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Impact of Sea-Level Rise on the Hydrologic Landscape of the Mānā Plain, Kaua'i

Basil Gomez

Department of Geography and Environment, University of Hawai'i, Mānoa, Honolulu, HI 96822, USA; basilg@hawaii.edu

Abstract: The Mānā Plain is a land apart, buffered from oceanographic influences by ~3–35 m high backshore deposits, and drained by an intricate, >100-y-old ditch system and modern, large-capacity pumps. Quantifying present and prospective inputs and outputs for the hydrologic landscape suggests that, although sea-level rise (SLR) will begin to impact ditch system operations in 2040, transient, event-based flooding caused by rainfall, not SLR induced, multi-mechanism flooding, will continue to pose the most immediate threat. This is because as sea level rises the ability of gravity flows to discharge storm runoff directly into the ocean will diminish, causing floodwater to pond in low-lying depressions. Estimates of the volume of water involved suggests the risk of flooding from surface water is likely to extend to 5.45 km^2 of land that is presently $\leq$ 1 m above sea level. This land will not be permanently inundated, but weeks of pumping may be required to remove the floodwater. Increasing pumping capacity and preserving some operational ability to discharge storm runoff under the influence of gravity will enhance the ditch system's resilience to SLR and ensure it continues to fulfill its primary functions, of maintaining the water table below the root zone and diverting storm runoff away from farmland, at least until the end of this century.

Keywords: coastal plain; drainage ditch system; hydrologic landscape; Hawai'i; sea level rise

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1. Introduction

As a consequence of land ice melt and the thermal expansion of seawater, global mean sea level has risen ~210–240 mm since 1880 and, because of climate change that has already occurred, it is projected to continue rise throughout the twenty-first century and beyond [1]. The Hawaiian Islands have 1700 km of coastline, and a ~1 m rise in sea level, which is thought to be representative of the magnitude of sea-level rise (SLR) the State will experience in the mid to latter half of this century, would potentially make ~105 km^2 of low-lying coastal land unusable [2].

The threat SLR induced, multi-mechanism flooding poses to the urbanized coastal plains on O'ahu has been well researched [3–6], and the vulnerability coastal wetlands across the State have to SLR has also been assessed [7]. These and other studies have emphasized that, to provide insight to potential future conditions and evaluate the utility of different adaptation measures in both urban and rural settings, it is necessary to move beyond the "bathtub" model and account for factors other than relative SLR [2]. Among these factors, the influence surface water inputs from adjacent uplands will have on flooding depths and inundation extents on Hawai'i's coastal plains has received little attention, because most of the State's small streams are ungauged. Geomorphology has also been shown to be an especially strong biophysical metric of coastal vulnerability in Hawai'i [8], and the disparity between what is assumed and what should be known has profound implications for the development and assessment of adaptive measures.

Like Hawai'i's other coastal plains, the Mānā Plain in West Kaua'i is buffered from oceanographic influences by a narrow swath of wave- and wind-formed backshore deposits. The local rate of SLR is 1.71 $\pm$ 0.42 mm/y and, although modelling suggests sustained marine inundation involving a direct connection to coastal waters poses the dominant long-term threat to this coastal landscape, it is thought pumping could diminish the impact of near-term flooding [2]. However, in this case, the hydrological enforcement is invalid because there are no natural streams on the Mānā Plain and, to enable the ambient water level in the artificial drainage system to be controlled by pumping, all outlets to the ocean are blocked and filled by sand or earthen plugs.

This paper provides a new perspective on the multi-mechanism effects of SLR on the Mānā Plain by quantifying inputs and outputs for the hydrologic landscape. By including runoff impacts it is possible to evaluate the extent to which an adaptation strategy that is reliant on pumping will help preserve the functionality of land on the Mānā Plain.

2. Materials and Methods

2.1. Field Setting

The Kekaha-Mānā Plain is a crescentic, 24 km long, northwest-southeast trending coastal plain (Figure 1). Land northwest of Kekaha was traditionally described as *mānā* (arid) [9], and this nomenclature for the study area is used herein. The Mānā Plain is underlain by a wave-cut platform and bounded by abandoned sea cliffs (pali) formed in 5.1–4.3 Ma old layered tholeiitic lavas of the Waimea Canyon volcanic series' Nā Pali formation [10,11]. Landscape evolution modelling suggests the cliffs were created by wave erosion in the 2 Ma period following the cessation of shield-building volcanism and reactivated during the last interglacial (130–120 ka) highstand [12].

2.2. Physical Landscape

Dissected by closely spaced, ephemeral, bedrock streams, the 50–250 m high pali decrease in height from north to south, and steeper slopes with exposed bedrock outcrops and talus accumulations at their base transition to lower gradient soil-mantled hillslopes (Figure 1). These streams drain 109 km^2 of upland on Pu'u Ka Pele slope and are consequent on the volcanic edifice. The elongate drainage network is relatively immature [13]. Many interfluves have undergone a minimal amount of physical erosion and are mantled by mature laterite carapaces [14]. However, the up-basin divides were truncated by the south-southeast trending fault scarp that created the west wall of Waimea Canyon [10]. Ranging from ~5–16 km in length and rising to elevations of ~300–1120 m, the streams have linear or slightly convex profiles with small or no knickpoints [15]. As a result of sandalwood harvesting and the introduction of cattle and goats, by the mid-nineteenth century the native vegetation on Pu'u Ka Pele slope had begun to be replaced by non-native species [16,17]. Subsequently, as plantation agriculture waned, the vegetation cover reverted to degraded, dry shrub and grassland comprising a mixture of native and exotic, invasive species [18].

Mantled by coralline beach and dune sand, beachrock, alluvium, talus, clay-rich lagoonal marl and fossil coral reefs, the low-gradient (~5°) wave-cut platform lies ~160–125 m below the ground surface [10,19]. Except in locations East of Kekaha immediately down-drift from the Waimea River, the present-day shoreline comprises ~25 km of gently sloping, coarse-grained, carbonate sand beaches interspersed with outcrops of beach rock that are backed by ~3–35 m high beach ridges and fine-grained, moderately to well-cemented sand dunes [19]. Traversed only by the outlets of the drainage ditch system, the semi-parallel, wave- and wind-built ridges form a permeable barrier between the Mānā Plain and the ocean (Figures 1 and 2). There are two basal aquifers beneath the plain. The basaltic, artesian aquifer in the Nā Pali formation has a hydraulic conductivity of ~122 m/day and is confined by the much less transmissive (~0.037 m/day) overlying sedimentary cover, which is saturated with brackish and more saline water [17,20].

