes no observable adverse effect to the organisms in a chronic toxicity test.
Narrative toxicity and human health standards. (A) Acute Toxicity Standards: All state waters shall be free from pollutants in concentrations which exceed the acute standards listed in paragraph (3). All state waters shall also be free from acute toxicity as measured using the toxicity tests listed in section 11, or other methods specified by the director. (B) Chronic Toxicity Standards: All state waters shall be free from pollutants in concentrations which on average during any twenty-four hour period exceed the chronic standards listed in paragraph (3). All state waters shall also be free from chronic toxicity as measured using the toxicity tests listed in section 11-54-10, or other methods specified by the director. (C) Human Health Standards: All state waters shall be free from pollutants in concentrations which, on average during any thirty day period, exceed the "fish consumption" standards for non-carcinogens in paragraph (3). All state waters shall also be free from pollutants in concentrations, which on average during any 12 month period, exceed the "fish consumption" standards for pollutants identified as carcinogens in paragraph (3).
Numeric standards for toxic pollutants applicable to all waters. The freshwater standards apply where the dissolved inorganic ion concentration is less than 0.5 parts per thousand; saltwater standards apply above 0.5 parts per thousand. Values for metals refer to the dissolved fraction. See §11-54-4 for a comprehensive list of inorganic compound and metals standards.
Requirements applicable to discharges to state waters. See §11-54-4 for a these standards which shall be enforced through effluent limitations or other conditions in discharge permits.

Table 5-3. Basic water quality criteria applicable to all Hawaii waters including Inland Waters and "Low Wetlands" and "Coastal Wetlands."

6.0 GROUNDWATER LEVELS AND SALINITY

6.1 Groundwater Development

Water development on the Mana Plain was not restricted to surface water diversions. Development of the basal groundwater by wells in the lava flows under the Mana Plain began in the early 1880s (MacDonald et al., 1960; Burt, 1979). By 1890, there were about a dozen wells near Kekaha and Mana and more wells were drilled near Waimea and Kaunalewa by 1898 (Burt, 1979). MacDonald et al., (1960) report that from the time of the first well until about 1906 perhaps 50 or more wells were drilled throughout the Plain for the irrigation of rice and sugarcane. Nine wells were installed in 1929 and 1930 alone. Many of the early wells were abandoned due to salt water intrusion and are now lost. Most of the early wells that have been abandoned were located within or became exposed to the brackish water transition zone as it shifted due to increased groundwater pumping.

During the period of their studies on impacts to groundwater resources, MacDonald et al., (1960) report 52 wells existed in the Mana Plain while Burt (1979) reports “60-odd” wells. Most of the wells on the plain are between 210- and 280-feet deep, casing off the caprock and are left with open holes within the basaltic rocks (Burt, 1979). In addition to the pumped groundwater during the sugarcane era, an undetermined amount of water discharged to the surface from artesian wells that were abandoned or were used for irrigation. Most wells were initially artesian when installed, but with groundwater pumping and unregulated discharges from old or abandoned wells, heads in individual wells declined and many wells stopped flowing during the peak production period (Burt, 1979). At that time, the unchecked flow of water from abandoned artesian wells contributed to the land-ward migration of the transition zone and salt water in the basal aquifer, which lead to the deterioration of water quality from wells leading to their abandonment.

In addition to groundwater wells in the Plain, shafts and tunnels were drilled into the base of the Napali lava cliffs near Kekaha starting in 1931 (Ibid). Between 1931 and 1957, six shafts were installed along the inland edge of the Plain to supply irrigation and domestic water. Between 1940 and 1960, the average daily groundwater pumping rate for the Kekaha-Mana Plain ranged from 6.5 to 14 MGD, with about three-fifths of that water coming from drilled wells, the rest from shafts and tunnels (Ibid). Average pumping rates between 1958 and 1968 increase to about 24 MGD (Burt, 1979) and up to 42 MGD between 1969 and 1973 (Burt, 1979). However, between 1974 and 1978, groundwater pumping rates declined to about 30 MGD (Ibid). Groundwater use estimates from the Kauai Water Use and Development Plan (R.M. Towill Corporation, 1990) for the Kekaha hydrologic system for 1990 are down to 19.5 MGD (19.2 MGD to irrigation and 1.3 MGD for municipal use) Ground water pumping on the Mana Plain has decreased since 1990 to an estimated annual pumping rate of 4 MGD during 2011 (personal communication, Landis Ignacio of ADC, December 2011). . Using these data, a plot of average annual groundwater pumping rates from the Kekaha-Mana Plain basal groundwater system was prepared and is provided in Figure 6-1 to demonstrate the historic and existing demands on groundwater supply. Likely factors that contributed to the rise and fall in groundwater demands and uses in the project area over this time include: a) by 1940, Kekaha Sugar Company changed completely to a mechanical sugarcane production process, with increased and improved management and processing occurring through World War II and into the 1950s (Hawaiian Sugar Planters' Association, 2004); b) by 1970, returns from sugarcane production diminish and plantation closures begin throughout Hawaii (Water Resource Associates, 2004); and c) sugar plantation closures are near complete and the post-plantation period starts with sugar cane being replaced by diversified crops that are irrigated more efficiently (drip irrigation) and require nearly half (3,400 – 4,000 gpd/acre; Ibid) the applied water per acre versus modern sugarcane application rates (6,850 to 8,700 gpd/acre per Shade, 1995; 10,000 gpd/acre per Water Resources Associates, 2004). Of particular note are the decrease in both recent (2011) groundwater withdrawal and KEDIS deliveries back to the 1900-1910 levels.

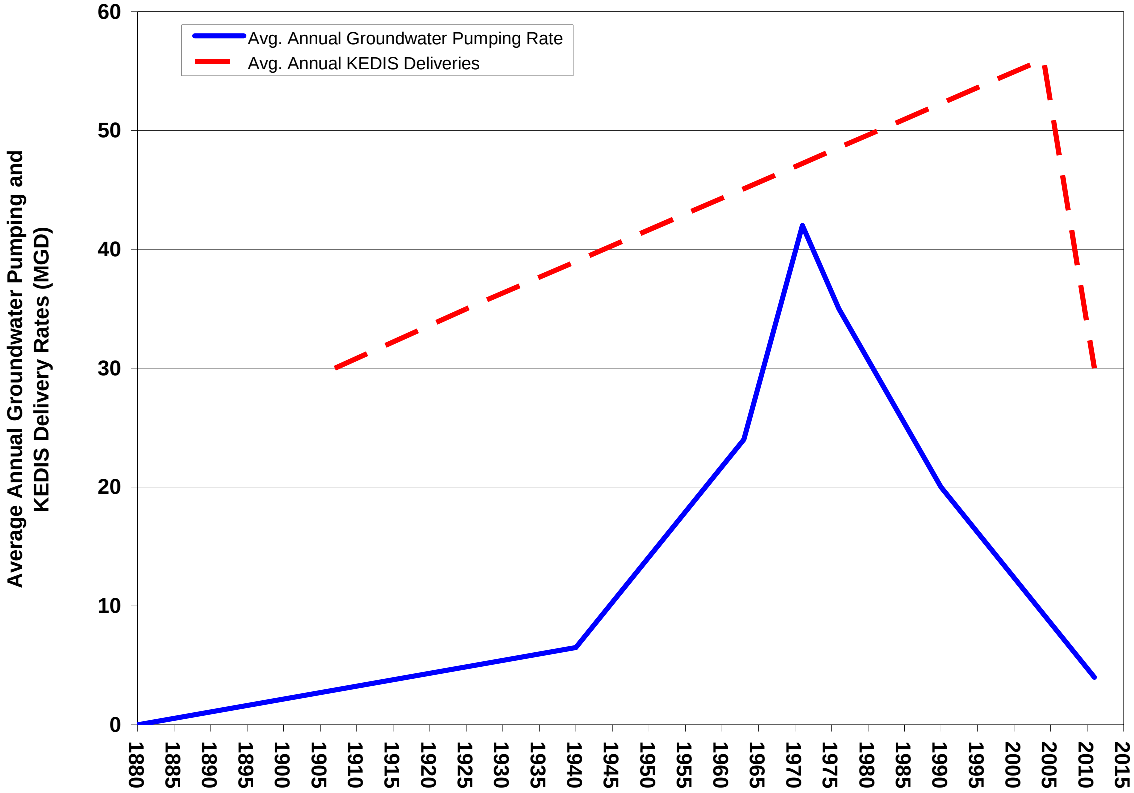

FIGURE 6-1: Estimated average groundwater withdrawal rates for Kekaha-Mana Plain basal aquifer system and Kekaha Ditch Irrigation System delivery rates from 1880 to 2011. Groundwater withdrawal rates prior to 1940 are unknown and assumed to range from 0.0 to 6.5 by 1940. Although a linear increase is plotted from 1940 to 1960, groundwater withdrawal rates are reported to fluctuate between 6.5 and 14.0 MGD (MacDonald et al., 1960).

6.2 Basal Confined Aquifer

The best historical records of groundwater levels and salinity come from three sources: 1) the report by MacDonald et al., (1960), which provides pre-1950 well data; 2) the report by Burt (1979); and 3) from the USGS National Water Information System website, which provides post-1970 data. Unfortunately, the lack of consistency in groundwater monitoring locations between the two data sets prevents development of a single, long-term comprehensive record of water level or salinity. Also, early studies of groundwater quality used chloride concentration as in indicator of water salinity. Chloride is a conservative ion which constitutes approximately 55% of the ionic composition of sea water; twice the chloride concentration is a reasonable estimate of water salinity. For example, because an elemental solution with a concentration of 1 mg/l is equivalent to a solution containing 1 part per million (ppm) of that element, water with a chloride concentration of 500 mg/l is roughly equivalent to a salinity concentration of 1,000 mg/l (equivalent to 1000 ppm) or 1-part per thousand (ppt). Sea water has an average salinity of 32-ppt (Hem, 1995).

All data reviewed came from wells completed in the basal lava aquifer located between 150 and 200-feet below the surface of the caprock sediments. All water levels[19] displayed artesian conditions, as water levels rose above sea level to near the ground surface. Upon review of available reports and groundwater monitoring records, two basic processes dominate. First, pumping from individual and surrounding wells effectively lowers well water levels; the greater the pumping rate, the more the drawdown in the local groundwater head. Second, increased pumping of the basal groundwater increases the draw and capture of the deeper brackish/transition water zone that occurs beneath the Mana Plain, leading to increased salinity (chloride) concentration in well samples (illustrated schematically in Figure 3-3). Thus, when reviewing the available groundwater data, decreases in average groundwater levels over time are likely attributed to increased groundwater pumping, especially if the decrease in well water level is accompanied by an increase in salinity concentration. The magnitudes of change observed in well records were highly variable, but some wells displayed changes in head on the order of 10-feet and salinity concentrations that ranged from 150 mg/l to 4200 mg/l chloride (0.3-ppt to 8.5-ppt salinity). Burt (1979) reports that maximum chloride concentrations from wells drilled in 1929 and 1930 ranged from 80 to 500 mg/l (0.15 ppt to 0.91 ppt salinity). By the 1970s, maximum chloride concentrations were regularly around 2000-mg/l (3.6 ppt salinity) and average chloride concentrations increased several-fold from early levels in response to increased pumpage (Burt, 1979). Chloride levels from the 1990s were lower than those measured during the 1970s (see Figure 6-2), likely as a result of the decreased pumping. No data is available on groundwater salinity or chloride levels since sugarcane production ceased in 1997. Interestingly, the high rate of freshwater recharge from irrigation of the highland canefields and leakage from the unlined Kekaha Ditch east of Kekaha helps maintain lower salinities in downgradient wells around Kekaha.

Figures 6-2 and 6-3 are paired plots of groundwater head and chloride for two local area wells that best display the changes and relationships associated with groundwater withdrawals both locally and across the Mana-Kekaha plain in general. The locations of these wells are provided on Figure 5-2. Figure 6-2 compares well head and aquifer chloride content for Kekaha well S13 over the period 1973 through 1996. Well head levels display sharp annual cycles of fluctuation likely attributed to seasonal changes in winter recharge and summer dry-out. More importantly are the long-term trends in base groundwater levels which display a period of depressed well head elevations around 3-feet between 1977-1978 and rising to a relatively static head level of 9-feet by 1987, a rise of 6-feet over 10 years. The amplitude of yearly seasonal variability in well head levels also decreases after 1987.

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[19] Water levels in confined wells are also referred to as hydraulic head or simply head.

Mirroring the general long-term trend in base head elevations are chloride concentrations, which peak in 1977-1978 at around 350 mg/l (0.6 ppt salinity) and then fall off and stabilize around 150 mg/l (0.3 ppt salinity) by 1989. These head and salinity level trends agree well with the general groundwater withdrawal rates presented in Figure 6-2 where the peak in pumping around 1977 leads to the lowest well heads and highest salinity concentrations followed by decreasing pumping rates into the late 1980s (rising well head and falling salinity concentration) to a relatively constant pumping rate from 1990 to 1995 and static well head and chloride concentrations.

Although the pumping history is less detailed or unknown for the first half of the 20th century, Figure 6-3 plots well head and chloride concentration for a well at Kaunalewa for the period 1936 to 1957. Similar to the changes displayed for the Kekaha well, changes to the local area well pumping rates can be inferred from these data as: a) increased pumping from 1936 to a period of maximum pumping around 1945 is indicated by falling well head levels accompanied by sharply rising aquifer chloride concentration; b) decreased pumping rate from 1945 to 1949 is indicted by rising heads and falling chloride concentration; and c) uniform pumping rate from 1949 to around 1956 is suggested by steady well head levels and aquifer chloride concentrations. Again, these local relationships between groundwater pumping and degrading water quality are ubiquitous across the Mana-Kekaha plain. There is a good chance that the transition zone in the basal aquifer migrated beneath the wetland restoration project site during the period of high groundwater pumping (see Figure 3-3). Decreased groundwater pumping after the peak in the 1970s has likely resulted in the transition zone shifting back to the west, similar to where it was under natural conditions.

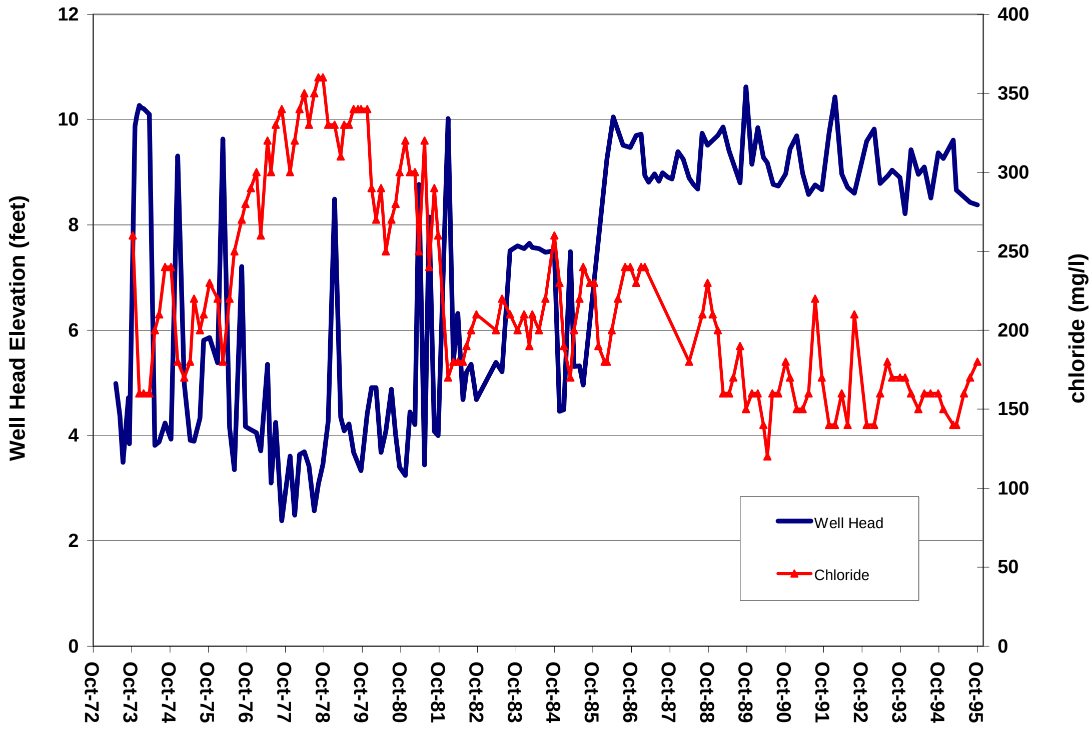

FIGURE 6-2: Well levels and groundwater chloride concentrations for well S13 in Kekaha (USGS well no. 215937159434201, Local no. 2-5943-01).