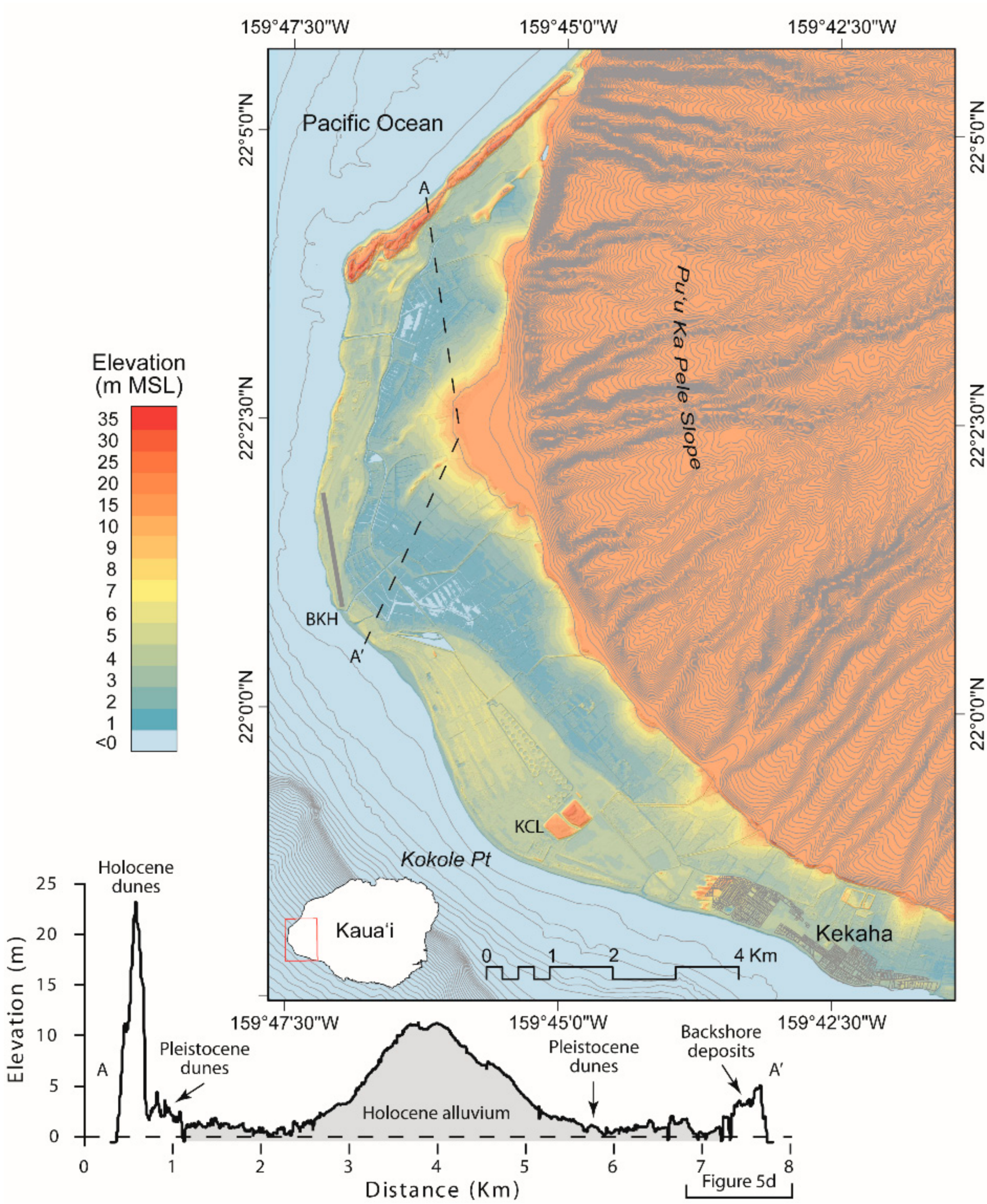

Figure 1. Topography of the Mānā Plain and adjacent areas (location is indicated by red rectangle in inset map). This segment of the NOAA Coastal Services Center's hydro-flattened, 3 m DEM was developed from 2006 Hawai'i FEMA Lidar. It is referenced vertically to the local mean sea level tidal datum (MSL, with vertical units of meters) and horizontally to the North American Datum of 1983 (NAD83), and is superimposed upon the University of Hawai'i's School of Ocean and Earth Science and Technology (SOEST) Kaua'i hillshade. The unlabeled 10 m nearshore bathymetric and elevation contours on Pu'u Ka Pele Slope were derived from SOEST's 50 m bathymetry and topography grid for the main Hawaiian Islands, and call attention to changes in the elevation and shape of the adjacent terrain. The location of section A–A' is shown by the dashed line. In addition to the irrigation and drainage ditch systems, prominent anthropogenic topographic features on the Mānā Plain include the runway (BKH) at the 8.64 km^2 U.S. Navy's Pacific Missile Range Facility and the Kaua'i County landfill (KCL).

Table 1. March 2020 and hypothetical storm rainfall for different recurrence intervals (years, y), basin characteristics (CN is the SCS curve number), and HEC-HMS runoff estimates for the March 2020 storm and specified 24-h duration frequency storms (see Figure 3 for basin locations).

	Event				**2020**	**2-y**	**5-y**	**10-y**	**50-y**	**100-y**
	Rainfall–Puʻu Ka Pele Slope (mm)				392	97	140	168	227	251
	Rainfall–Mānā Plain (mm)				305	85	123	148	200	221
	Basin	**Area (km^2)**	**CN**	**Lag (minutes)**	**Runoff ($m^3 \times 10^6$)**					
1	Kahoaloha	6.27	66.51	75.5	1.69	0.21	0.36	0.48	0.77	0.90
2	ʻŌhaiʻula	5.05	67.69	54.2	1.39	0.18	0.30	0.40	0.64	0.74
3	Waiakamoʻo	1.90	61.31	48.5	0.47	0.05	0.09	0.12	0.20	0.24
4	Kahelunui	6.47	66.16	80.5	1.73	0.21	0.37	0.49	0.79	0.92
5	Nahomalu	9.96	65.84	89.9	2.65	0.32	0.56	0.75	1.21	1.41
6	Kaʻawaloa	8.47	64.68	103.5	2.22	0.26	0.45	0.61	1.00	1.16
7	Nui	2.85	73.38	47.2	0.85	0.13	0.21	0.27	0.41	0.47
8	Wailau	3.16	68.11	44.9	0.87	0.11	0.19	0.26	0.41	0.47
9	Kuapaʻa	3.54	64.21	59.0	0.92	0.11	0.19	0.25	0.41	0.48
	Mānā Plain	14.69	–	–	4.48	1.25	1.81	2.17	2.93	3.24
			Total runoff		17.27	2.83	4.52	5.80	8.78	10.05