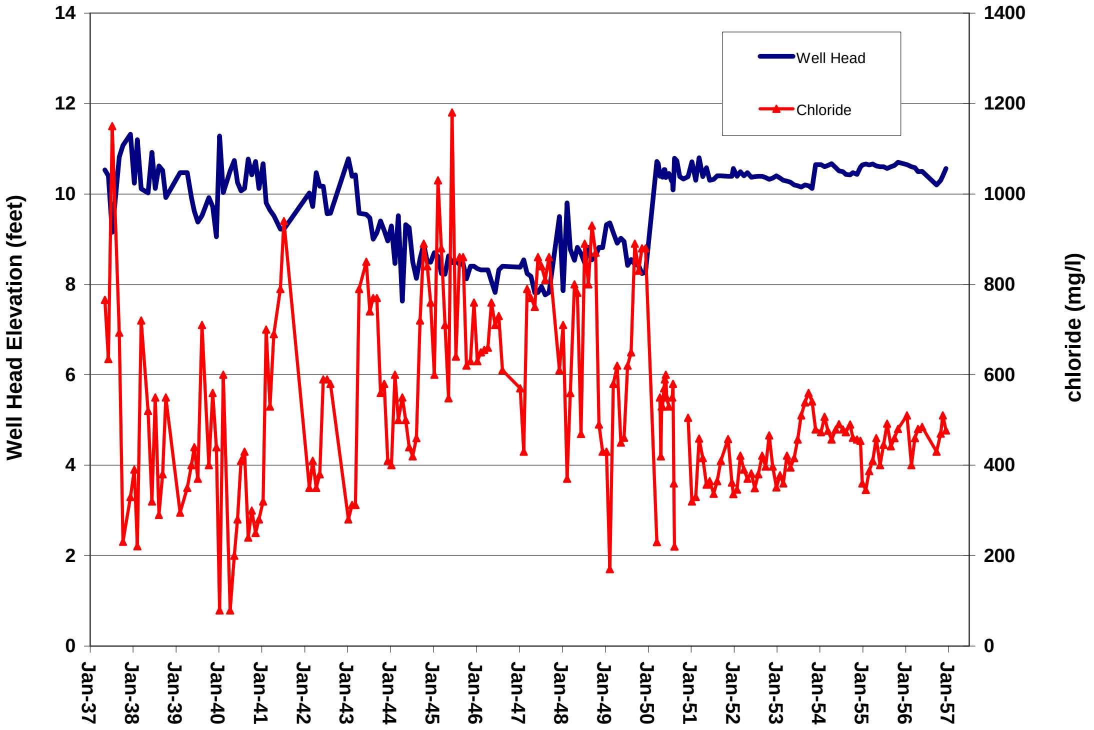

FIGURE 6-3: Well levels and groundwater chloride concentrations for well in Kaunalewa (USGS well no. 220019159444801, Local no. 2-0044-14).

6.3 Shallow Alluvial Aquifer

Since 2005, DOFAW has been monitoring shallow groundwater conditions at the project site. A total of 15 wells were installed in four transects designated as A through D. Well locations are indicated on Figure 6-4 with well name letters designating the associated transect (Henry, 2007). During monitoring, water depth measurements are collected at each well, referencing both the top and bottom of well casing. Top of well casings and ground elevations have been surveyed allowing water level measurements to be converted to water surface elevations on a common vertical datum (NAVD88). Groundwater hydrographs for wells are plotted by transect on Figure 6-5A through 6-5D.

Observations applicable to all transect hydrographs include the following.

- Water levels range from above ground surface (during floods) to 3.0 feet below ground surface
- Similar seasonal peaks in water surface elevations appear in all wells associated with recharge from winter storm and high flow events. Notable peaks occur in the wet season months of 2006, 2009, and 2010.
- The dry season low groundwater elevations are very consistent and stable from year to year at any given transect. However, these dry season lows show significant

variability between transects. Summer lows at Transect A are -1.0 feet NAVD88, -0.7-feet at Transect B, -1.8-feet NAVD88 at Transect C; and -0.5-feet NAVD88 at Transect D. This magnitude of variability between transects is surprising as it was expected that all site shallow groundwater levels would reflect adjacent ditch water levels maintained at a constant elevation by the downstream Kawaiele pump station. Ditch water levels measured at the Kawaiele pump station are plotted on Figure 5-8, but the elevation datum is in Mean Sea Level (msl) not NAVD88 and no datum conversion was found to correlate these water surface elevations during this study. However, ditch water levels appear to be maintained reasonably constant over the monitoring period. Observations unique to selected transects are as follows.

- Water levels for wells comprising Transect A are essentially equal over the monitoring period (Figure 6-5A). The ground surface elevation at Transect A ranges from 1.0- to 1.5-feet in elevation. Ground water levels for the 2006 high flow event were above ground surface water approaching 2.0-feet during this monitoring event (Henry, 2007). The water table remains essentially flat along this transect line and does not display a consistent flow direction towards or away from ditch (i.e., groundwater flow direction is from high to lower water level).

- Water levels between wells comprising Transect B (Figure 6-5B) show more variability that the Transect A wells. Generally, water levels are highest at well B80 and get lower moving toward the main drainage ditch, suggesting a groundwater flow direction towards the ditch. The ground surface elevation at Transect B is about 2.5-feet in elevation.

- Water level data for Transect C (Figure 6-5C) contains large gaps and breaks compared to the other well transects[20]. However, data suggest the summer groundwater level surface is around -1.8 feet in elevation, the lowest base level of all transects.

- Water levels between wells comprising Transect D (Figure 6-5D) show a moderate amount of variability between each other. Generally, water levels are highest closest to the ditch and deepen moving away form the ditch, suggesting a groundwater flow direction away from the ditch. The ground surface elevation at Transect D is about 3.0-feet in elevation.

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[20] Gaps in the data from wells in Transect C indicate the water level was below the bottom of the well.

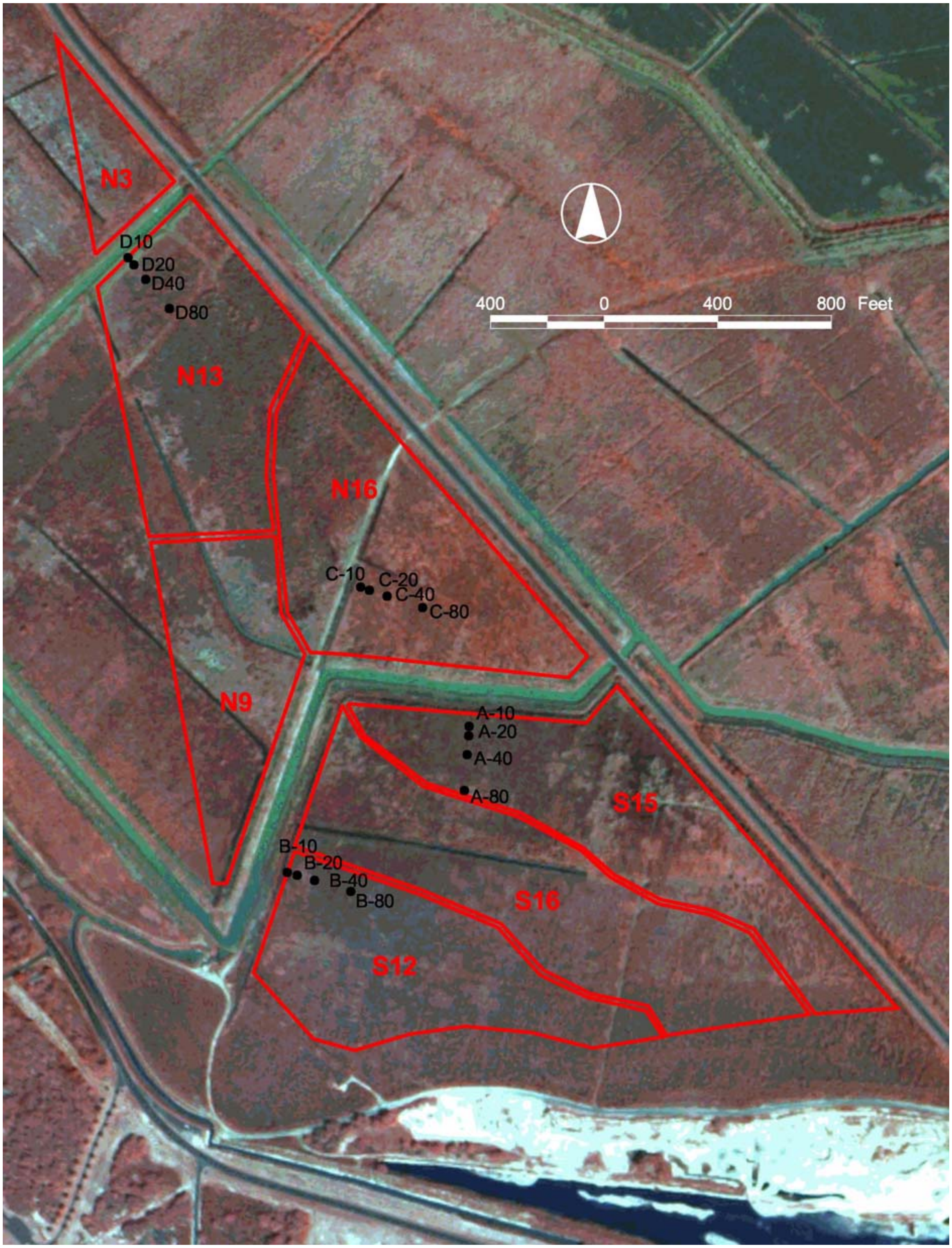

FIGURE 6-4: Shallow well locations.

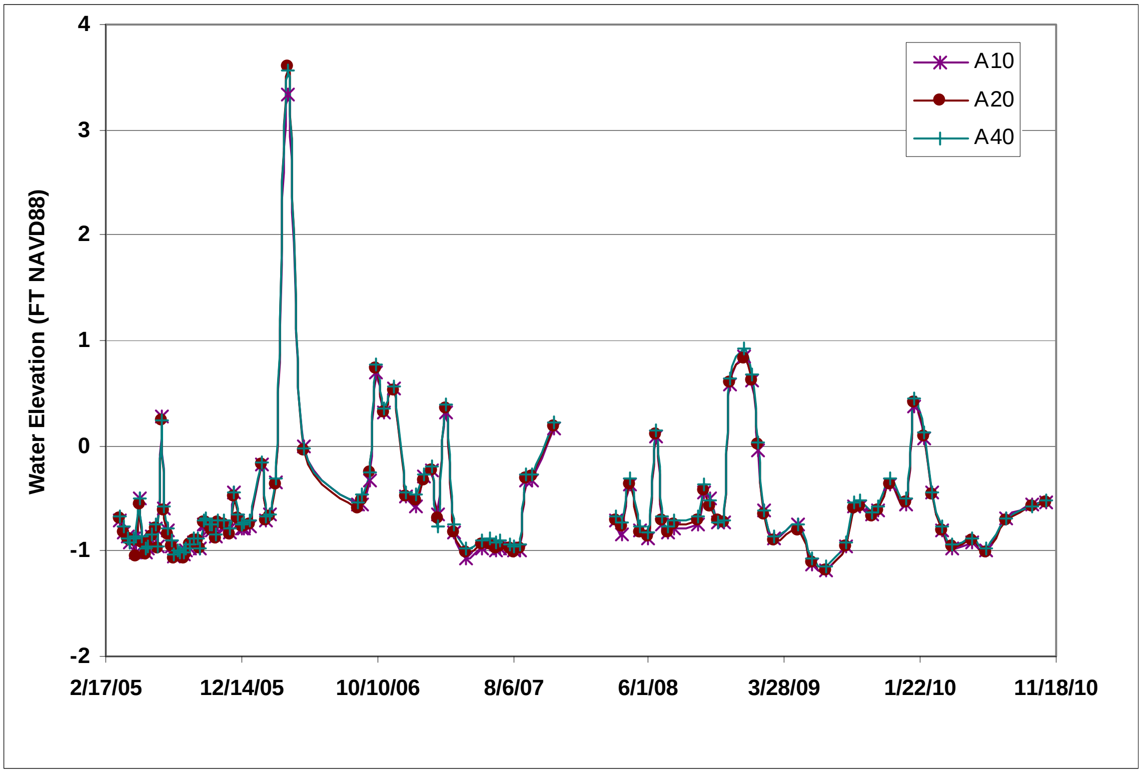

FIGURE 6-5A: Shallow groundwater levels, Transect A.

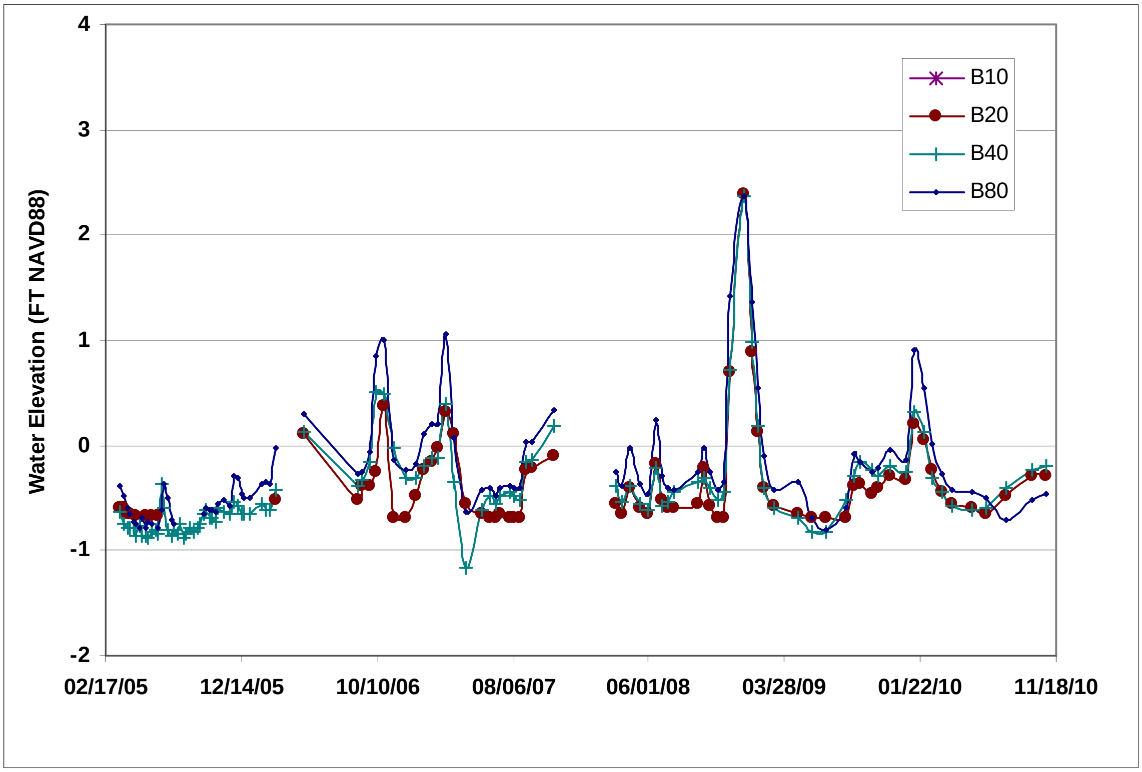

FIGURE 6-5B: Shallow groundwater levels, Transect B.

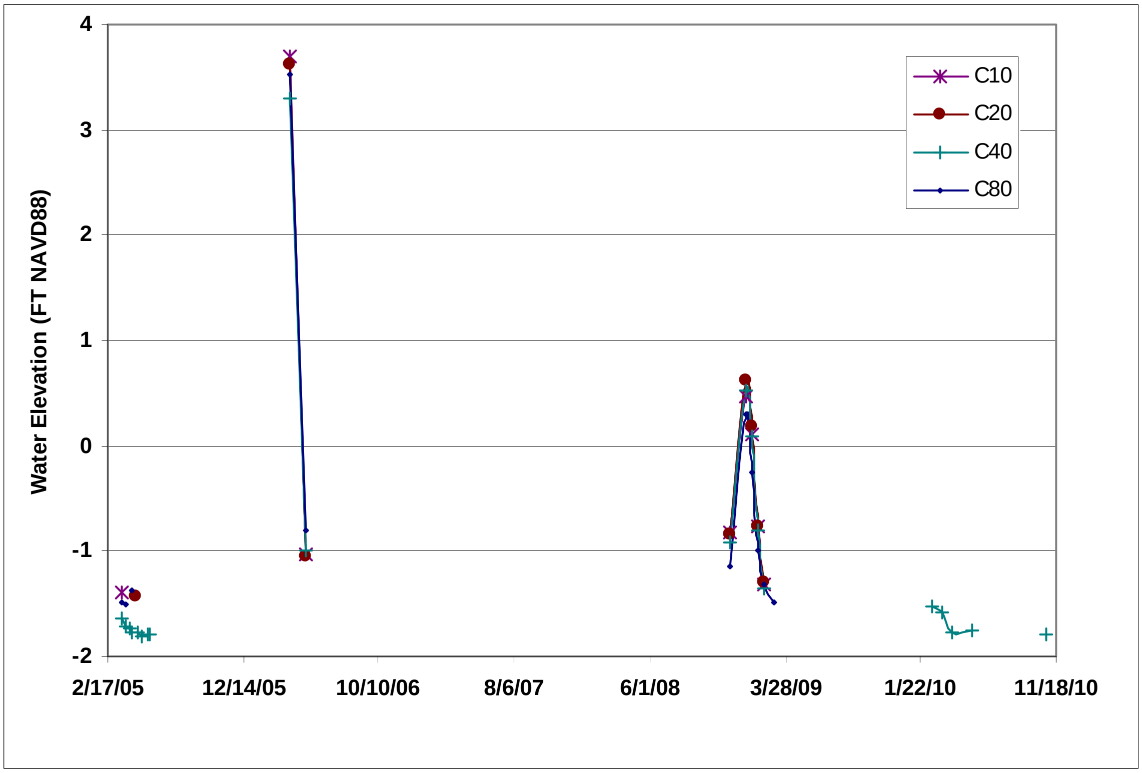

FIGURE 6-5C: Shallow groundwater levels, Transect C.