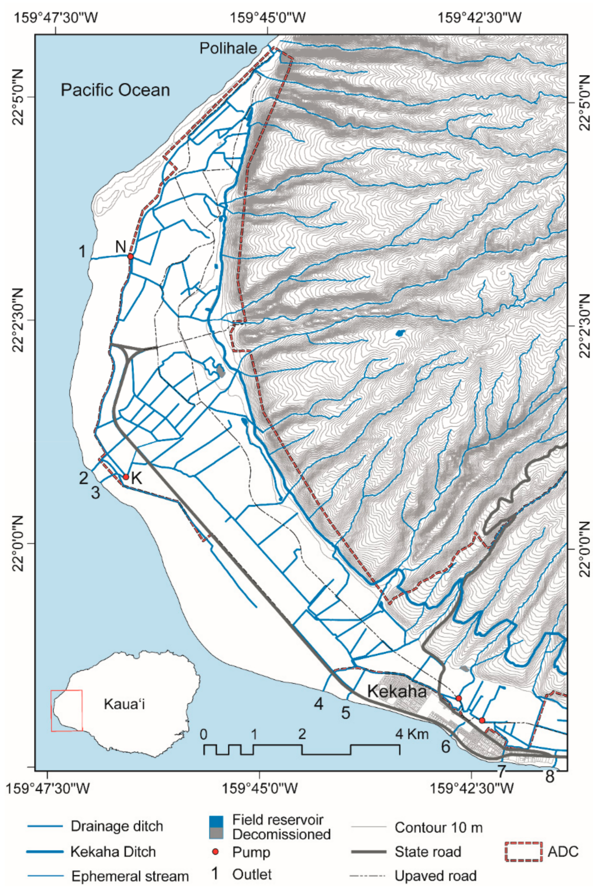

Figure 2. Hydrography of the Mānā Plain and Puʻu Ka Pele Slope (see text for discussion). Contour interval 10 m (cf. Figure 1). K and N indicate the location of the main pumping station at Kawaiʻele and the inoperative pumps at Nohili. The location of two booster pumps on the ditch system near Kekaha is also shown. Numbers (1–8) indicate the location of the drainage ditch system's outlets: 1, Nohili Ditch; 2, Kinikini Ditch; 3, Dry Ditch; 4, Second Ditch; 5, First Ditch; 6, Mill Drain; 7, Cox Drain; 8, Kīkīaʻola Harbor Drain. The boundary of the State of Hawaiʻi Agribusiness Development Corporation's (ADC) land facilitates comparison with Figures 3 and 4.

The landward edge of the plain lies at ~10 m elevation. Here, the Holocene alluvium that laps onto the lagoonal deposits is clearly manifest as alluvial fans that have developed in locations where the ephemeral streams emerge from the uplands on to the plain (Figure 1). A section across the Mānā Plain reveals two depressions, bounded by Holocene alluvium and Pleistocene–late Holocene backshore (wave- and wind-formed) deposits, within which most of the land is <2 m above mean sea level (MSL; Figure 1). The hydromorphic, alluvial soils in the center of both depressions are poorly drained [21,22], and before the drainage ditch system was excavated water derived from groundwater seepage, direct precipitation and storm runoff that accumulated in them could only be evacuated by evaporation and lateral groundwater flow through the backshore deposits [10]. These and other low-lying, cryptorheic regions formerly supported perennial wetlands [23], that expanded in wet and contracted in dry periods. In 1920, the wetlands covered an area of 7.26 km^2 [24]. Today, a waterbird sanctuary contains 0.42 km^2 of restored wetland, and the non-agricultural vegetation cover of the Mānā Plain is dominated by kiawe, koa haole, nama and pohinahina-naupaka scrub, and grasses [25].

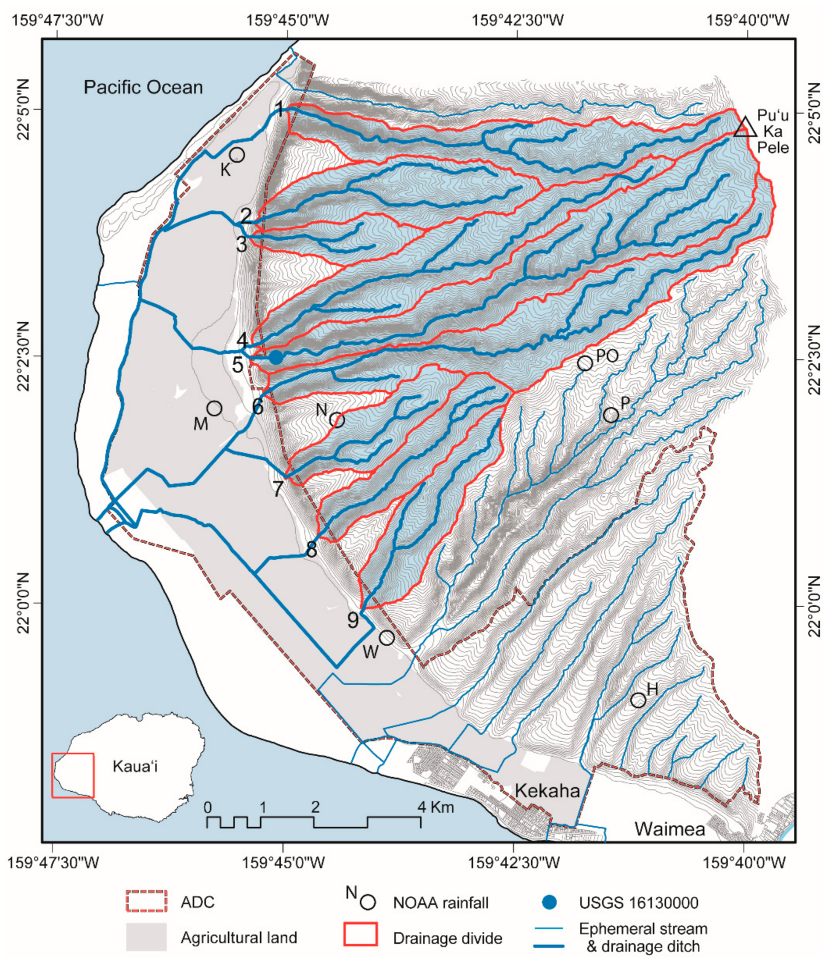

Figure 3. Storm runoff flowpaths to Kinikini and Dry Ditch (heavy blue lines) and other drainage ditch system outlets (light blue lines), and HEC-HMS basins and stream networks (see Table 1 for basin names, 1–9). Contour interval 10 m (cf. Figure 1). The locations of the USGS gauging station on Nahomalu Steam (USGS 16,130,000), and the NOAA atlas rainfall stations on Pu'u Ka Pele Slope and the Mānā Plain from which point precipitation frequency estimates were derived are also shown: H, Hukipo; N, Nui Ridge; P, Puehu Ridge; PO, Pu'u 'Ōpae; K, Kolo; M, Mānā; W, Waiawa. The boundary of the State of Hawai'i Agribusiness Development Corporation's (ADC) land facilitates comparison with Figures 2 and 4.