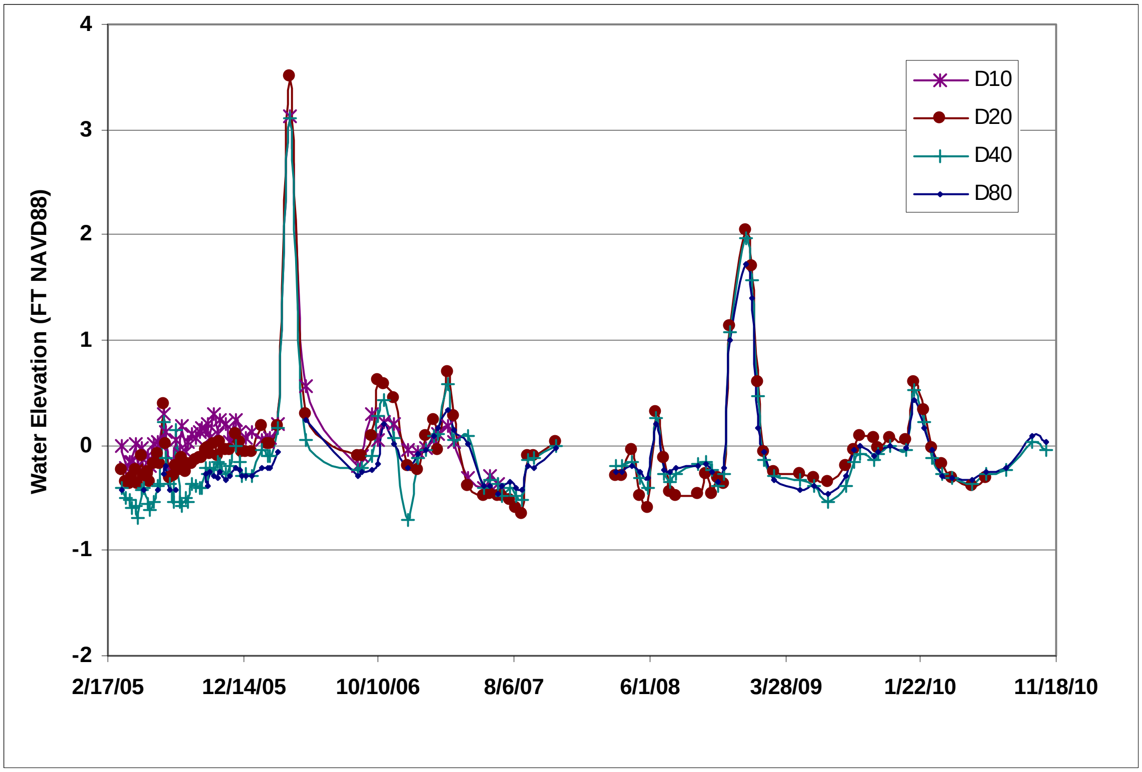

FIGURE 6-5D: Shallow groundwater levels, Transect D.

7.0 REGIONAL CONCEPTUAL HYDROLOGIC MODEL

The objective of this section is to describe how water moves into, through and beneath the project site because groundwater and/or ditch water may serve as the primary water sources to project wetland basins. As such, this conceptual hydrologic model considers not only the Kekaha-Mana coastal plain but the highlands to the east, which serves as the primary recharge area for the underlying Nohili basal aquifer. This description is best accomplished through a narrative of a watershed-scale hydrologic budget analysis. Therefore, this section presents a series of water budgets over time in order to provide a picture of how hydrologic conditions have changed in response to local land use changes and associated water development.

In 1979, R.J. Burt of the U.S. Geological Survey completed a detailed water budget analysis to evaluate the availability of groundwater for irrigation on the Kekaha-Mana Plain focusing on the “Predevelopment” and 1958-68 periods. The scale and quality of his work are relevant to this study so a summary of his findings is presented here. In addition, KHE was able to expand on Burt’s work by developing an additional water budget for the more recent 2011 period (hereafter referred to as the “Recent” period), which is also presented below.

Table 7-1 presents a summary of the regional hydrologic water budgets for the three representative periods. Table 7-1 presents water budgets for two areas – the upper table is a water budget for the Highland Area and the lower table represents the Kekaha-Mana Coastal Plain. Most groundwater recharge reaching the Kekaha-Mana plain occurs in the Highland Area as infiltration of rain and irrigation water and seepage from creeks and leakage from ditches. Surface runoff from the Highland Area also flows onto the Coastal Plain. Therefore, an independent water budget of the Highland Area is necessary to quantify some of the water budget variables to the Coastal Plain Area.

All major inflows and outflows to each area are quantified in Table 7-1 and are numbered to aid in this discussion. As indicated above, the three representative water budget periods include: Predevelopment (or natural); the 1958-68 period; and Recent (2011) period. For more detail regarding the assumptions and data sources utilized to generate estimates of inflow and outflow the reader is referred to Burt (1979).

7.1 Predevelopment Conditions

Under natural or predevelopment conditions, infiltration of rainfall was the primary source of recharge to the basal basalt aquifer, equating to a total annual inflow of 74,000 AF. Burt (1979) estimates that the total annual amount of recharge that exits the Highlands as basal groundwater outflow (Outflow item 10. on Table 7-1) is 25,000 AF. This estimate was calculated as rainfall minus evapotranspiration and surface runoff and assumes:

- Annual rainfall total of 74,000 AF (33-inches/yr across 42-square mile Highland Area [26,900-acres]);
- Evapotranspiration total of 45,000 AF (20-inches/yr across 42-square mile natural, unirrigated Highland Area [26,900-acres]); and

HIGHLAND AREA				
		Predevelopment AF/yr	**1958-68 AF/yr**	**Recent AF/yr**
INFLOW				
1. Rainfall	33" on 26,900 acres	74,000	74,000	74,000
2. Irrigation	Kekaha Ditch	0	40,000	
3. Irrigation	Kokee Ditch	0	18,000	
4. Irrigation	Waimea Ditch	0	3,000	33,600
	Total Inflow	**74,000**	**135,000**	**107,600**
OUTFLOW				
5. Runoff	5% of rainfall from highlands	4,000	4,000	4,000
6. Runoff	57% applied irrigation	0	35,000	19,100
7. Evapotranspiration	Non-irrigated highlands	45,000	41,000	41,000
8. Evapotranspiration	Irrigated highlands	0	12,000	8,500
9. GW outflow	Rainfall	25,000	25,000	25,000
10. GW outflow	Ditch/Reservoirs (30% ditch)	0	18,000	10,000
	Total Outflow	**74,000**	**135,000**	**107,600**

COASTAL PLAIN AREA				
		Predevelopment AF/yr	**1958-68 AF/yr**	**Recent AF/yr**
INFLOW				
11. Rainfall	20" on 11,200 acres	19,000	19,000	19,000
12. Runoff	From Highland Area	4,000	4,000	4,000
13. Runoff	Irrigated areas in Highlands	0	35,000	19,100
14. Groundwater	Inflow from basaltic aquifer	25,000	13,000	13,000
15. Groundwater	Pumping	0	27,000	4,500
16. Groundwater	Abandon well leakage	0	3,000	3,000
	Total Inflow	**48,000**	**101,000**	**62,600**
OUTFLOW				
17. Runoff	Surface drainage	25,000	3,000	3,000
18. Runoff	Mill ditch	0	3,000	3,000
19. Runoff	Kawaiele drain	0	37,000	18,100
20. Runoff	Nohili drain	0	16,000	7,300
21. Evapotranspiration	Non-irrigated plain	17,000	9,000	9,000
22. Evapotranspiration	Open water	6,000	0	
23. Evapotranspiration	Irrigated plain	0	33,000	22,200
	Total Outflow	**48,000**	**101,000**	**62,600**

Table 7-1. Estimates of inflow and outflow of water in the Highland Area (upper table) and Kekaha-Mana Coastal Plain area (lower table). Revised from Burt, 1979.

- Stream runoff of 4,000 AF (estimated at 5% of rainfall from Highland Area[21]).

Thus, under Predevelopment conditions, the surface water outflow of 4000 AF/yr and groundwater outflow of 25,000 AF/yr from the Highland Area serve as inflows to the Coastal Plain Area water budget (Inflow items 12. and 14. in Coastal Plain Area water budget, Table 7-1). The only other Predevelopment inflow to the Coastal Plain is direct rainfall, estimated at 19,000 AF/yr (20-inches/yr over a 17.5-square mile area (11,200 acres]), yielding a total inflow of 48,000 AF/yr. The only Predevelopment outflows from the Coastal Plain are surface water drainage (estimated at 25,000 AF/yr) and evapotranspiration (estimated total of 23,000 AF/yr). Burt's Predevelopment Coastal Plain outflow assumptions include the following:

- Burt estimated that there were approximately 1000-acres of marsh and wetlands on the Kekaha-Mana Plain during Predevelopment times and total annual evapotranspiration occurred at a rate of 70-inches/yr. This yields an annual loss of approximately 6000 AF.
- Plant water demands in non-marshy Predevelopment areas are estimated to be less than half the water demand required by sugarcane (44-inches/yr). Burt used an annual total evapotranspiration rate of 20-inches for these areas and assumed an annual loss of 17,000 AF/yr from the remaining 10,200 Coastal Plain acres.
- Burt's surface water outflow estimate (25,000 AF/yr) was back-calculated from all other known inflow and outflow variables to the Predevelopment Coastal Plain water budget. Early natural drainages to the Ocean occurred at the Kawaiele (from both the Nohili and Kawaiele marsh lands) and near Kekaha at the present Mill Ditch.
- An important assumption in the Predevelopment water budget is that water losses by infiltration and associated shallow caprock groundwater outflow to the Ocean is considered insignificant because of the presence of the relatively low hydraulic conductivity of the caprock. These low permeable deposits restrict both the downward infiltration and upward discharge of groundwater, leading to a pressure build up in the basal basalt aquifer. The expression of the pressure buildup is artesian heads in the underlying basal aquifer; these potentiometric heads are higher than any water table that may have existed in the caprock. Hence, water from the basal aquifer tends to move upward toward the surface (i.e., towards lower head) and "leaks" into the confining caprock sedimentary deposits. Groundwater reaching the surface in the Coastal Plain is subsequently lost to evapotranspiration or by runoff to the marshes and the Ocean.

- Burt acknowledges the presence of spring discharges from permeable coralline beds exposed by wave action on the Coastal Plain, but there is no way of knowing the number of springs or measuring the extent of this discharge. He concluded this volume of water was insignificant to the proportion of water needed to irrigate the Plain.

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[21] Based on an analysis of available streamflow records, KHE estimated runoff at 77.6 AF per square mile or 3260 AF per year, which is in reasonable agreement with Burt's estimate).

7.2 1958-68 Period

With land and water development on the west side of Kauai, came irrigation from surface water diversions from the Waimea River (KEDIS) and increased groundwater pumping. Although not a significant change to the large-scale post development water budget, the construction of the drainage ditch network throughout the Coastal Plain effectively lowered both the shallow caprock water table and basal aquifer potentiometric head. This was accomplished as the ditches drain the unconfined caprock water as well as any upward groundwater seepage from the basal aquifer. Essentially, the drains expedite the drainage of groundwater recharging from the surface or leaking into the caprock from below.

Based on Burt's 1958-68 water budget, rainfall inflow to the Highland Area remains the same as Predevelopment conditions, but there is the added inflow of irrigation delivered via the Kekaha, Kokee and Waimea ditch systems. The Cumulative total inflow from irrigation ditches during the 1958-68 period is reported at 61,000 AF/yr (sum of irrigation Inflow items 2. through 4. on Table 7-1). Thus the total 1958-68 inflow to the Highland Area is 135,000 AF/yr.

Burt's Highland Area water budget indicates that groundwater recharge and subsequently groundwater outflows from rainfall remain at 25,000 AF/yr as does rainfall runoff at 4,000 AF/yr. However, new outflows emerge, including approximately 57% of applied irrigation that exits the highlands as surface water runoff (35,000 AF/yr) and an additional 18,000 AF/yr of groundwater recharge, mostly from the infiltration of irrigation water (estimated at 30-perent of applied irrigation water) which exits the highlands as additional groundwater outflow to the Coastal Plain.

Evaporation totals also increase under 1958-68 development conditions as approximately 2,200 acres of previously non-irrigated land is brought into agricultural production. Assuming a Highland Area evaporation rate of 65-inches/yr from irrigated lands, there is 12,000 AF/yr of evaporation outflow from the 2,200 acres of irrigated area. In addition, there is still the Predevelopment evapotranspiration rate of 20-inches per year applied to the remaining 24,700-acres of non-irrigated Highlands, leading to an additional evapotranspiration outflow of 41,000 AF/yr.

Thus, total 1958-68 outflows from the Highland Area sum to 135,000 AF/yr. Of this total, 39,000 AF/yr of rainfall and irrigation runoff feed into the surface water inflow to the Coastal Plain Area and 43,000 AF/yr of total groundwater water outflow, also from rainfall and irrigation, account for groundwater inflow to the Coastal Plain. Additional 1958-68 period inflows to the Plain include 19,000 AF/yr of rainfall (same as Predevelopment conditions) and an additional 3,000 AF/yr estimate by Burt (1979) of basal aquifer leakage from abandoned artesian wells. These inputs total to 101,000 AF/yr.

Outflow from the 1958-68 Coastal Plain Area remains as surface water runoff and evapotranspiration, but subtotals from both of these sources are around double the subtotals of Predevelopment conditions. Sources of Coastal Plain outflow include the following:

- Ditch outflows totaling 56,000 AF/yr from the Mill (3,000 AF/yr), Kawaiele (37,000 AF/yr) and Nohili (16,000 AF/yr) ditch systems;
- Surface water runoff (mostly from storms) directly to the Ocean (3,000 AF/yr);
- Approximately 33,000 AF/yr of evapotranspiration from irrigated Coastal Plains (70-inches/yr over 5,600 acres); and
- 9,000 AF/yr as evapotranspiration from non-irrigated lands (20-inches/yr over 5,600 acres).

7.3 Recent (2011) Period

The recent water budgets reflect important input from the ADC during 2011 regarding irrigation and groundwater pumping volumes. Inflows to the Highland Area for the Recent water budget consist of rainfall and irrigation. The 74,000 AF/yr inflow from rainfall remains consistent with the Predevelopment and 1958-68 water budgets. As of 2011, the ADC reports that irrigation contributions via the ditches are down to 33,600 AF/yr as opposed to 61,000 AF/yr for the 1958-68 period. This yields a total inflow to the Highland Area of 107,600 AF/yr.

The reduction in irrigation also leads to a decrease in surface water runoff, and groundwater outflow as well as reduced evapotranspiration loss from irrigated highlands. This translates into less surface water and groundwater inflows to the coastal plain. Pursuant to the methods used by Burt (1979), both of the irrigation runoff and groundwater outflow estimates are taken as percentages of the total irrigation inflow – the irrigation runoff estimate (19,100 AF/yr) is taken as 57-percent of applied irrigation and the groundwater outflow estimate (10,000 AF/yr) is taken as approximately 30% of applied irrigation. The reduction in irrigation also leads to a reduction in evapotranspiration from the irrigated highlands, estimated at 8,500 AF/yr as opposed to the 12,000 AF/yr under the 1958-68 period. Thus, total outflow from the Highlands is 107,600 AF/yr.

Recent inflows to the Coastal Plain Area that differ from the 1958-68 period include the decreased irrigation runoff and groundwater inflow as discussed above and a large decrease in groundwater pumping. ADC staff indicates that the 2011 groundwater pumping rate is approximately 4 MGD or 4500 AF/yr for 2011 as opposed to 27,000 AF/yr during the 1958-68 period. The only Coastal Plain outflow variables that we found justification in changing for the Recent period was the combined Kawaiele and Nohili drain outflows and the evapotranspiration loss from the irrigated plain. An annual combined average total drain outflow estimate of 25,400 AF/yr (7,300 AF/yr from Nohili and 18,100 AF/yr from Kaaiele) was calculated from the ADC NPDES annual reports for the 2005 through 2009 period, which reported average daily flow rates for each pump station (see Section 5.4 of this report). This combined rate is much lower than the combined Kawaiele and Nohili outflow rates for 1958-68 (53,000 AF/yr). Also, the estimated evapotranspiration loss (22,200 AF/yr) from the irrigated portion of the Mana Plain is reduced due to reduced irrigated acreage and more efficient irrigation practices relative to the 1958-68 period.

The addition of the Recent water budget analysis has been valuable in better characterizing recent trends in groundwater use and recharge. As a result of the decreased groundwater pumping since the 1990s, the groundwater inflows to the coastal plain aquifer exceed outflows by almost 70% as opposed to the representative sugarcane era (1958-68) when groundwater inflows exceeded outflow by only 28%. The current level of groundwater inflow to the deep Mana Plain aquifer also exceeds the degree of recharge experienced during the pre-development period when inflow exceeded outflow by 54%. Theoretically, both the significantly decreased groundwater pumping from the Coastal Plain and enhanced groundwater recharge associated with increased irrigation in the Headland Area will reduce or ameliorate the adverse impacts of increased basal aquifer salinity associated with historical over-pumping. In addition to recharging historically depleted groundwater resources, the net increase in groundwater recharge should also push the brackish water transition zone to the west, possibly back to pre-development position and therefore reducing the potential for salt water intrusion.

8.0 WATER SOURCE ANALYSES

8.1 Project Conditions Analyzed

As indicated above, the project will consist of habitat restoration through the creation of seven distinct wetland basins. Wetland basins will have fresh to brackish water salinities, and support emergent, submergent, and mudflat plant species. Each wetland basin will be constructed with a perimeter berm to separate it from adjacent basins and the two main drainage ditches that feed the Kawaiele pump station. For purposes of the feasibility assessments described below, the project basin configuration is presented in Figure 3-1. In addition to the wells, pumps, piping and water input/output structures indicated on Figure 3-1, the project design will include trails, fencing, overlooks, and a visitor center with parking.