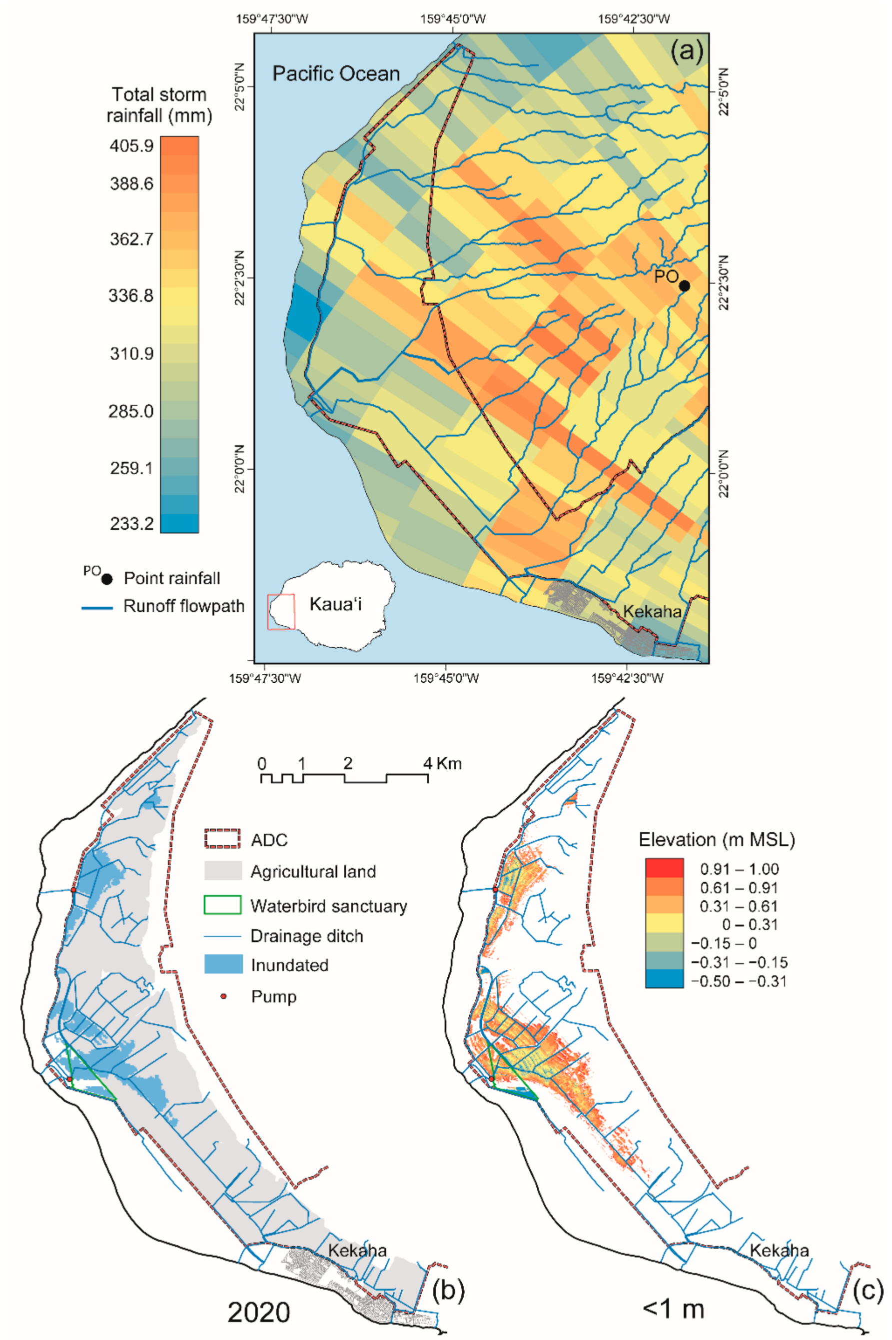

Figure 4. (**a**) South Kaua'i (HKI), NEXRAD Level-III total storm rainfall 16–17 March 2020, runoff flowpaths, and location of the Puʻu ʻŌpae rain gauge; PO. (**b**) Extent of inundation following the March 2020 storm extracted from Landsat 8 OLI/TIRS scene LC80660452020088LGN00 acquired on 28 March 2020. (**c**) Location and elevation of low-lying land (<1 m MSL) on the Mānā Plain that is and likely will become susceptible to transient, storm event-based flooding by the end of this century. N.B. The NOAA Coastal Services Center's 3 m DEM (see Figure 1) is hydro-flattened and water elevations in the waterbird sanctuary and drainage ditch system are expressed as ≤ -0.5 m MSL. To facilitate conversion to U.S. customary units specified intermediate elevations are rounded to 2 decimal places. The boundary of the State of Hawai'i Agribusiness Development Corporation's (ADC) land facilitates comparison with Figures 2 and 3.

2.3. Anthropogenic Landscape

Commercial agriculture on the Mānā Plain began with rice cultivation around the fringes of the wetlands in the 1860s [26]. After the treaty which removed the import tax on Hawaiian products entering the United States was ratified in 1875, sugar cane began to be grown commercially in 1878 [27]. Groundwater was initially used to irrigate the cane fields and rice paddies, with spring water being supplemented by well water from 1890 [20]. However, crop failures soon motivated the construction of irrigation ditch systems that drew water from the perennial Waimea River. The 9.5 km long Waimea Ditch was constructed in 1903 and the 32 km long Kekaha Ditch, which connected with the pre-existing Mānā Pump Ditch, was completed in 1907 [28,29]. By 1920, water from Kekaha Ditch was being used to irrigate 10.9 km^2 of land [30], and it is still the primary source of the irrigation water that supports diversified agriculture on the Mānā Plain.

Agricultural land on the Mānā Plain has never been in private ownership. Originally bestowed as "Crown Land" in 1848, it became "Public Land" when the Republic of Hawai'i was created in 1893. This designation was retained after the islands became a territory of the United States in 1898, and subsequently a State. Some land was initially leased to commercial rice growers and antecedents of Kekaha Sugar Company (KSC) [27]. Created in 1898, KSC gradually acquired more leases and retained its position of dominance in the agricultural landscape until the plantation closed in 2001 [31,32]. In 2003 the State of Hawai'i Agribusiness Development Corporation (ADC) assumed control of the defunct sugar company's lands and infrastructure; management of which was successively assigned to Kekaha Agriculture Association in 2007.

The landscape of the Mānā Plain changed dramatically once the wetlands began to be drained and sugar cane started to be planted on a commercial scale in the 1870s. An initial connection to the ocean was established at Kawai'ele in 1878 [33], First Ditch had been completed by 1907 [34], Cox Drain and Kīkīa'ola Harbor Drain were in use by 1910 [20], and Nohili Ditch was excavated in 1922 [33] (Figure 2). Large-capacity drainage pumps were installed, and the drainage ditch system was extended after KSC acquired the leases on the land used for rice cultivation in 1922 [20]. Most of the remaining wetlands surrounding the loko pu'uone (ponds) at Kawai'ele, Kolo and Nohili had been drained by 1931 [35,36]. What amounted to the largest reclamation project in the Territory's history was completed when the final parcel was drained and planted in 1959 [35,37].

Drainage ditches were initially dug to move surplus irrigation water and rainfall water away from the cane fields on the Mānā Plain's higher (>2 m) elevation hinterland and 12.2 km of ditches had been excavated by 1910 [23,38]. As lower elevation land with poorer internal drainage began to be utilized by the planation, the lateral movement of water within the hydromorphic, clay soils was facilitated by mole drainage and the field-scale plowing under of partially decomposed mill-waste and bagasse [22,39]. The amount of surplus irrigation water declined dramatically with the introduction of drip irrigation, which began to replace furrow irrigation in 1973 [40]. By 1990 drip irrigation technology was being used to irrigate 75% of KCS's land, with mill water being used to furrow-irrigate the cane fields nearest Kekaha [41]. The drainage system, which consists of a ~55 km long network of interceptor, side and arterial ditches, had assumed its contemporary operational configuration by this point in time [20,42] (Figures 2 and 3). Its primary functions are to support agricultural production during the growing season, by maintaining the water table below the root zone, and divert storm runoff from the adjacent uplands away from farmland.

2.4. Hydrologic Landscape

In the absence of rainfall, the pumping station at Kawai'ele presently discharges ~56,000 m^3/d (0.65 $m^3\ s^{-1}$) of water into the Pacific Ocean through Kinikini Ditch. This water is primarily derived from leaks in the unlined portion of Kekaha Ditch, which runs along the base of the pali (Figure 2); the upward seepage of groundwater; and water leaking from artesian wells and shafts in the basaltic aquifer. Water in the drainage system as a whole is fresh to mildly brackish, with more saline water present in areas of the system that are isolated from direct inflows and where the bed of a ditch intersects the water table in the overlying sedimentary cover [43].

Under ambient operating conditions all the outlets are blocked and filled by sand or earthen plugs, and the flow of water in the entire drainage system, from Kekaha to Polihale (Figure 2), into Kinikini Ditch is controlled by pumping. Almost all of the energy the pumps currently require is generated by the two hydroelectric power plants KSC constructed on Kekaha Ditch [31]. Following heavy rain, if the plugs do not give way naturally due to the pressure of water on their up-ditch side, they are removed manually. At such times, runoff from the northern-most stream that drains the uplands flows directly into the sea at Polihale, and water from the southern streams variously enters the ocean though Kīkīa'ola Harbor and Cox drains and First and Second ditches (Figures 2 and 3). At the present time, water cannot flow into the ocean at Nohili under the influence of gravity and the pumps there are inoperative. Thus, runoff generated from the nine remaining drainages on the Pu'u Ka Pele slope either flows directly into the ocean through Kinikini Ditch or is pumped into Dry Ditch (Figure 3). The pumping station at Kawai'ele has a capacity of 189,270 m^3/day (2.19 m^3 s^{-1}). Consequently, gravity flows are relied upon to deliver the majority of storm runoff to the ocean.

All the short, steep, elongate streams draining Pu'u Ka Pele slope are dry > 50% of the time and respond rapidly to rainfall. However, none are continuously gauged. For this reason, the U.S. Army Corps of Engineers Hydrologic Modeling System (HEC-HMS version 4.4.1) [44] was employed to estimate runoff volume. HEC-HMS has been used to simulate flood events in ephemeral, ungauged streams throughout the State, and there is often a close correspondence between observed and estimated peak flows [45].

The U.S. Geological Survey's 10-m resolution land surface DEM for the island of Kaua'i was used to delimit each drainage basin and generate the stream network (Figure 3). Terrain processing was accomplished using the HEC-GeoHMS extension to ArcMap™ developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, CA, USA [46], which was also utilized to create a curve number grid for Pu'u Ka Pele slope from Hawai'i's Soil Survey Geographic Database and Carbon Assessment Land Cover Map [47,48], and construct the basin models.

A 30-min computation time interval was used for optimization, storm and frequency storm calculations. Each of the nine basins was treated as a single computational unit (Figure 3; Table 1), and the response to rainfall was only evaluated at the outlet, because there were insufficient data to determine how routing parameters affect the runoff hydrograph. The SCS curve number loss and unit hydrograph methods were used to obtain excess rainfall from total rainfall and transform the excess rainfall into runoff, and the curve number lag method was used to generate runoff at the outlet [49]. Baseflow is considered negligible, because runoff only occurs in response to high-intensity rainfall, and prolonged periods without rainfall-runoff minimize the effect antecedent conditions have on the runoff hydrograph. However, to transform the standard SCS dimensionless unit hydrograph into a discharge versus time hydrograph the basin area, time of concentration (computed using the curve number lag method) and peak rate factor, which determines the ratio of the time to peak to the time of recession, must be known.

Available rainfall and runoff data limit the model calibration to a single event on Nahomalu Stream with a ~10 y return period, which occurred on 25 August 2015. In this storm, the 194.8 mm of rain which fell at Pu'u 'Ōpae in a 12 h (h) period (maximum intensity 67 mm/h) generated a peak discharge of 32.85 m^3 s^{-1}. Assuming the storm hydrograph has a simple structure with a well-defined peak, the optimization priority was to match the peak flow rate. A trial-and-error approach revealed that applying a peak rate factor of 150 to the basin model for Nahomalu Steam yielded a peak discharge 32.86 m^3 s^{-1}. On this basis HEC-HMS was adjudged to provide a good representation of basin hydrology, and a peak rate factor of 150 was applied to all subsequent model runs involving the streams draining Puʻu Ka Pele slope that deliver runoff to the outlet at Kinikini Ditch (Figure 3).

To calculate the amount of runoff generated by a frequency storm, in which rainfall depths for various durations within the storm have a consistent exceedance probability, the intensity position, which determines where the peak intensity of the synthetic storm will occur, must also be specified. Inspection of the simulated hyetograph and modelled Nahomalu Steam hydrograph for the August 2015 storm indicated ~90% of the rainfall contributed to the peak flow, and a value of 67% was selected as the intensity position for storms of 24 h duration. This timing implies the peak flow occurs ~15 h after a storm begins and ~6 h after the peak rainfall intensity. The specified intensity duration was 2 h. No depth-area reduction was applied because all the basins were <10 km^2 in area.