During the construction of the wetland basins, grading of the current surface soils will be completed to contour basins that maximize wetland habitats. Abandoned field irrigation ditches that are no longer used will be filled with low permeability soils from on-site. In order to ensure continued maintenance of surrounding lands and maintain flood control capabilities, the shape and elevation of the two main drainage canals that bisect the project site will not be altered.

Each wetland basin is designed with a low-profile perimeter berm. The berms will allow independent water control within each wetland basin. Berms will be set back 40 feet from the main drainage canals in order to accommodate equipment access for the maintenance of the canals, currently leased by the U.S. Navy. The maximum depth of excavation will be limited to less than approximately 3 feet to avoid intersecting lower permeability subsurface soils and the shallow groundwater table. One of the design objectives is to balance cut and fill on-site, but if off-haul of excess soil is necessary, material will be placed in an approved upland area within the Mana Plains Forest Reserve. Figure 8-1 presents a schematic cross-sectional east-west project profile through the southern ponds during maximum flooding conditions. The alignment of this cross-section is indicated on Figure 3-1.

In order to create a diversity of desired habitats for target species, the project will include flooding each basin to variable depths and for varying durations each year. Flooding depths are designed to target optimal foraging conditions for endangered Hawaiian waterbirds, promote the growth of native wetland plants, and increase the availability of shallow-water wetland habitats on the Mana Plain. Figure 8-2 presents the proposed basin flood levels and durations developed by DOFAW and other partner biologists. These flood depths and durations dictate the required water supply for each individual wetland basin. Table 8-1 shows the water level ranges, depths and estimated flooded areas for each and all wetland basins under the proposed wetland basin configurations.

All basins will be designed to be supplied by fresh groundwater originating from an existing but unused artesian well located approximately one mile east of the project site. The use of this well will be through a Memorandum of Understanding with the

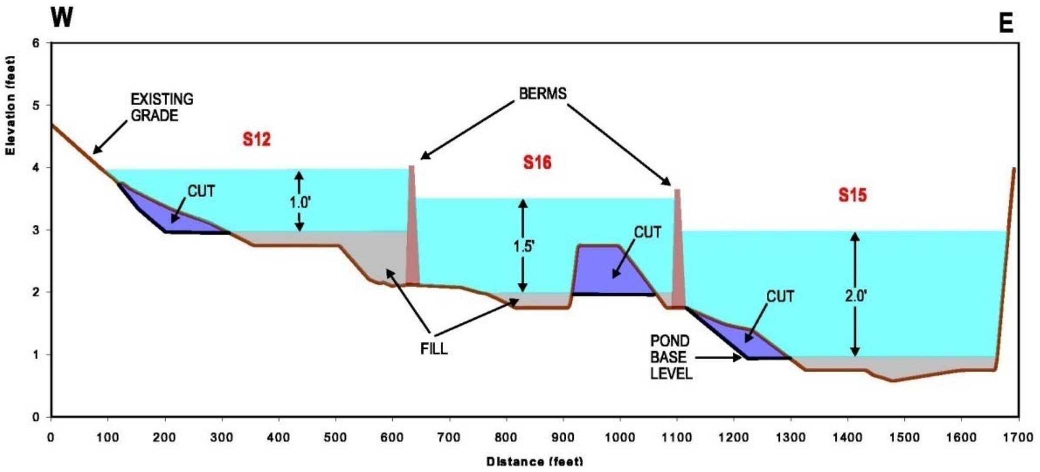

Figure 8-1. Schematic cross-sectional profile through the proposed southern wetland basins.

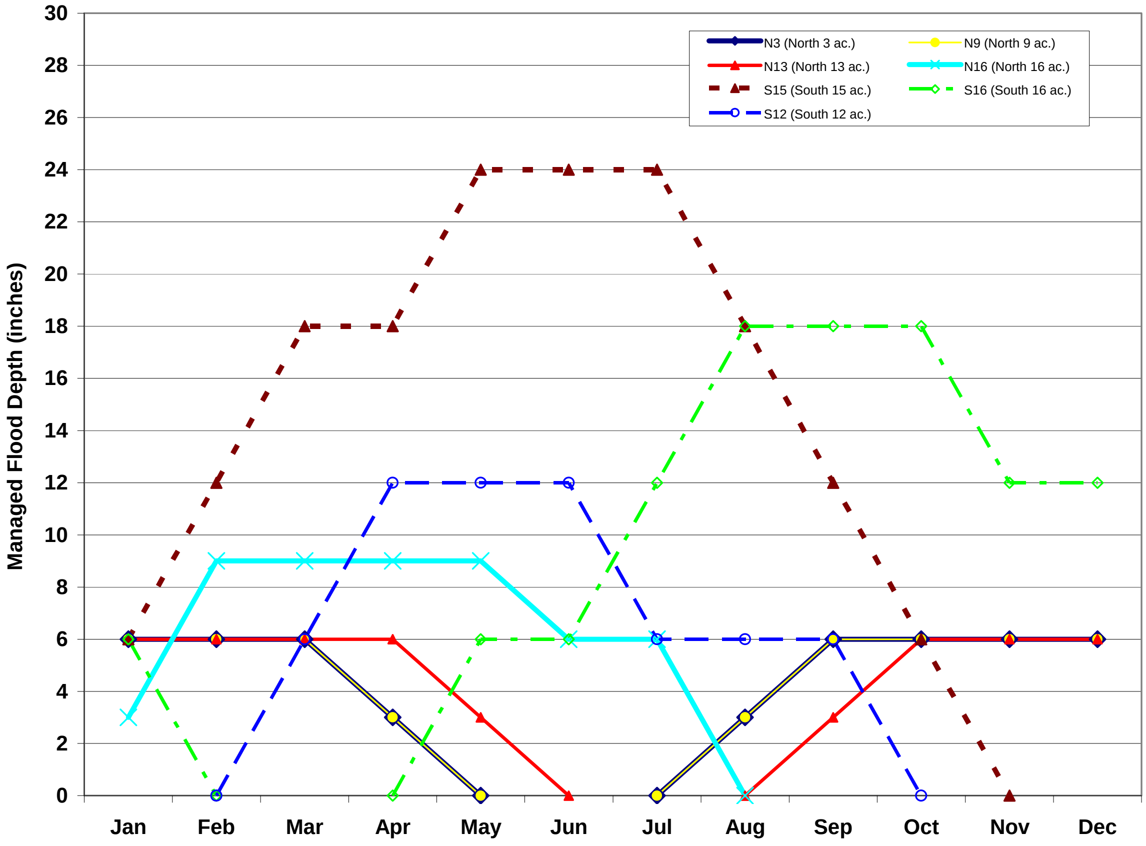

Figure 8-2. Proposed managed flood depths and durations.

Agribusiness Development Corporation (ADC), who owns the well. This well historically produced around 1,000,000 gallons per day (gpd) or 700 gallons per minute (gpm), of fresh water and was used for irrigation of sugarcane. The currently unused well is flowing under artesian pressure at a rate between 30 and 35 gpm.

An existing pipeline extends from the well and crosses under Highway 50. Water will be conveyed from the well to the on-site water distribution system, in either the existing, or if needed, anew 12 to 24 inch pipe. The ADC has agreed to provide the electricity necessary to operate the well at reduced rates from their own supply generated by the upslope irrigation system hydroelectric facilities. The project site water distribution system will include a network of piping and valves that supply water to each wetland basin. In order to facilitate control of invasive species and manage for native wetland plant species, the water distribution system will allow for the independent water-level control in every wetland basin. Therefore water levels within each wetland basin can be managed independent of one another. The layout for the on-site water distribution system is provided on Figure 3-1.

Some basins may also be supplied with canal surface water or a mixture of surface and ground water. Surface water pumped from the canals will require installation of an independent canal water supply system (e.g., pumps, piping and controls). All basins will have piping directed from the groundwater distribution system available in the event that surface water is no longer available or no longer desired as a sole supply to this basin.

In order to bracket the likely range of water supplies necessary to sustain the proposed project wetland basins, water source assessments need to start by quantifying the water supplies required under scenarios of high infiltration losses and low infiltration losses. The High Infiltration Loss assessment included quantifying wetland basin demands assuming untreated basins and existing basin infiltration rates as described in Section 3.4.2 of this report. The Low Infiltration Loss assessment assumes engineering measures are integrated into design and construction that reduce water loss via infiltration. Based on the soil investigations completed by DOFAW with the assistance of NRCS and other project partners (Henry, 2010), there are lenses of shallow and highly permeable sand deposits beneath the site that appear to laterally drain subsurface water that infiltrates the project area into the adjacent irrigation ditches and main drainage channel. Engineering measures that would reduce infiltration losses from the project area include amending the basin bottoms with clay to reduce vertical infiltration and/or installing shallow slurry walls[22] around the perimeter of the basins to restrict the horizontal flow and drainage for shallow groundwater. For purposes of this assessment, these engineering measures are represented by a uniform infiltration rate of 0.01-ft/day. This rate reflects the published saturated hydraulic conductivity values for soil material with grain sizes falling between silt/loam and clay (Bear, 1972; Heath, 1987; Fetter, 1980; and Domenico and Schwartz, 1990). This uniform infiltration rate is representative of materials that could be used to line or fill trenches around the border of the proposed basins to restrict infiltration losses and/or horizontal movement. For comparison, a No Infiltration Loss assessment was also completed to quantify water demands assuming a 100% impermeable substrate to project wetland basins and no losses of water due to infiltration. The water budget analysis of the Low and No Infiltration Loss scenarios bracket

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[22] Slurry walls in this context refer to trenches filled with impermeable material to restrict horizontal groundwater flow that are installed to a recommended depth around the edges of wetland basins.

the likely water demands that will be realized under a project alternative that incorporates engineered methods to reduce if not eliminate infiltration losses. The Low Infiltration Loss scenario may also represent a minor amount of fresh groundwater through-flow, incorporated in an impermeable basin to maintain minimal turnover in wetland basins as a way to reduce salinity. Table 8-1 presents the water level ranges and estimated flooded areas for each and all wetland basins under the proposed wetland basin configuration and managed flood depths/durations discussed above. The estimated volume of water that will be required to maintain the desired levels and durations of managed flooding depends significantly on the water losses associated with infiltration from each basin.

Basin	Water Depth (ft)	Base Elev. (ft)	Flood Elev. (ft)	Flooded Area (acres)
N3	0.50	3.25	3.75	3
N13	0.50	2.00	2.50	13
N9	0.50	1.50	2.00	9
N16	0.75	1.50	2.25	16
S12	1.00	3.00	4.00	12
S16	1.50	2.00	3.50	16
S15	2.00	1.00	3.00	15
TOTALS				**84**

Table 8-1. Project wetland basin range in water levels and estimated maximum flooded area.

8.2 Water Budget Analysis

8.2.1 Methods

A water budget provides a quantitative accounting of water supplies and demands (loses) to a water body. The primary components of the water budget equation are:

$$I - O = \Delta S/\Delta t \qquad \text{(Eq. 1)}$$

where:

I is the volume of inflow,
O is the volume of outflow, and
$\Delta S/\Delta t$ is the net change in the volume of water storage per unit time, t.

Surplus water accumulates within the wetland basins during periods in which inflow exceeds outflow. Conversely, water is removed from storage during periods in which outflow exceeds inflow. The corresponding rise or fall in water level to a given increase or decrease in storage is also influenced by the topographic characteristics of the storage site.

An analytical water budget model was developed to calculate the volume of surplus water necessary to maintain the target wetland basin flooding management levels in each individual basin as presented above in Figure 8-1. The water budget models separate the primary inflow and outflow components into discrete monthly volumes and provide analytical solutions to the water balance equation for each time step. The expanded water budget equation utilized for the project basins takes the form:

$$P + Q_{in} + G_{net} - Q_{out} - I - ET = \Delta S/\Delta t \qquad \text{(Eq. 2)}$$

where:
P is direct precipitation,
Q_{in} is surface water inflow,
Q_{out} is surface water outflow (spilling of excess waters),
I is infiltration, and
ET is evapotranspiration.

The relationship between wetland basin water surface elevation (stage) and the available water storage capacity was determined by terrain analysis of topographic survey data collected by Ducks Unlimited in 2008. This exercise included generating stage-area and stage-volume curves for each basin in order to calculate evapotranspiration water losses and storage volumes for each model time-step. Precipitation, evapotranspiration and infiltration data used in the model are presented and discussed above in Sections 3.0 and 4.0. For High Infiltration Loss scenarios, infiltration estimates from Test Pond #5 (0.136-ft/day) were applied to all northern wetland basins, while infiltration estimates from Test Pond #1 (0.220-ft/day) were applied to Southern Basins S12 and S16, and estimates from Test Pond #2 (0.036-ft.day) was applied to Basin S15. Modeling assumed no surface runoff supply or shallow groundwater inflow to the basins. No “pass-through” flows were incorporated into the water budget assessments – “pass-through” flows are defined as excess surplus water that is pumped into a full basin so that cumulative inflow exceeds cumulative outflow in order to maintain turnover and results in spillage out of the wetland basin.

8.2.2 Results

High Infiltration Losses

Water budget modeling results for the High Infiltration Loss scenario are summarized in Table 8-2 and plotted in Figure 8-3. Again, this scenario assumes no treatments to basin substrate or borders to alter the existing infiltration rates. Both individual basin and cumulative project water demands are provided in Table 8-2 and Figure 8-3. Translating these demands into standard pumping rates of gallons per day (GPD) and gallons per minute (gpm; continuous pumping, 24-hours per day) yields the following values

- Minimum pump rate: 1,488,253 GPD or 1,034 gpm;
- Maximum pump rate: 3,210,954 GPD or 2,230 gpm; and
- Average pump rate: 2,640,516 GPD or 1,834 gpm.

Low Infiltration Losses

Water budget modeling results for the Low Infiltration Loss scenario are summarized in Table 8-3 and plotted in Figure 8-4. Again, this scenario assumes engineered treatments to the basins to significantly reduce existing infiltration rates and subsurface drainage. Pumping rates required to satisfy these estimated water demands are as follows.

- Minimum pump rate: 86,156 GPD or 60 gpm;
- Maximum pump rate: 491,253 GPD or 341 gpm; and
- Average pump rate: 310,317 GPD or 216 gpm.

No Infiltration Losses

Water budget modeling results for the No Infiltration Loss scenario are summarized in Table 8-4 and plotted in Figure 8-5. This scenario assumes engineered treatments to the basins to eliminate any water loss due to infiltration. Pumping rates required to satisfy these estimated water demands are as follows.

- Minimum pump rate: 9,778 GPD or 7 gpm;
- Maximum pump rate: 344,809 GPD or 240 gpm; and
- Average pump rate: 191,653 GPD or 133 gpm.

	N3 (AF)	N13 (AF)	N9 (AF)	N16 (AF)	S12 (AF)	S16 (AF)	S15 (AF)	Monthly Subtotal
Jan	8.0	28.5	35.8	31.3	0.0	31.7	65.4	**200.7**
Feb	7.6	27.6	33.8	48.0	0.0	0.0	77.7	**194.7**
Mar	8.5	30.7	37.7	49.4	37.9	0.0	99.2	**263.4**
Apr	7.4	31.4	27.6	50.0	75.1	0.0	92.7	**284.2**
May	0.0	22.3	0.0	52.4	74.6	44.6	111.6	**305.5**
Jun	0.0	0.0	0.0	46.0	72.9	39.5	102.9	**261.3**
Jul	0.0	0.0	0.0	49.7	34.3	78.7	106.6	**269.3**
Aug	10.7	0.0	37.0	0.0	37.7	103.3	91.2	**279.9**
Sep	9.1	25.8	39.7	0.0	36.0	93.8	75.9	**280.4**
Oct	8.6	32.7	38.1	0.0	0.0	94.6	60.0	**233.9**
Nov	8.1	29.5	36.1	0.0	0.0	63.2	0.0	**137.0**
Dec	8.0	28.7	35.8	0.0	0.0	68.4	0.0	**140.9**
Totals	**76.1**	**257.1**	**321.7**	**326.8**	**368.6**	**617.8**	**883.1**	**2,851.2**

Table 8-2. Predicted monthly and total wetland basin water demands assuming high infiltration losses.

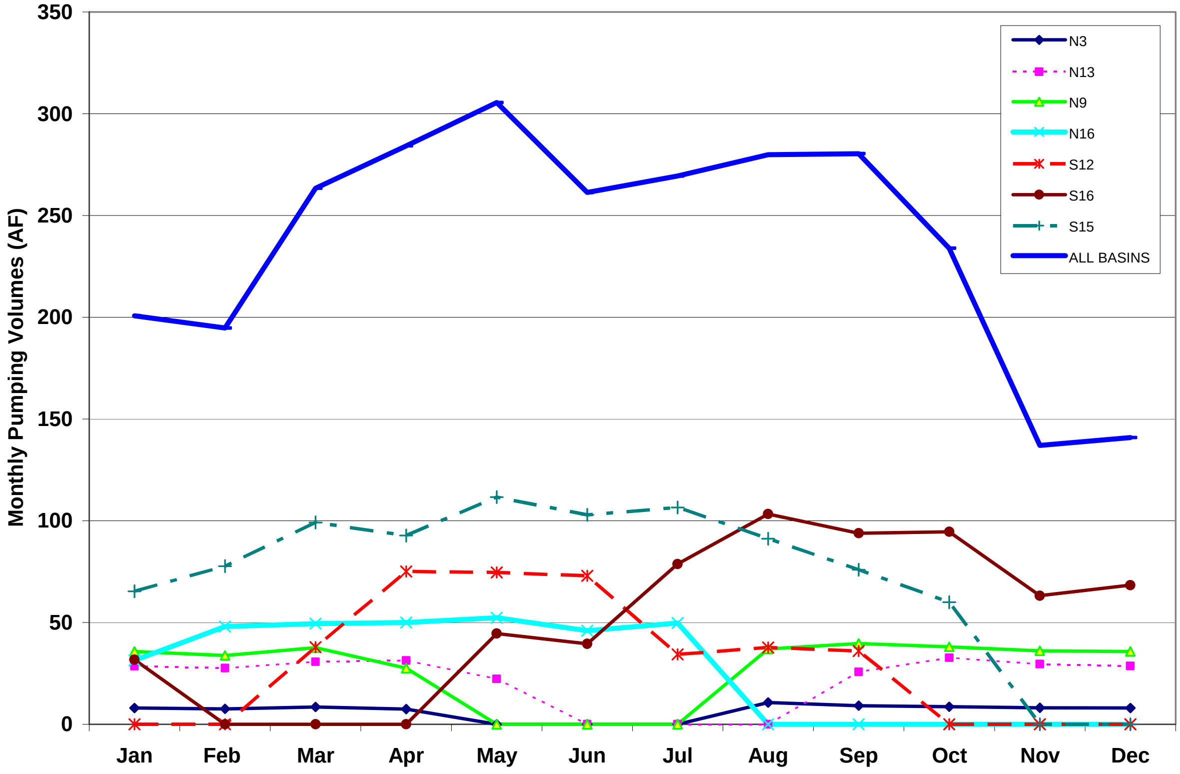

Figure 8-3. Predicted monthly wetland basin water demands assuming high infiltration losses.

	N3 (AF)	N13 (AF)	N9 (AF)	N16 (AF)	S12 (AF)	S16 (AF)	S15 (AF)	Monthly Subtotal (AF)
Jan	0.6	1.2	3.5	5.0	0.0	0.0	5.8	**16.1**
Feb	0.9	2.9	4.6	9.0	0.0	0.0	9.7	**27.2**
Mar	1.1	3.4	5.3	6.3	4.6	0.0	13.0	**33.7**
Apr	0.8	4.9	3.4	8.3	11.4	0.0	9.3	**38.1**
May	0.0	2.4	0.0	9.3	8.7	8.6	17.7	**46.7**
Jun	0.0	0.0	0.0	7.2	9.2	4.6	12.0	**33.0**
Jul	0.0	0.0	0.0	9.7	1.0	13.1	12.7	**36.5**
Aug	3.9	0.0	12.0	0.0	4.4	17.6	5.0	**42.8**
Sep	2.0	6.5	8.4	0.0	3.7	10.9	3.0	**34.6**
Oct	1.2	5.4	5.8	0.0	0.0	8.9	0.4	**21.6**
Nov	1.0	3.1	4.9	0.0	0.0	0.0	0.0	**8.9**
Dec	0.6	1.4	3.5	0.0	0.0	2.8	0.0	**8.2**
Totals	**12.0**	**31.3**	**51.3**	**54.8**	**43.1**	**66.4**	**88.6**	**347.5**

Table 8-3. Predicted monthly and total wetland basin water demands assuming low infiltration losses.

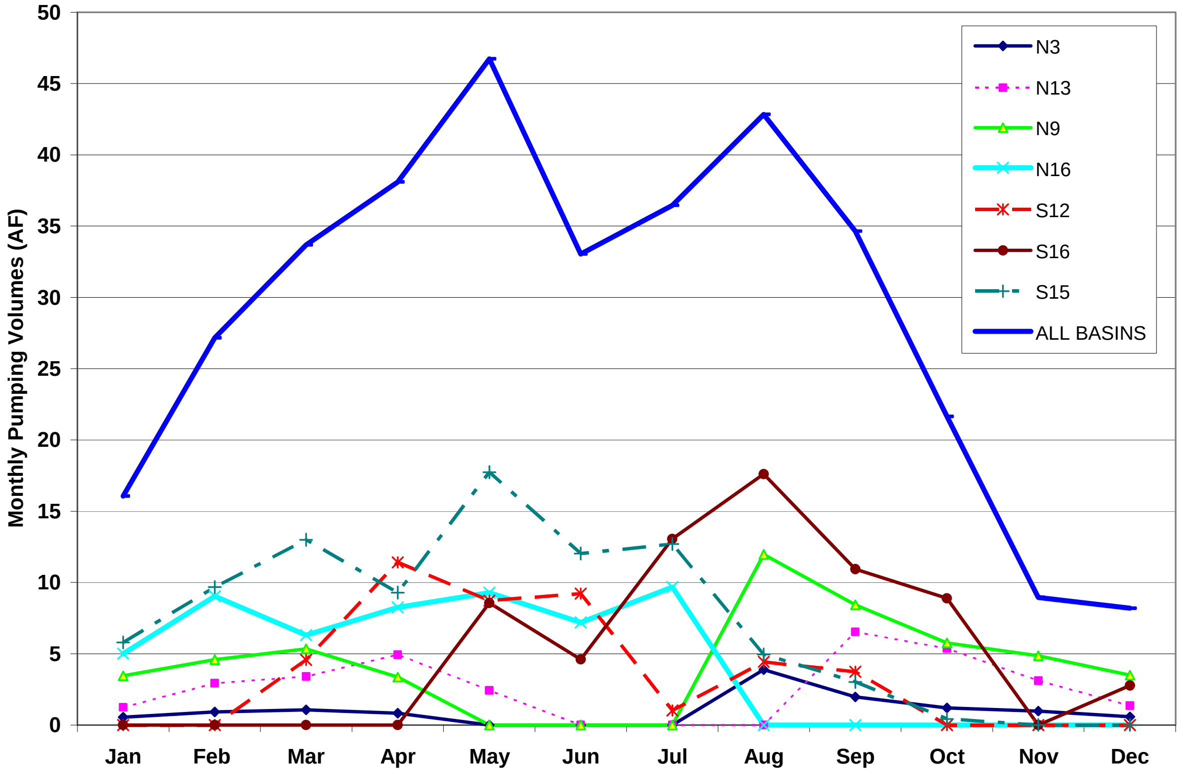

Figure 8-4. Predicted monthly wetland basin water demands assuming low infiltration losses.

	N3 (AF)	N13 (AF)	N9 (AF)	N16 (AF)	S12 (AF)	S16 (AF)	S15 (AF)	Monthly Subtotal (AF)
Jan	0.0		0.9	2.9	0.0	0.0	3.2	**7.0**
Feb	0.4	1.0	2.3	6.0	0.0	0.0	6.7	**16.3**
Mar	0.5	1.2	2.8	2.9	3.0	0.0	9.2	**19.6**
Apr	0.3	2.8	1.4	4.9	8.4	0.0	5.7	**23.6**
May	0.0	0.8	0.0	5.9	5.6	6.8	13.7	**32.8**
Jun	0.0	0.0	0.0	4.1	6.2	2.9	8.1	**21.3**
Jul	0.0	0.0	0.0	6.5	0.0	9.9	8.6	**25.1**
Aug	3.3	0.0	10.0	0.0	2.8	13.5	1.2	**30.9**
Sep	1.4	5.0	5.9	0.0	2.2	7.0	0.0	**21.6**
Oct	0.6	3.2	3.2	0.0	0.0	4.8	0.0	**11.8**
Nov	0.4	1.0	2.4	0.0	0.0	0.0	0.0	**3.8**
Dec	0.0	0.0	0.9	0.0	0.0	0.0	0.0	**0.9**
Totals	**6.9**	**15.1**	**29.8**	**33.2**	**28.2**	**45.1**	**56.4**	**214.7**

Table 8-4. Predicted monthly and total wetland basin water demands assuming no infiltration losses.

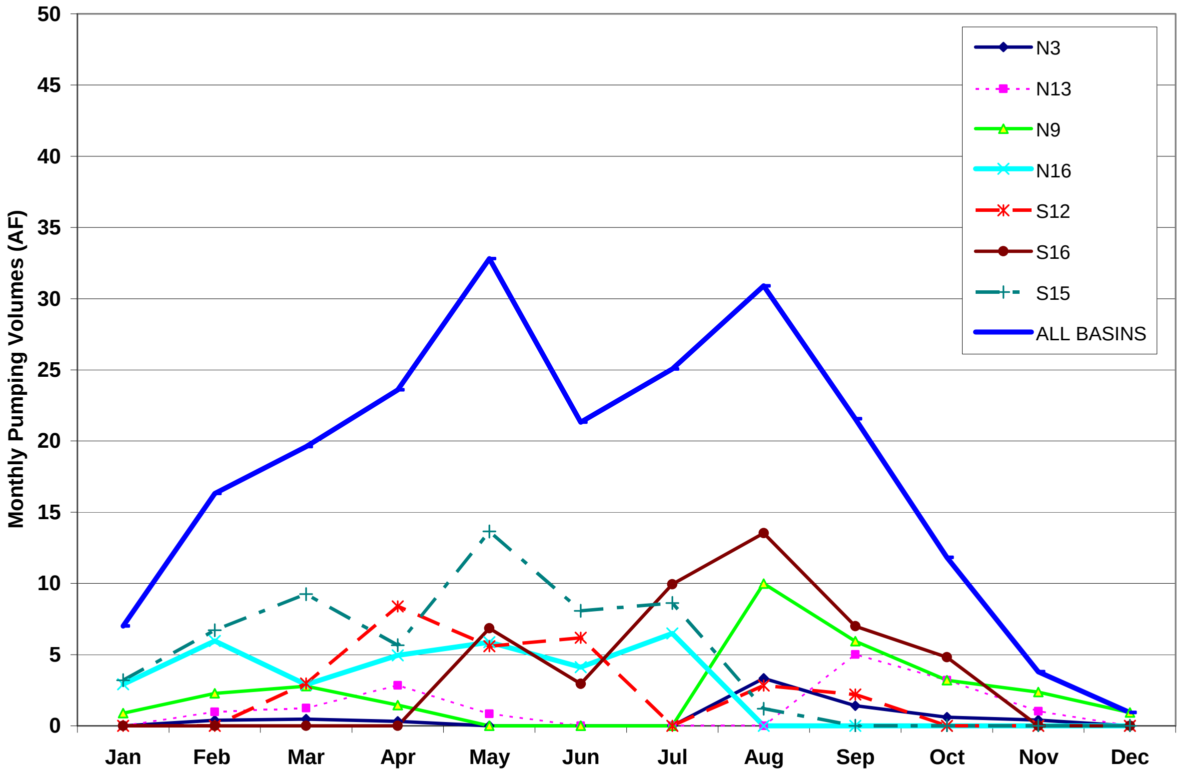

Figure 8-5. Predicted monthly wetland basin water demands assuming no infiltration losses.

8.3 Salt Budget Analysis

8.3.1 Methods

In order to predict project basin salinities, the water budget model was modified to track basin chloride concentrations (representative of salt) using the mass balance equation:

$$\Delta S = S_{ppt} + S_{sup} - S_{infilt} \qquad \text{(Eq. 3)}$$

Where: ΔS is the change in the mass of salt dissolved in the basin (kg)

S_{ppt} is the mass of salt dissolved in rainwater (kg);

S_{sup} is the mass of salt dissolved in the supplemental water either diverted from the main drain or pumped from groundwater (kg); and

S_{infilt} is the mass of salt dissolved in the water lost to infiltration (kg).

The mass of salt dissolved in the individual components of the water budget for any given month is calculated as the product of the volume of water associated with that component (AF) and the salinity level (kg/AF) of that component.

The salt budget model does not compute salinity directly, but instead accounts for chloride concentration and converts final chloride concentrations (mg/l) to salinity (ppt) by dividing chloride concentration (in mg/l) by 550. This conversion is possible as chloride is a conservative ion that occurs in a stable and consistent proportion to total water ionic concentration and constitutes 45% of total sea-water ion concentration (Hem, 1985). Initial chloride/salinity levels used in the water budget simulations include:

- Rain water: 2.00 mg/l Cl (per Root et al., 2004).
- Pumped groundwater: 130 mg/l Cl based on the average concentration of 14 chloride measurements in USGS well number 220148159453501 (site name 2-0145-10 W45F MANA), located approximately 1500 feet north of the proposed ADC water supply well and from the period 1990 through 1995.
- Pumped main drain: 4.00 ppt (2200 mg/l Cl), based on January 2012 ditch salinity concentration measured by DOFAW at likely main drain water diversion locations.

The product of this initial chloride and the initial volume of water in each wetland basin yields an initial mass of salt dissolved in the basin water (S_i). For each month: (1) ΔS is calculated using eqn-2, (2) a final mass of dissolved salt (S_f) is calculated as $S_i + \Delta S$, (3) S_f is divided by the volume of water stored in the basin at the end of each month to calculate the mass of salinity. The final mass of dissolved salt is then used to set the initial condition for the next month and the model repeats.

8.3.2 Results

Groundwater Supply

Simulated average monthly salinity concentrations within each basin receiving supplemental water from groundwater pumping of the basal aquifer are plotted on Figures 8-6, 8-7 and 8-8 for the High, Low, and No Infiltration Loss scenarios, respectively. These results indicate an inverse relationship between salinity concentration and basin infiltration rate. This relationship results from the need for larger volumes of low-salinity supplemental groundwater to off-set higher infiltration losses. Thus, in the High Infiltration Loss scenario, basin salinity most closely reflects the groundwater salinity. Salinities increase in the Low and No infiltration loss scenarios because salts are becoming evapo-concentrated. For example, the infiltration rate used in Basin S15 is significantly lower than any other basin, which contributes to an elevated salinity concentration in that basin. Salinities are also higher in the southern basins than northern basins as they maintain flooding through the summer months and are exposed to more evapo-concentration. Regardless, no salinities exceed 3.5-ppt in any of the basins under any scenario.

Main Drain Water Supply

Simulated average monthly salinity concentrations within each basin receiving supplemental water from the main drainage ditch are plotted on Figures 8-9, 8-10 and 8-11 for the High, Low, and No Infiltration Loss scenarios, respectively. Again, for alternatives using the drain water supply, the alternative with the highest infiltration rates yield the lowest salinity conditions. Wetland basin salinities range between 5- and 12-ppt for the High Infiltration Loss scenario. Under the Low Infiltration Loss scenario, basin salinities range a bit higher, from 3- to 31-ppt, with Basins S12 and S15 displaying salinities around double the concentration of other basins. Under the No Infiltration Loss scenario, all basins with the exception of Basin N3 reach a salinity of around 20-ppt, while basins S12 and S15 reach hypersaline concentrations. Basin N3 salinity remains the lowest, ranging from about 6- to 12-ppt.

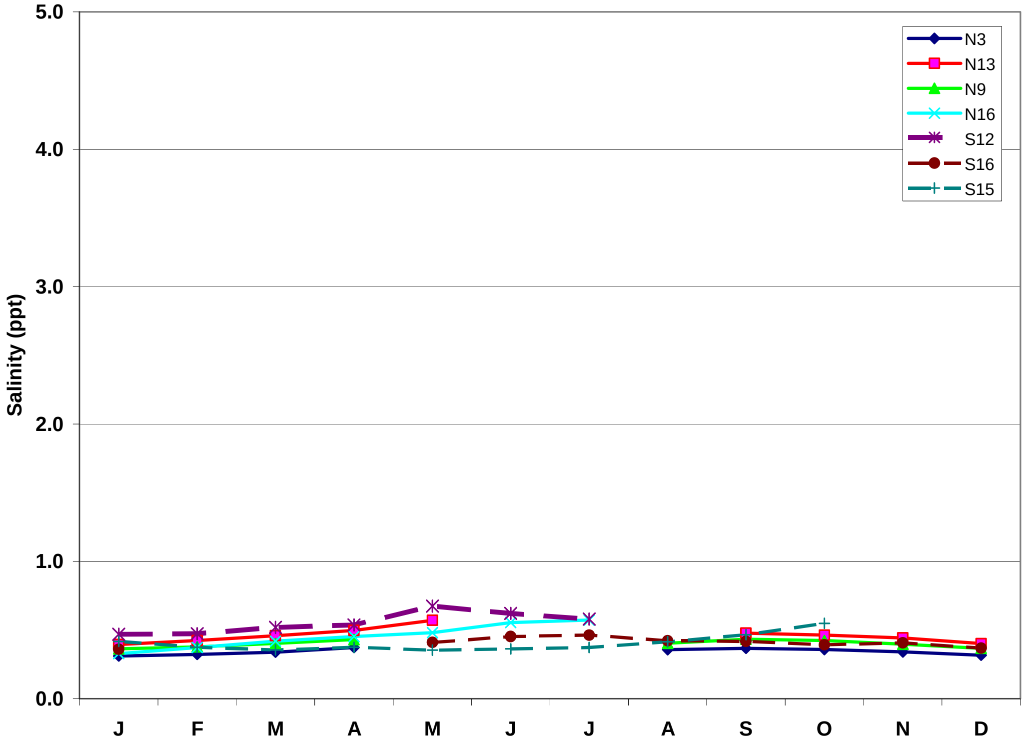

Figure 8-6. Predicted average monthly wetland basin salinity concentrations assuming groundwater supply and high infiltration losses.