3. Results

3.1. Delineating the Hydrologic Landscape

The concept of a hydrologic landscape is predicated on the assumption that flows of surface and subsurface water are physiographically linked hydrologic systems, with a characteristic geologic and climatic setting, comprising an upland and an adjacent lowland, connected by a hillslope [50]. Puʻu Ka Pele slope, the Mānā Plain landward from the reverse slope of the backshore deposits and the intervening pali constitute a hydrologic landscape, within which interactions between surface, ground and atmospheric water and the form and features of the land surface can be quantified.

3.1.1. Present Conditions

The hydrologic inputs to and outputs from the 28.56 km^2 of publicly owned agricultural land provide an index of current conditions against which future changes can be evaluated. Precipitation records for the period 1920–2007 have been compiled for 11 stations on the Mānā Plain [51]. The aggregated mean annual rainfall for all locations is 498.5 mm, which equates to 38,990 m^3/day. Runoff has been measured continuously at only one location, on Nahomalu Stream (Figure 3), where there are daily statistics for the period 1962–1971. Scaling the mean daily flow from Nahomalu Stream by drainage area, runoff from the ephemeral streams draining Puʻu Ka Pele slope is estimated to be 9080 m^3/day. Currently, Kekaha Ditch delivers 30,280 m^3/day and wells supply an additional 3780 m^3/day of irrigation water. Direct groundwater inflow, estimated from the amount of water pumped in the absence of significant rainfall when Kekaha Ditch was shut down for 10 days prior to the August 2015 storm, is 41,640 m^3/day. The sum of these inputs is 123,770 m^3/day.

Based on the record for 2016–2019, the average rate of pumping at Kawaiʻele is 56,020 m^3/day. Estimates of the amount of evapotranspiration that rely on recent, spatially distributed observations of climate, vegetation and soil conditions on the Mānā Plain [52], suggest evapotranspiration from crops and scrubland and evaporation from open water surfaces (field reservoirs and drainage ditches) is 66,240 and 1510 m^3/day, respectively. The sum of these outputs amounts to 123,770 m^3/day, which equates to the sum of the inputs. This result is consistent with the knowledge that, because water levels in the field reservoirs and drainage ditch system are maintained at constant levels, there is little overall change in storage.

3.1.2. Prospective Conditions

To assess how prospective conditions will respond to SLR, the critical variables are the amounts of direct groundwater inflow and rainfall. The contemporary estimate of groundwater inflow (41,640 m^3/day) is consistent with a plantation-era estimate of the discharge from the basaltic aquifer [20]. Although the head in the basaltic aquifer remains above the ground surface, it was formerly ~2.4–3.7 m above sea level and was presumably even higher (~83,280 m^3/day) before groundwater began to be used for irrigation at the end of the 19th century [10,20]. Groundwater levels in the backshore deposits, which have a hydraulic conductivity of $\lesssim$30 m/day [53], are expected to rise as sea level rises. Assuming water levels in the overlying sedimentary cover continue to be regulated by pumping and the hydraulic gradient is equivalent to the difference in height between the superelevated groundwater surface above the elevation of mean sea level and the water level in the ~15 km of arterial drainage ditches between Polihale and Kokole Point; applying Darcy's law suggests a 1 m rise in sea level could increase groundwater inflow by ~2600 m^3/day. It is assumed groundwater levels away from the shoreline will remain constant as sea level rises. Thus, although the freshwater-saltwater interface will continue to advance inland, there should not be a significant increase in groundwater discharge from the basaltic aquifer because the high-elevation recharge zone is far removed from the coast.

HEC-HMS model runs were made to determine runoff estimates for storms with an annual exceedance probability of 50%, 20%, 10%, 2% and 1%. To account for variations in the amount of rainfall with altitude, the 24-h frequency storm input was expressed as the average of the NOAA Atlas point precipitation frequency estimates for the four stations on Puʻu Ka Pele slope [54] (Figure 3, Table 1). The amount of runoff derived from the 14.69 km^2 of hydrologically connected agricultural land was computed directly from rainfall depth, defined as the average of the point precipitation frequency estimates for three stations on the Mānā Plain (Figure 3, Table 1). Although flow from the small streams draining the pali is discounted, the accumulated results of the model runs are assumed to represent maximum estimates of total storm runoff (Table 1). This is because the intense rainfall on Puʻu Ka Pele slope that produces the largest floods is not always evenly distributed or experienced at lower elevations on the Mānā Plain.

3.1.3. March 2020 Storm

A 48-h, ~100-y storm occurred on 16–17 March 2020, when 343.4 mm was recorded as falling in 38 h (maximum intensity 48.8 mm/h) at Puʻu ʻŌpae. The record from the NEXRAD weather radar on Kaua'i shows that between ~300 and 400 mm of rain fell on Puʻu Ka Pele slope (Figure 4a). An additional 48.8 mm of rain fell on 18–19 March (Figure 5a). Knowledge of the extent of flooding gained from field observations and satellite imagery, in combination with estimates of the amount of storm runoff derived from the basin models and the record of pumping at Kawaiʻele, permits the response to this extreme event to be quantified.

HEC-HMS model runs for the 4-day storm rainfall of 392 mm suggest the nine basins draining to Kinikini Ditch collectively generated 12.79 $\times$ 10^6 m^3 of runoff, and 4.48 $\times$ 10^6 m^3 of runoff is estimated to have been generated by the ~305 mm of rain that fell on the hydrologically connected land on the Mānā Plain (Table 1, Figure 4). Kinikini Ditch was open for a 20-day period, between 18 March and 7 April, and a further 17 days of pumping were required to lower the water level in the ditch system to its pre-storm elevation (Figure 5b). A Landsat 8 OLI/TIRS scene acquired on 28 March showed standing water covering ~3.0 km^2 of land (Figure 4b), most of which is <0.6 m MSL. The amount of water that evaporated from this surface area between 17 March and 23 April is estimated to be 0.48 $\times$ 10^6 m^3, and from the beginning of storm rainfall on 16 March, 4.12 $\times$ 10^6 m^3 of water were handled by the pumps at Kawaiʻele, at an average rate of ~105,650 m^3/day. The runoff estimate is incomplete because it does not account for flow from the five small streams draining the pali (Figures 2 and 3), but the implication is ~75% (~12.67 $\times$ 10^6 m^3) of the remaining ~16.79 $\times$ 10^6 m^3 of runoff flowed into Kinikini Ditch under the influence of gravity.