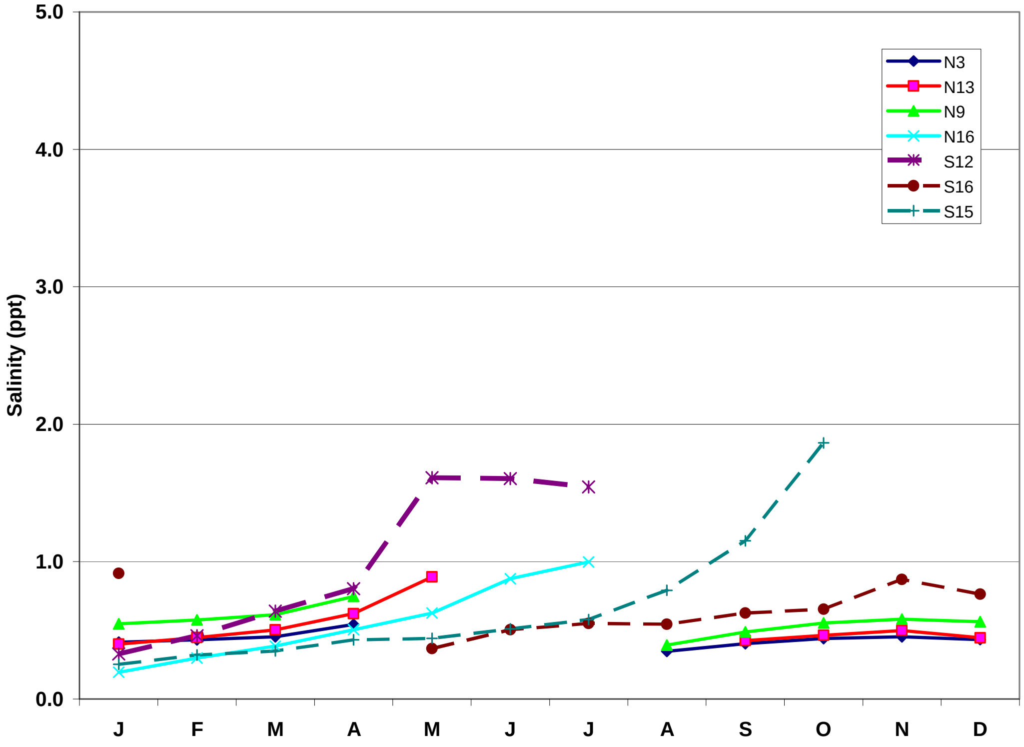

Figure 8-7. Predicted average monthly wetland basin salinity concentrations assuming groundwater supply and low infiltration losses.

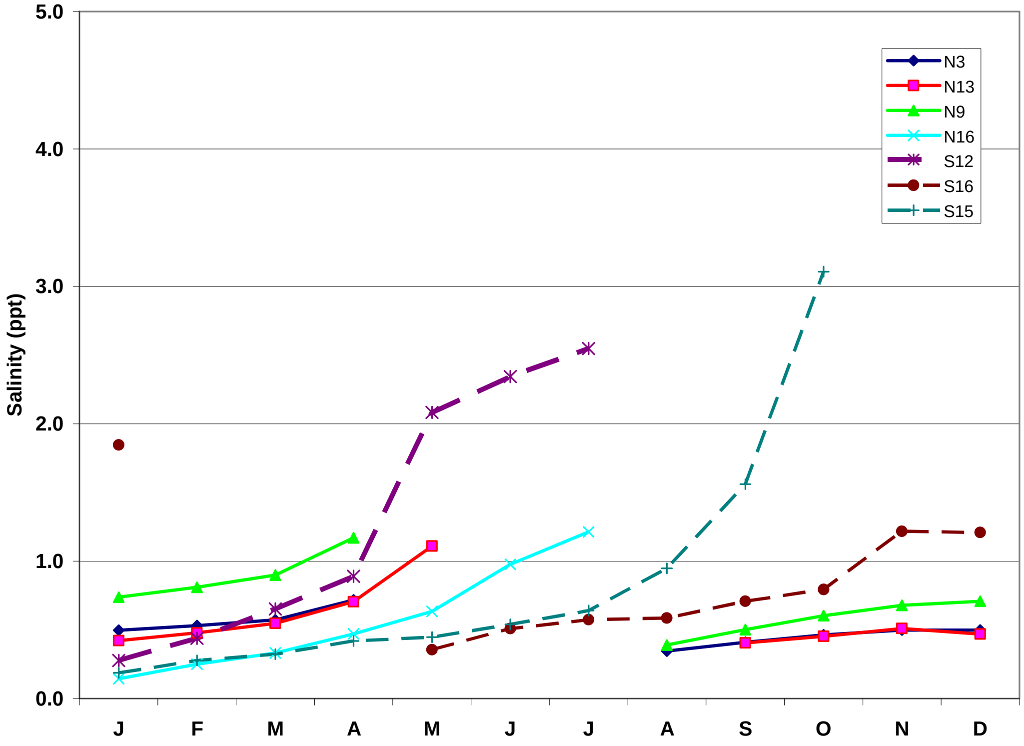

Figure 8-8. Predicted average monthly wetland basin salinity concentrations assuming groundwater supply and no infiltration losses.

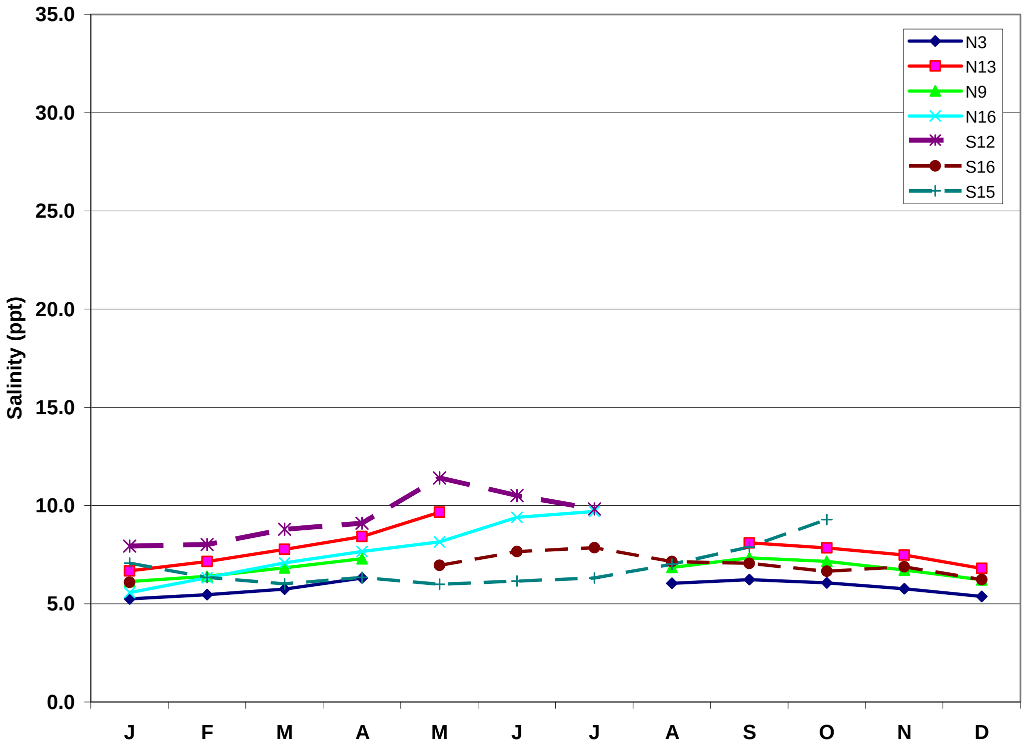

Figure 8-9. Predicted average monthly wetland basin salinity concentrations assuming main drain water supply and high infiltration losses.

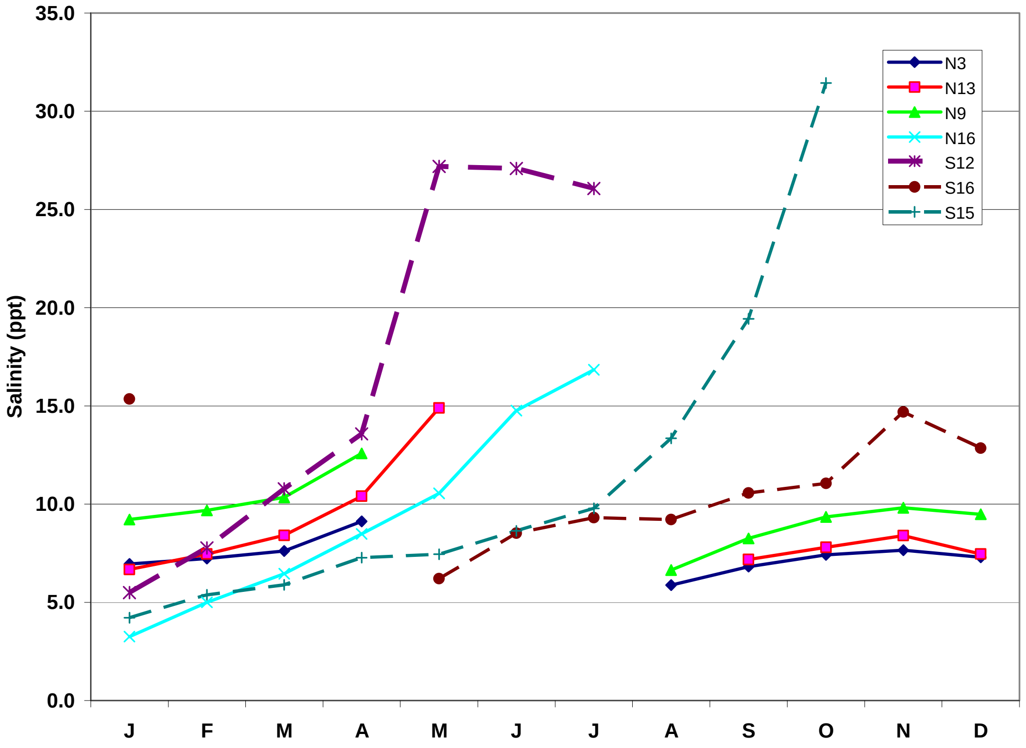

Figure 8-10. Predicted average monthly wetland basin salinity concentrations assuming main drain water supply and low infiltration losses.

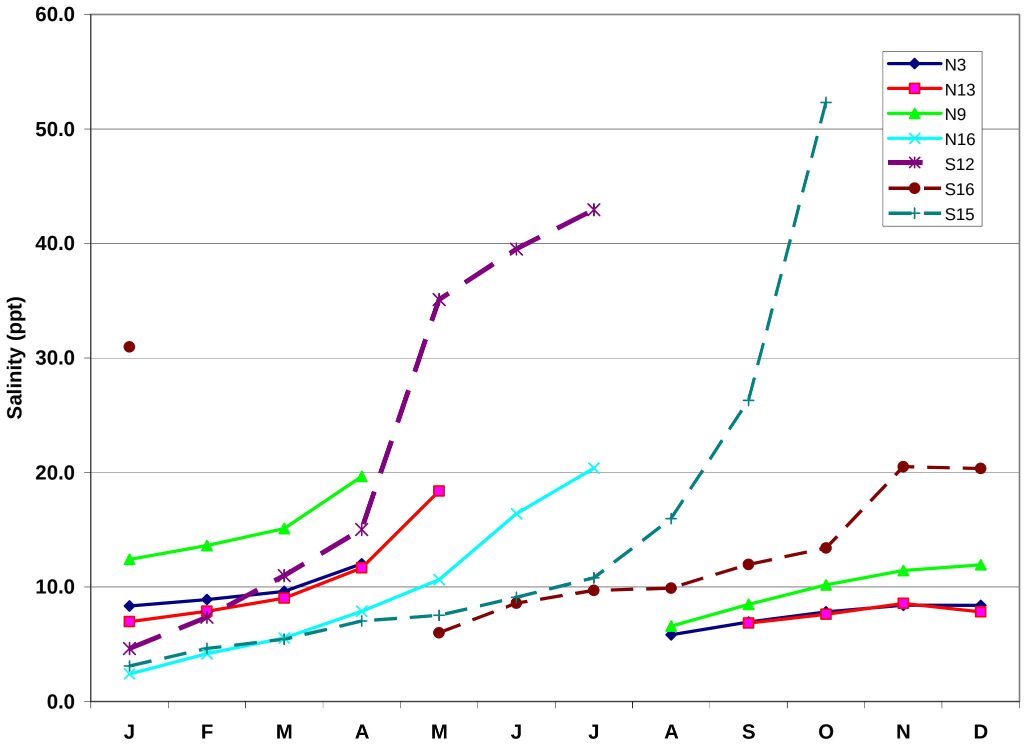

Figure 8-11. Predicted average monthly wetland basin salinity concentrations assuming main drain water supply and no infiltration losses.

8.4 Water Supply Feasibility

Water budget modeling provides estimates of the water supply required to maintain the desired levels of ponding in each of the wetland basins under the proposed wetland basin configuration. This section of the report discusses the feasibility of utilizing groundwater and main drain water as the primary water supply for the project. The restrictions to using the main drainage ditch water as a supply to the wetland basins are primarily driven by ditch water quality. Constraints to ditch water use are already presented in Section 5.5 of this report.

Based on the water budget modeling results, monthly wetland water demands are converted to daily demands in units typically used to express daily groundwater or drainage ditch pumping yields (see Section 8.1.2 above). To evaluate the feasibility of using groundwater to satisfy wetland water demands, we compare these daily water demands to representative pumping yields from local area basal aquifer wells. Factors that play into this analysis beyond simply achieving a satisfactory well yield include pumping rates that don't lead to salt water intrusion as well as the long-term costs of well pumping.

As indicated in Sections 3.3 and 6.1 of this report, the basal confined aquifer underlying the Mana Plain is the primary, if not sole source for municipal and irrigation water supplies. Reports by Burt (1979), MacDonald et al., (1960) and R.M Towill Corporation (1990) provide the best picture of historic groundwater production occurring in the project area. The overall historic groundwater production from the basal confined aquifer is summarized in

Section 6.1 and Figure 6-1. Burt (1979) indicates that yields from individual large-diameter wells or shafts may be as little as 1.4-million gallons per day (MGD) or as much as 22 MGD. The Agribusiness Development Corporation (ADC) owns a well located one-mile east of the project site that historically produced around 1,000,000 gallons per day (gpd), or 700 gallons per minute (gpm), of fresh water and was used for irrigation of sugarcane. The currently unused ADC well is flowing under artesian pressure at a rate between 30 and 35 gpm. Groundwater withdrawals reported in the 1990 R.M. Towill Corporation report indicate total groundwater withdrawals from the Kekaha-Mana Plain during that period to be 19.5 MGD (19.2 MGD from irrigation wells and 0.3 MGD from municipal wells). Wells and their capacities/yields reported in the 1990 report are summarized in Table 8-5. More recently, information provided by the ACD suggest that groundwater yields from the Mana-Kekaha Plain in 2011 have been reduced to around 4.0 MGD, significantly lower than the values reported for the 1990's. This reduction is due to a decrease in current agricultural demand. Based on comparison of the individual daily well yields presented in Table 8-5 and discussed above with the daily wetland water demands presented in Section 8.2.2, it appears that existing well yields are better able to meet the daily water demands for the Low and No Infiltration Loss water budget scenarios, while the High Infiltration scenario demands are 2- to 3 –times higher than a single wells available yield.

Well Type	Well Yield (GPD)	Well Yield (gpm)
municipal	108,720	76
municipal	205,000	142
municipal	192,600	134
municipal	154,250	107
municipal	56,040	39
municipal	95,530	66
municipal	60,180	42
municipal	28,900	20
irrigation	5,000	3
irrigation	4,000	3
irrigation	301,370	209
irrigation	25,000	17
irrigation	15,000	10
irrigation	3,000	2
Irrigation*	18,260,000	12,681
TOTAL	**1,254,590**	**13,552**
MINIMUM	**3,000**	**2**
MAXIMUM	**301,370**	**209**
AVERAGE	**89,614**	**62**

Table 8-5. Individual well yields within project vicinity. Irrigation well marked with asterisk represents cumulative yields for an undisclosed number of Kekaha Sugar company irrigation wells. This cumulative well yield is not included in statistical calculations. Source of data: (R.M. Towill Corporation, 1990)

Well installation and long-term pumping costs are also important considerations in designing the wetland water supply system. Proposed water development plans presented in R.M. Towill Corporation's 1990 report cite a $2,240,000 cost[23] for the installation of a single well with 600-gpm capacity. There is no detailed break-down of this cost, but it may include, "source production, storage, and transmission" elements. In discussions with a local area well driller Barry Simons of Oasis Water Systems, Inc. (personal communication, July 2011), Mr. Simons expressed concern about salt water intrusion on the Mana Plain when pumping at even the low pump yields necessary for the Low and No Infiltration Loss project designs. Based on unit costs provided by Mr. Simons, KHE estimates that well, pump and distribution line installation will cost approximately $100,000 and annual groundwater pumping costs are dependent on the volume of water pumped and power rate[24], but are summarized as follows.

- High Infiltration Loss scenario average pumping at 1834 gpm ($33,300/year);
- Low Infiltration Loss scenario average pumping at 216 gpm ($4,000/year); and
- No Infiltration Loss scenario average pumping at 133 gpm ($2,500/year).

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[23] Reported costs were developed from the Oahu Board of Water Supply 6-year Capital Improvement Program cost estimates for well development and reservoir construction.

[24] A power rate of $0.22 per kilowatt hour was used in this calculation. Annual pumping costs also assume 30-feet of lift, a pump efficiency of 60% and constant pumping.

9.0 FLOOD HAZARD ASSESSMENT

This section of the report documents hydraulic modeling studies describing existing and proposed flood hazard conditions within the Mana Plain Restoration Project. The hydraulic modeling process was completed to evaluate potential project benefits and impacts to flood hazards. In addition, the assessment provides design guidance towards construction of viable wetland habitat improvements and ecological benefits for the Project.

9.1 Approach and Methods

The study focused upon characterizing the difference between existing- and proposed-potential water surface elevations simulated at the restoration site over a series of different magnitude flood events and during post-storm conditions. The work was accomplished through development of the computer-based hydraulic model HEC-RAS (USACOE, Jan. 2010), which simulates existing and proposed project alternatives, including current operating conditions employed at the Kawaiele Pumping Station. Information regarding the Kawaiele pump station was provided by DOFAW (Hawaii DOFAW, 2011). The hydraulic model predicts water surface elevations and channel velocities.

9.2 Hydraulic Model Development

KHE developed a HEC-RAS one-dimensional unsteady state flow model of the main drainage canal crossing the restoration site, its contributing upstream channels, and the overbank areas within the restoration site. The overbank areas are slated to become the restored wetland basins, which will be contained by berms on both sides of the drainage canals crossing the site. The model includes channel junctions where flow may separate into two channels or join into one. Below the final channel junction, the pump station removes flow from the main drainage canal based on pump on/off elevations, capacity, and efficiency (Hawaii DOFAW, 2011).

The HEC-RAS model geometry consists of five upper channel contributing drainage area (DA) branches, four of which originate from DA-1 through DA-4 (see Figure 9-1) that ultimately feed into the main drainage canals that bisect the project site. A fifth drainage area (DA-5) contributes to a canal that border the east side of the Kaumualii Highway before it joins the main drainage canal.

A total of 36 cross-sections define channel geometry. Inputs to the model geometry file consist of the channel cross-sections and Manning's roughness coefficients. An initial HEC-RAS geometry file was developed utilizing cross-section locations developed from the Ducks Unlimited topographic map of the site (June 2008) and vicinity contours available through the USGS, "Hawaii Data Clearinghouse" (http://hawaii.wr.usgs.gov/kauai/data.html).

The Manning's roughness coefficient applied to the channels was 0.025, due the deficit of dense channel vegetation when compared to overbank areas. An overbank roughness coefficient of 0.04 was applied to the more densely vegetated overbank areas. Manning's coefficients were estimated based on field observations at the site and methods outlined by Arcement and Schneider (1989). Estimated coefficients were also confirmed by comparison to published values in a variety of texts (Barnes, 1967; Chow, 1959; Limerinos, 1970; and Coon, 1998).

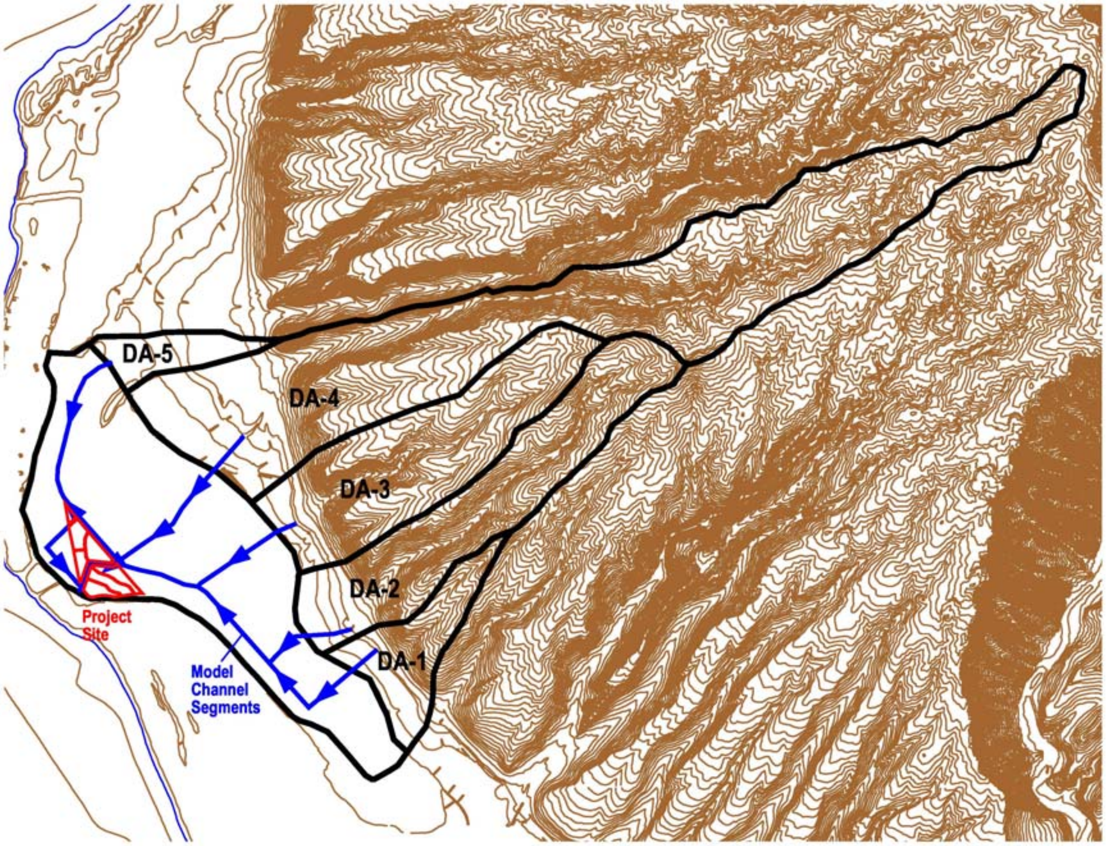

Figure 9-1. Contributing drainage areas (DA) and model channel segments.

9.2.1 Existing and Proposed Geometry

The upper reaches of the five main channels located east of Kaumualii Highway exhibit the same geometry under existing and proposed conditions. West of the highway, the differences between existing and proposed conditions are the creation of wetland basins and construction of berms around the basins that will require modifications to the existing levees along the sides of the main canals within the project site boundaries. Proposed levees along the main drainage canal range from 3.5 to 4.5 feet (MLLW datum) in elevation along the left bank and 2.5 to 2.75 feet along the right bank (bank designations given as facing downstream). At the northern area of the project where the fifth contributing drainage area (DA-5) enters the site (joining with the Kaumualii Highway Canal), the levee elevations are 4.25 feet on the right bank and 3.0 feet on the left bank. Canal flow lines within the site are assumed to be -4 feet elevation and have no slope.

9.2.2 Design Flow Estimates

Peak flows for the 2-, 5-, 10-, 25-, 50- and 100-year flood events were developed for each of the five contributing watersheds. Estimates were derived using the peak flow estimates presented in Oki et al. (2010) for the USGS Nahomalu Valley gauge (No. 16031000; see Figure 5-2). Once peak flow values were analyzed and established for Nahomalu Valley, an area ratio was applied for each drainage area (DA-1 through DA-5) contributing to the site in order to derive site specific peak flow values. Existing and proposed peak flow rates do not differ. Peak flow rates for the five contributing watersheds are provided in Table 9-1.

Flood Recurrence Interval (yrs)	DA-1 (cfs)	DA-2 (cfs)	DA-3 (cfs)	DA-4 (cfs)	DA-5 (cfs)
2	43	116	118	320	21
5	109	294	299	812	54
10	182	492	501	1,359	91
25	323	872	888	2,411	161
50	469	1,265	1,289	3,499	234
100	646	1,744	1,776	4,823	323

Table 9-1. Modeled Design flood flows.

KHE developed hydrographs applicable for each watershed at each recurrence interval by extrapolating 2-year and 100-year 24-hour peak flow rate vs. time patterns for a watershed study in Oahu (USACOE, 2008). The resulting peak flow hydrographs are applicable to this study because the dynamic modeling process allows for incoming and exiting (pump) flows to equalize the system water surface over time, producing resultant water surface elevations at any point in time, including peak water surface elevations as well as post-storm conditions during the storm recession. Each input hydrograph includes a minimum baseflow rate ranging from 2- to 4-cfs, which serves to mimic low flow conditions.

9.2.3 Boundary Conditions

At the downstream end of the model, the Kawaiele Pumping Station pumps water from the Main Drainage Canal into the Kinikini Drainage Canal, which outlets to the Pacific Ocean. The final model cross section describes the levee wall separating the canals.

The elevation of the levee separating the main drainage canal and the Kinikini Canal is approximately 8 feet (MLLW datum). As waters in the main drainage canal rise above 3.33 feet MLLW during large storm events, flow is directed through an overflow outfall created by a weir in the earthen levee separating the two canals. The breach dimensions are assumed to be 30 feet wide with an overflow weir elevation of 3.33 feet MLLW. The downstream boundary condition is based on normal depth with a channel slope of 0.004 for the “channel” below the notch.

Three pumps operate at the Kawaiele Pumping Station. Water pumped from the main drainage canal essentially exits the model. Operating conditions for each of the pumps and the system in general is as follows:

- The primary pump turns on at -0.67 feet elevation and off at -1.67 feet MLLW. The 14,000 gallon per minute (31.2 cfs) pump operates at 85% efficiency, pumping approximately 26.5 cfs.
- The lead pump turns on at -0.17 feet elevation, off at -1.17 feet MLLW. The 28,000 gallon per minute (62.4 cfs) pump operates at 85% efficiency, pumping approximately 53 cfs.
- The lag pump turns on at 0.83 feet elevation and off at -0.17 feet MLLW. The 28,000 gallon per minute (62.4 cfs) pump operates at 85% efficiency, pumping approximately 53 cfs.
- As water levels rise above 3.33’ MLLW, the levee separating the main drainage canal and the Kinikini Canal is overtopped through a designed overflow weir and excess water flows into the Kinikini drainage canal and Pacific Ocean.

9.2.4 Simulation Parameter Output

Parameters observed throughout the study include water surface elevations at peak and post-storm conditions, length of time for water surface elevation recession, pump output hydrographs, and peak channel velocity. Peak velocities are an indicator of long term channel scour potential, sediment movement, and channel-maintaining (neither aggrading nor degrading) flows.

9.3 Simulation Results

9.3.1 Velocity

The highest velocities occur within the upper channel reaches, due to the slope of the land. The highest upstream velocity for the 2-year event is slightly less than 8 feet per second. The highest upstream velocity for the 5-year event is slightly more than 10 feet per second. The 10-year event peak upstream velocity is 12 feet per second. The 25-year event peak upstream velocity is 14.5 feet per second. The 50-year event peak upstream velocity is 16.5 feet per second.

Within the project area, even the highest 2-year velocity was less than 1 foot per second for both existing and proposed conditions flows. The 5, 10, 25, and 50-year onsite peak velocities are 1.5 feet per second.

Flow velocities in canals crossing the project site remain below sediment mobilization thresholds even during high storm flow events (Fortier & Scobey, 1926; Chow, 1959). This suggests that sediment aggradation may be a problem within the canal system adjacent to the project site, further exacerbated by the downstream levee wall, which stops most coarse sediment from exiting. Even as water is released through the earthen overflow weir during high flow events, the only sediment to exit the system is suspended sediment, leaving all bed load particles to accumulate within the main drain upstream and near the pump intake system. Project designs should consider the long-term channel maintenance needs, perhaps by setting wetland basin berms back away from the main drain to allow unimpeded construction access for future channel maintenance (dredging).

9.3.2 Water Surface Elevation

Time series of water surface elevations within the main drainage canal and project area are best described in profile plots of stage vs. time at the Kawaiele Pumping Station. Existing and project conditions flood hydrographs for the 2- through 50-year floods are presented on Figures 9-2 through 9-6. Simulated Kawaiele pump outflow hydrographs are also displayed on these profiles. Storm events occur during the first day of each profile, with each profile extending for six and one-half days. Existing and project condition water surface profiles for simulated flood flow events are plotted on Figure 9-7. The location of this section through the main drainage canal within the project area falls between the Kawaiele pumping station and Kaumualii Highway.

The 2-year project peak water surface elevation is 0.26 feet higher than existing conditions (Figure 9-2). In this case, the project water surface is confined within the ditch corridor created by the wetland basin berms constructed with a 40-foot setback from the main drainage canal (see Figure 9-7). Under project conditions, the confined water surface rises more quickly than if it was able to spread out into the overbank areas (existing conditions). After nearly 3-days, the lag pump draws down both existing and proposed water surfaces to the same level and shuts off. As the lead pump begins to cycle through post-storm conditions, the existing and proposed water surfaces remain at the same elevations. The 2-year event water levels do not reach the elevation of the levee overflow weir between the main drainage canal and the Kinikini Canal.

The 5-year existing and proposed peak water surfaces (Figure 9-3) attain approximately the same elevation, 4.2 feet. Both recede to post-storm levels after approximately 3½ days, when the lag pump shuts off. Existing conditions take minimally shorter time to recede, causing the timing of the existing-conditions lead pump cycle to precede proposed conditions by a few minutes – thus the offset in post-peak pumping. The 5-year and more severe storm events cause water levels to reach and exceed the overflow weir crest feeding the Kinikini Drainage Canal. Peak water levels also exceed the height of the wetland basin berms, leading to complete inundation of the project area.

The 10-year existing and peak water surfaces (Figure 9-4) also attain approximately the same elevation, 5.3 feet. After 3½ days, the pumps draw down the water surfaces and the lag pump shuts off. Existing conditions is drawn down slightly more quickly than proposed conditions, causing the proposed-conditions lead pump cycling to be delayed by one hour.

The 25-year storm event attains peak water levels of 7.3 and 7.2 feet for both existing and proposed conditions (Figure 9-5), respectively. Existing conditions lag pump shuts off after nearly 4 days and the proposed conditions lag pump shuts off an hour later. There is a delay in the proposed-conditions lead pump cycle by approximately one hour.

The 50-year storm event attains 9.3 and 9.2 feet peak water surface elevations for both existing and proposed conditions (Figure 9-6), respectively. Existing conditions lag pump shuts off after 4¼ days and proposed conditions lag pump shuts off an hour later. There is a delay in the proposed-conditions lead pump cycle by approximately one hour.

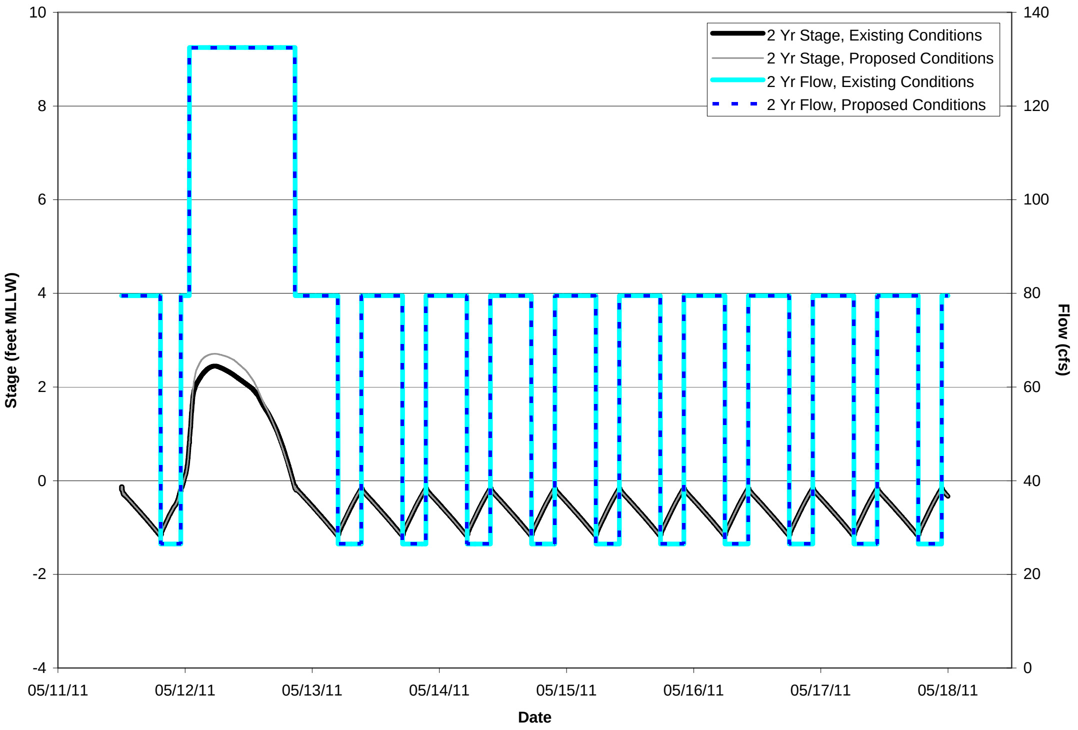

Figure 9-2. Simulated existing and project condition water levels and flow rates upstream of Kawaiele pump station during a flood with 2-year recurrence interval.