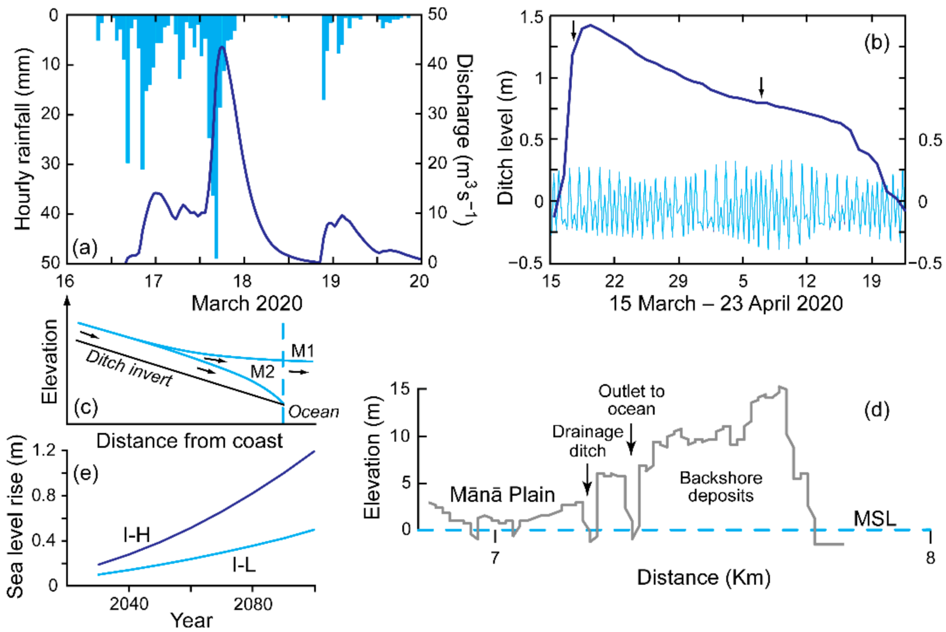

Figure 5. (**a**) 16–20 March 2020 hourly rainfall at Puʻu ʻŌpae (see Figure 4a for gauge location) and HEC-HMS simulated hydrograph for Nahomalu Stream. (**b**) Water level in the drainage ditch system at the Kawaiʻele pumping station and NOAA tide predictions for Port Allen, Kauaʻi (Station 1611347). Arrows indicate dates when the ditch plug was removed to permit storm runoff to flow into Kinikini Ditch under the influence of gravity, and (second arrow) subsequently replaced. (**c**) Schematic hydraulic curves describing the shape of the water surface profile of gradually varied, sub-critical flow in a mildly sloping channel, when discharge in the channel is high and: M2, the normal depth in the channel is at a higher elevation than the water surface at the coast; and M1, the water level at the coast is at a higher elevation than the normal depth in the channel. (**d**) Ground surface elevation in the vicinity of Kinikini Ditch (see Figure 1 for section location). (**e**) Projections of SLR, based on the intermediate-low (I-L) and intermediate-high (I-H) scenarios used in the West Kauaʻi Community Vulnerability Assessment [1,55]. SLR of ~1 m is considered likely by 2100 and is utilized as a mid-to-late century projection for planning purposes.

4. Discussion

SLR Impact and Adaptation Measures

By enhancing the hydrological connectivity of the ephemeral streams draining the uplands to the coast, for the past ~100 y the drainage ditch system has helped to prevent storm runoff from Puʻu Ka Pele slope from persistently ponding in low-lying areas of the Mānā Plain. The current management strategy is to maintain the beds of the ~4.57 m deep arterial drainage ditches between Nohili and Kawaiʻele −0.31–−1.22 m MSL and Kinikini Ditch at −0.91 m MSL [56]. Storm runoff elevates water levels in the arterial drainage ditches, and when Kinikini Ditch is opened the majority of storm runoff is discharged into the ocean under the influence of gravity. Any remaining water is discharged by pumping, which also maintains the ambient water level in the arterial drainage ditches at −0.31–0 m MSL. Under normal operating conditions, the flow of water in the entire ditch system is directed towards the pumping station at Kawaiʻele; including water pumped from ditches draining low-elevation land in the vicinity of Kekaha (Figures 1 and 2). This land is considered to be vulnerable to SLR induced flooding in the mid-to-latter part of this century [55], but water in these ditches cannot flow into the arterial drainage ditches under the influence of gravity and storm runoff converges on Cox and Kīkīaʻola Harbor drains, not Kinikini Ditch (Figures 2 and 4).

Theory dictates the depth at which gravitational forces are balanced by frictional forces in the drainage ditch system is determined by channel geometry, slope, discharge and sea level at the coastline [57], and the water surface elevation at the coast relative to the normal depth of flow in Kinikini Ditch determines the shape of the water surface profile in the arterial drainage ditches. The water surface elevation maintained, a concave down, M2 profile and floodwater drained freely to the ocean all the time Kinikini Ditch was open during the March 2020 event, because the water level up-ditch from the outlet was higher than the sea surface elevation at the coast (Figure 5b,c). The modelled frequency storms are expected to generate less runoff than the March 2020 event (Table 1), however, as sea level rises and the sea surface elevation at the coast approaches or exceeds the water level in the ditch system near the outlet, the water surface profile can be expected to assume a concave up, M1 form (Figure 5c). This will have a significant impact on water levels in the arterial drainage ditches and the length of time standing water ponds on the adjacent, low-elevation land because the attendant reduction in pressure gradient head means a much smaller proportion of storm runoff will be able to flow directly into Kinikini Ditch under the influence of gravity. For example, were an event of similar magnitude to the March 2020 storm to occur towards the end of this century, the mixed semidiurnal tidal cycle (which has a mean and diurnal range of 0.38 m and 0.56 m, respectively) superimposed on the projected 1 m rise in sea level would increase the amount of time required for floodwater to drain freely to the ocean by ~50%.

Although the invert of the drainage ditch system is below sea level, uncertainties related to the rate of SLR and the magnitude of future storms make it difficult to determine exactly how changes to the physical boundary conditions will impact the existing management strategy. However, the resilience of the management strategy can be evaluated with respect to the extent active drainage by pumping, for which there are quantifiable limits, can prevent standing water from accumulating on the low-elevation agricultural land. A higher rate of pumping might be required to counteract rising groundwater levels in the backshore deposits and overlying sedimentary cover, but before drip replaced furrow irrigation the rate of pumping was considerably higher (~178,000 m^3/day) than it is today [20]. Future gains in system efficiency, made possible by the replacement of the more than a century old terminal section of Kekaha Ditch with pressurized pipe, coupled with a more regulated irrigation flow regime (~22,710–37,850 m^3/day), mean ditch losses should continue to decline. Thus, the rate of pumping at Kawaiʻele, which has declined from ~80,760 m^3/day in the period 2001–2009 [25], is expected to fall below its present rate of ~56,000 m^3/day in the coming decade. In addition to an anticipated reduction in rainfall [58], the required ambient rate of pumping may also be positively impacted by air temperature, which drives evapotranspiration and is expected to increase in the future [59].