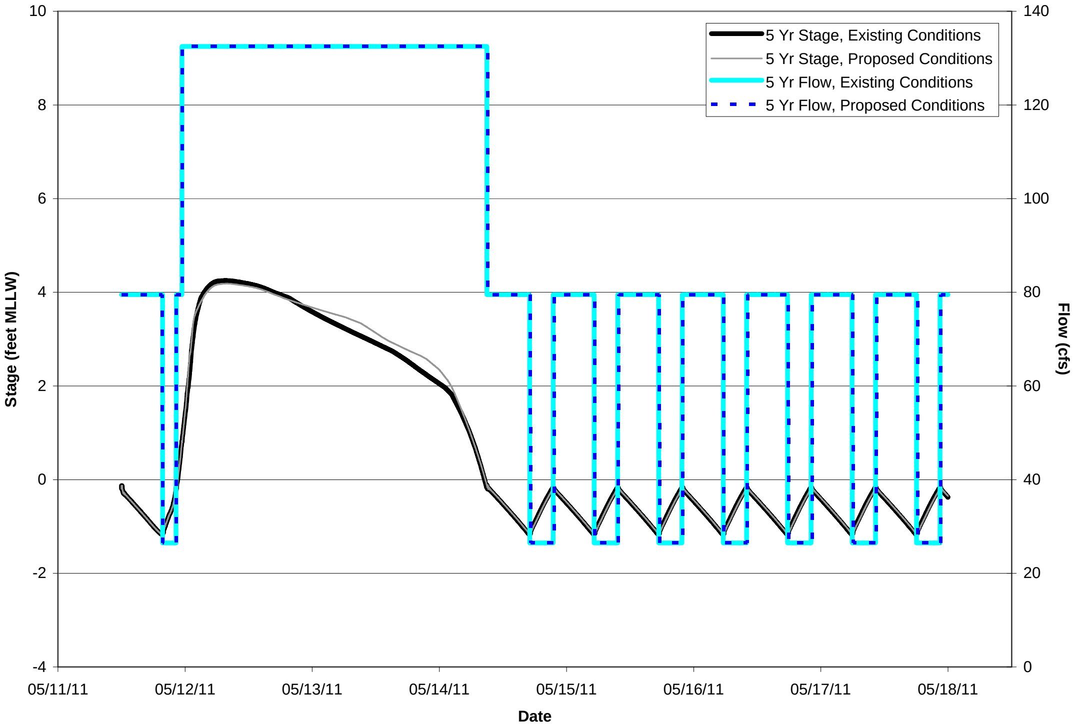

Figure 9-3. Simulated existing and project condition water level and flow rates upstream of Kawaiele pump station during a flood with 5-year recurrence interval.

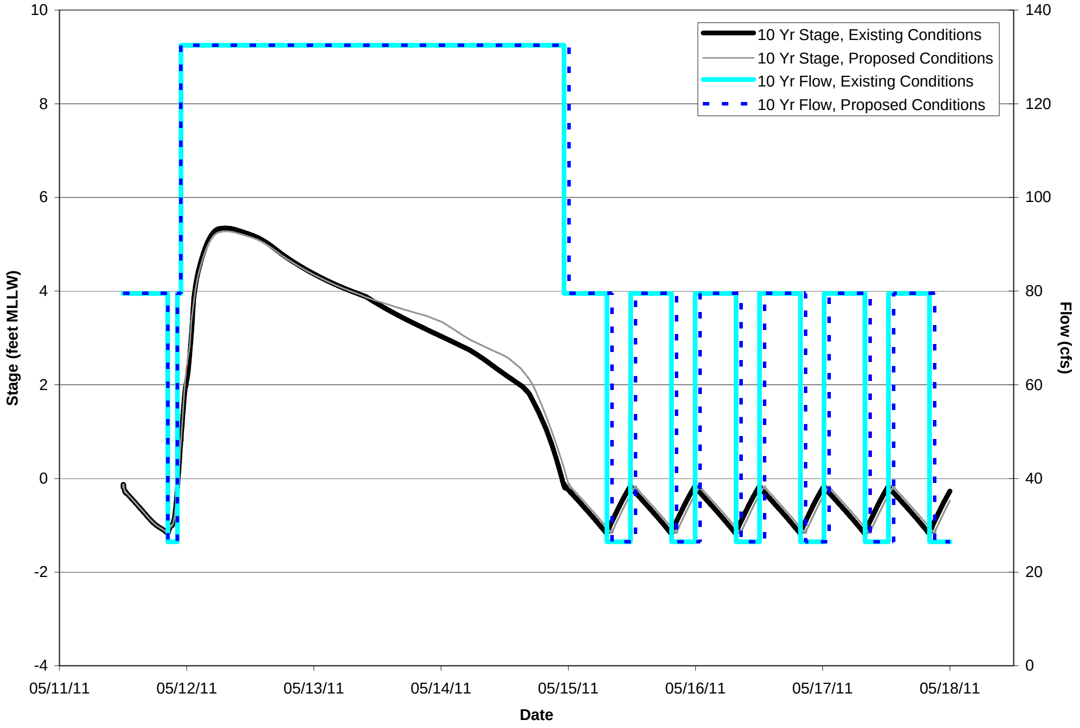

Figure 9-4. Simulated existing and project condition water level and flow rates upstream of Kawaiele pump station during a flood with 10-year recurrence interval.

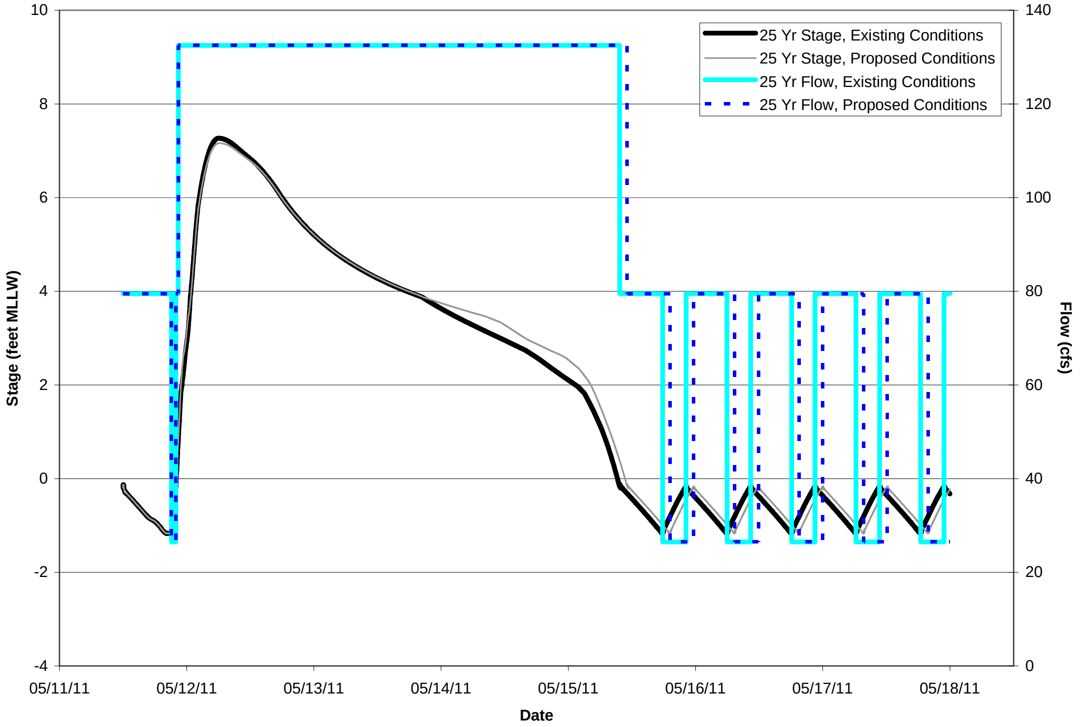

Figure 9-5. Simulated existing and project condition water level and flow rates upstream of Kawaiele pump station during a flood with 25-year recurrence interval.

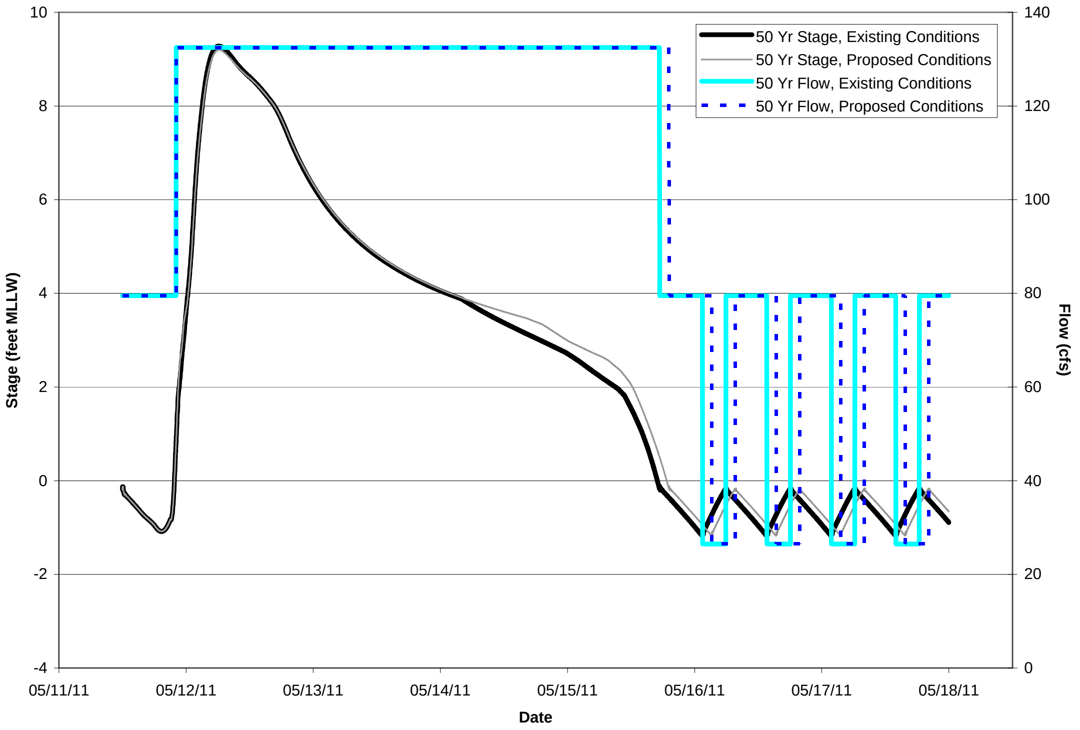

Figure 9-6. Simulated existing and project condition water level and flow rates upstream of Kawaiele pump station during a flood with 50-year recurrence interval.

Due to severely high water surfaces which rose above the limits of the available project geometry, the 100-year storm event did not produce viable information on proposed water surface elevations.

A specific event not modeled in HEC-RAS but worth discussing here is the profile of hourly staff gage water surface elevations at the Kawaiele Pumping Station from December, 2008 through January 2009. During this time period, over 11 inches of rain fell during a one day period at the Waimea Climate Station (December 16, 2008) just days after two smaller events. This event was extrapolated to be approximately 8.4 inches in 24 hours at the Mana Climate Station and 9.4 inches in 24 hours at the Kekaha Climate Station. The daily rainfall at three local stations is also plotted on Figure 9-8. The high flow event is clearly indicated by both the water level and rainfall hydrographs plotted on Figure 9-8. These data also indicate that it took approximately 12 days before ditch water levels receded to pre-flood levels.

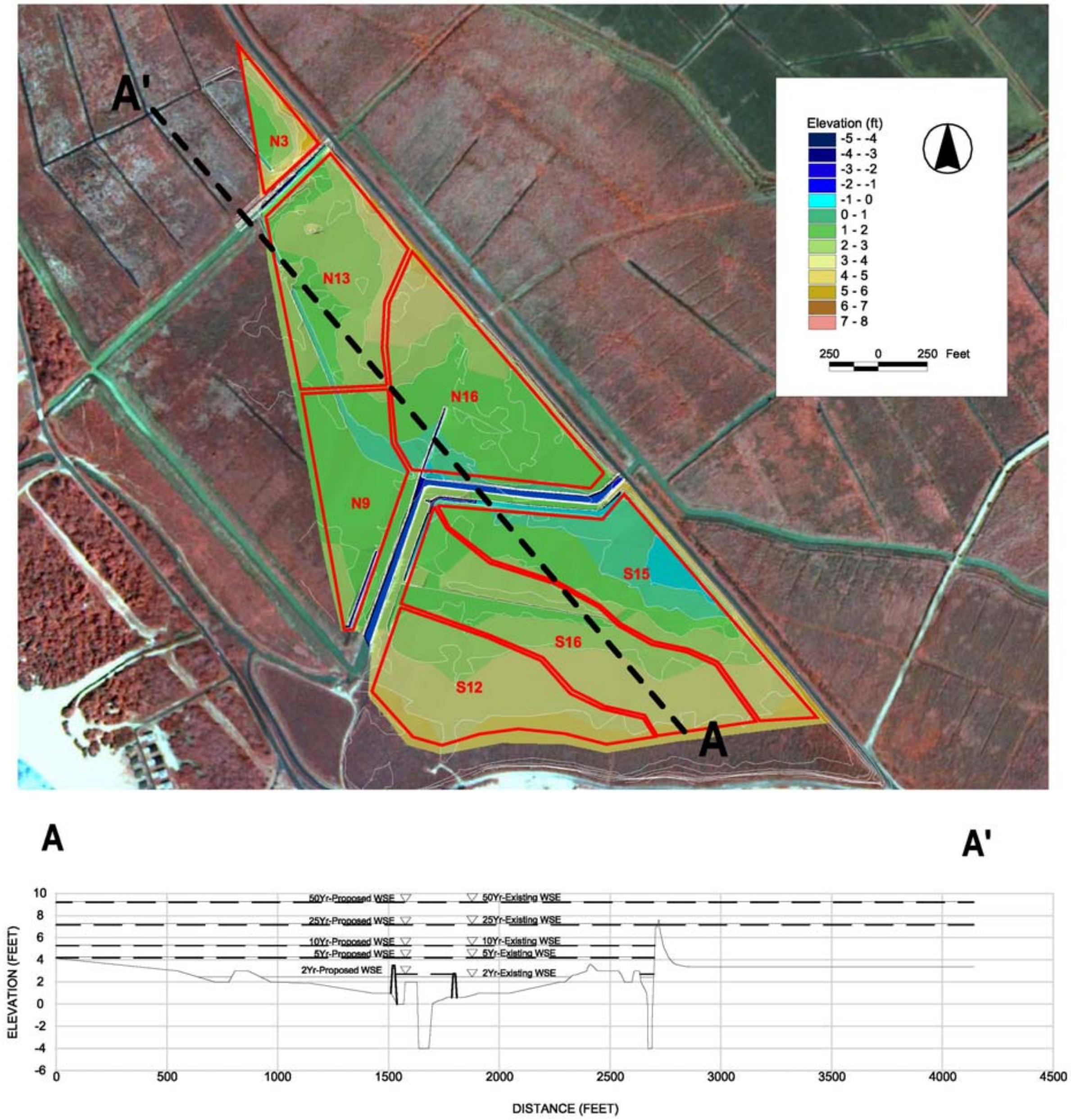

Figure 9-7. Cross-sectional profile A-A’ of simulated flood water levels across project site.

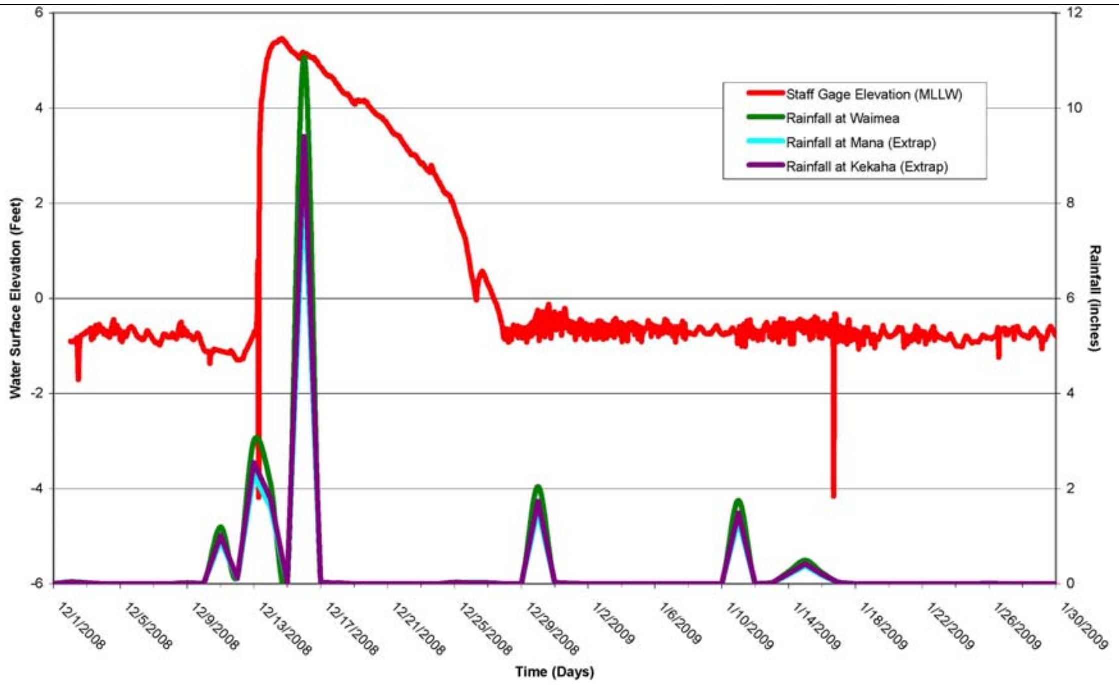

Figure 9-8. Water levels at Kawaiele pump station and rainfall for December 2008 storm.

9.4 Conclusions and Recommendations

Simulated project conditions do not significantly differ from pre-project (existing) conditions within the project area. Nor will the project introduce or increase the current levels of flooding to the adjacent Highway or agricultural properties. Under project conditions, water may recede slightly slower than during existing conditions, causing the lead pump cycle to be delayed by about an hour for larger events. Peak velocities are not affected by proposed conditions. Similar to existing conditions, main drainage canal velocities remain below 2 feet per second within the project area, regardless of the size of the storm event. Therefore, non-suspended sediment will continue to be trapped and accumulate in the main drainage canals adjacent to the project as this material has no way to exit the system (i.e. pass the Kawaiele pumps) except by mechanical means.

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