In the absence of any change in flow from underlying, confined basaltic aquifer into the overlying sedimentary cover, declining surficial recharge by rainfall and leakage from Kekaha Ditch, and increasing evapotranspiration and groundwater inflow through the backshore deposits; it appears reasonable to assume an ambient amount of pumping at or near the present rate of ~56,000 m^3/day will be sufficient to maintain the shallow (<1 m deep) unsaturated zone beneath all but ~0.54 km^2 of the lowest elevation agricultural land on the Mānā Plain (Figure 4c). This poorly drained land already lies below local mean sea level and has been waterlogged since KSC's demise, when the normal level of water in the arterial drainage ditches was allowed to rise above the −0.46 m MSL plantation era datum.

The local ground surface elevation in the vicinity of Kinikini Ditch is >2 m MSL (Figures 1 and 5d), and to prevent overtopping during high wave events the top of the ditch plug is maintained 0.9–1.2 m above the operating water level in the ditch system at Kawaiʻele. Standard operating procedure is to release floodwater under the influence of gravity, by removing the plug if the water level in the ditch system is $\gtrsim$0.76 m MSL (cf. Figure 5b). On the basis of locally relevant projections [1,55], SLR will begin to impact ditch operations by 2040 (Figure 5e). Thereafter, removing the plug will make the ditch system vulnerable to tide- and wave-driven seawater intrusion. There is only a small amount of unsaturated space above the water table and, based on the volume measurement calculated from the 1 m MSL reference surface, the water retention capacity of low-lying land on the Mānā Plain approximates the amount of runoff generated by a 2-y storm

(Table 1). Thus, as sea level rises, some of the drainage ditch system's ability to directly discharge storm runoff must necessarily be preserved. This could be accomplished by installing tide gates, actuated by the difference in water level in the drainage ditch system and the tidal portion of Kinikini Ditch, in a permanent ditch plug.

Although the drainage ditch system will maintain the ability to collect and divert storm runoff low-lying land on the Mānā Plain will become more susceptible to flooding. This is because as sea-level rises the ability gravity flows have to discharge runoff directly into the ocean will depend on tide and wave height, and if ditch flows continue to be unable to act in tandem with basin processes to pass the runoff volume, water will pond in the low-lying depressions. The extent and duration of flooding will be determined by the amount of rainfall and transient rate of pumping. An indication of the probable scale of inundation is provided by the ~3.0 km^2 of low-lying land that were flooded after the March 2020 storm but, given the potential volume(s) of water involved (Table 1), the risk of flooding could extend to all 5.45 km^2 of land $\leq$ 1 m MSL (Figure 4c). On this basis, by the end of this century 25% of the agricultural land on the Mānā Plain may be exposed to flooding that is an indirect operational consequence of SLR. This land will not be permanently inundated, but it could require weeks of pumping to remove the accumulated floodwater, and the present pumping capacity of ~189,000 m^3/day will likely need to be increased. In the near term, this could be accomplished by recommissioning the pumps at Nohili, which have a capacity of ~56,800 m^3/day.

Adaptation strategies that involve the creation of storage or retention areas on agricultural land are attracting growing interest as a nature-based means of mitigating the impact of riverine flooding and sea level rise [60,61]. In the present case, the open floodable spaces occupy natural depressions in the vicinity of the historic Kawaiʻele and Nohili loko puʻuone [24,36], and pumping is sustainable, because most of the required energy will continue to be generated by the Wiamea and Waiawa hydroelectric power plants on Kekaha Ditch.

5. Conclusions

In the first half of the twentieth century, plantation era agriculture on the Mānā Plain responded to water stresses and waterlogging by constructing an intricate network of irrigation and drainage ditches. The introduction of large-capacity drainage pumps a century ago allowed more land to be brought into production, and drainage ditch system operations continue to be optimized in support of agricultural activities. Protected from marine overwash by wave- and wind-formed backshore deposits (Figure 1), and isolated from tidal exchanges of seawater by ditch plugs, ambient water levels across the Mānā Plain are regulated by pumping at Kawaiʻele (Figure 2). Quantifying the inputs and outputs of the hydrologic landscape suggests that, as sea level rises, the projected increase in groundwater inflow through the backshore deposits will not present a significant challenge to day-to-day ditch system operations. This is because the projected rate of pumping required to sustain the shallow unsaturated zone in the foreseeable future approximates the present discharge rate (~56,000 m^3/day), which is considerably less than the capacity of the pumps (~189,000 m^3/day) at Kawaiʻele.

Today, water levels in the drainage ditch system rise after large rainstorms and, because ditch flows are unable to act in tandem with basin processes to pass the runoff volume even after the plug in Kinikini Ditch has been removed, excess runoff that accumulates in low-lying areas of the Mānā Plain is removed by increasing the rate of pumping in the days or weeks following a storm. The present analysis suggests transient, event-based flooding caused by rainfall, not SLR induced, multi-mechanism flooding, will continue to pose the most immediate threat to low-lying agricultural land on the Mānā Plain. This is because the higher elevation backshore deposits which buffer the agricultural land from marine influences also prevent water derived from groundwater seepage, localized rainfall and storm runoff originating from the hydrologically connected land on Puʻu Ka Pele slope from draining directly into the ocean. SLR will reduce the proportion of storm runoff that is able to flow into the ocean through Kinikini Ditch, and its near-term effects will begin to be felt by 2040. After which time the ditch system be vulnerable to seawater intrusion if the ditch plug is removed to allow water to be discharged under the influence of gravity. As sea level rises and gravity flows can no longer be relied upon to deliver water originating from drainages on Puʻu Ka Pele slope directly into the ocean, the propensity for low-lying land on the Mānā Plain to flood will also increase. The risk of flooding from surface water could extend to all 5.45 km^2 of land $\leq$ 1 m MSL (Figure 4c). Although this land will not be permanently inundated it may require weeks of pumping to remove the floodwater.

The agricultural drainage system on the Mānā Plain is an important element of West Kauaʻi's environmental infrastructure. Accepting that runoff from the adjacent uplands will continue to temporarily pond in low-lying depressions; a sustainable adaptation strategy to twenty-first century SLR involves permanently sealing Kinikini Ditch and preserving some of the ditch system's ability to discharge storm runoff under the influence of gravity by installing tide gates in the ditch plug, as well as increasing pumping capacity. These measures, which involve relatively minor, low-tech changes to the present ditch system infrastructure, should ensure the drainage system continues to fulfill its primary functions at least until the end of this century.

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