Assessing the spatial-temporal response of groundwater-fed anchialine ecosystems to sea-level rise for coastal zone management

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Keywords:

groundwater, brackish, habitat mapping, modelling, invertebrates, fish, alien species, climate change

Abstract

1. Due to sea-level rise (SLR), coastal anchialine pool habitats will be lost in some locations and expand inland into low-lying areas in others. New and existing habitats may risk additional SLR-related degradation from non-native species transmission, groundwater pollution, and increased contact with human infrastructure. Despite a worldwide distribution, anchialine ecosystems and biota have been largely omitted from SLR risk assessments for coastal ecosystems.

2. Anchialine pools and caves are composed of brackish groundwater that connects to the marine environment through porous, rocky substrate but have no overland connection to the ocean. They support unique endemic biota.

3. The goal of this study was to develop methods to assess potential impacts to anchialine pools from future coastal flooding, using the island of Hawai‘i as a case study. Flood predictions incorporated pool surveys, groundwater level measurements, and statistical analysis of flood frequencies observed in tide gauges combined with regional scenario-based projections of future sea levels. High-resolution geospatial models were then generated to predict anchialine pool location, density, and risk factors over the next 60 years.

4. Along 40 km of coastline, up to 80% of current anchialine pools will be lost by 2080 as pools merge with ocean habitats. However, as groundwater flooding occurs more frequently and new habitats are created inland, total pool counts will rise from 509 in 2018 to 1000 by 2080. Due to extreme water level events, non-native fishes are predicted to disperse into 42% of pools by 2030. Based on current conditions, development and cesspool risks are quite low for anchialine pools in the study area.

5. Outcomes from this study are guiding conservation actions including habitat restoration, non-native fish removal, and development planning decisions in coastal areas. This study illustrates methods that can be used to assess the effects of SLR on anchialine pool habitats worldwide.

1 Introduction

Coastal ecosystems and the human communities that depend on them are threatened by current and future sea-level rise (SLR). Under current models, Global

Mean Sea Levels (GMSL) are highly likely to rise by 0.3 m but may increase as much as 2.5 m by 2100 (Sweet et al., 2017). As sea level rises, coastal ecosystems such as wetlands, dunes, and forests will migrate inland if suitable areas exist (Enwright, Griffith & Osland, 2016; Feagin, Sherman & Grant, 2005; Krauss et al., 2014; Williams, Ewel, Stumpf, Putz, & Workman,1999). The biological communities within these migrating ecosystems will be determined by how species respond to various biotic and abiotic conditions. Strategies to protect biodiversity under these changing conditions include habitat restoration, managing upland hydrology, and reducing development in low-lying areas, actions that may also reduce coastal vulnerability to storms and large wave events (Hale et al., 2009; Spalding et al., 2014). Incorporating future sea level projections into adaptation planning is becoming more commonplace and can generate solutions that are likely to be more successful and efficient when prioritizing actions to reduce risk and increase resilience (Hinkel et al., 2014; USGCRP, 2018).

To be useful for planners and land managers, models of ecosystem risk from SLR must be applicable to relevant geographic scales and incorporate enough detail to adequately reflect local conditions (Thorne et al., 2018). Numerous models have been developed to examine how coastal ecosystems will change with SLR, including predictions for wetlands and salt marshes (Borchert, Osland, Enwright, & Griffith, 2018; Craft et al., 2009; Doughty, Cavanaugh, Ambrose, & Stein, 2019; Thorne et al., 2018; Traill et al., 2011); sandy beach and dune ecosystems (Keijsers, De Groot & Riksen, 2016; Le Cozannet et al., 2018); mangroves (Gilman, Ellison, Duke, & Field, 2008; McKee, Cahoon & Feller, 2007); and coastal freshwater forests (Doyle, Krauss, Conner, & From, 2010). In these studies, factors such as topography, hydrology, sedimentation, erosion, regional oceanographic conditions, and the response of dominant plant species to changing conditions were found to be key considerations in predicting the location and condition of future ecosystems. In developed areas, models also include the extent to which human infrastructure such as roads or dykes might block the horizontal migration of ecosystems inland. However, conditions and processes differ across various types of ecosystems requiring different model considerations. For example, predictions of beach loss and migration focus on the erosive forces of ocean waves, beach slope, and sediment transport and replenishment processes (Le Cozannet et al., 2018). Predictive models for wetland and mangrove ecosystems incorporate vertical accretion from organic matter production and sediment deposition offset by loss due to compaction, subsidence, erosion, and increased tidal inundation with SLR (Kirwan & Megonigal, 2013). These models are not easily applied to other types of coastal ecosystems. Specifically, there is limited research on how future SLR will impact groundwater-dependent anchialine ecosystems that are found in coastal margins around the world, especially at scales relevant for management.

Anchialine ecosystems are brackish water bodies with a subterranean connection to the marine environment but no overland connection to the ocean (Holthuis, 1973). Worldwide, anchialine caves and pools exist in porous limestone karst and basalt bedrock with less dense meteoric water buoyed above marine waters (Holthius, 1973; Iliffe, 2000). The groundwater in these systems typically has a tidal response, which is indicative of unconstrained aquifers that connect directly to the ocean (Oki, 1999). Anchialine systems support highly endemic biota such as molluscs, crustaceans, and fishes, many of which utilize both the hypogeal zone as well as surface pools (Iliffe, 2000; Maciolek, 1983; Maciolek & Brock, 1974). The high endemism and disjunct distribution of anchialine species across the globe are attributed in part to sea-level change through geologic time (Iliffe, 2000; Moritsch, Pakes & Lindberg, 2014). Over the past million years, and as recent as the last glacial maxima 18,000 years ago, sea level has fluctuated over 100 metres (Miller et al., 2005). When sea levels were lower, anchialine species ranges were fragmented driving allopatric speciation in some locations. Subsequent SLR led to dispersal of species into expanded habitat and potential connectivity between species that were previously separated (vanHengstum, Cresswell, Milne, & Iliffe, 2019). While sea-level change has been an important driver for the evolution of anchialine biota, it is unclear what impacts SLR will have on anchialine species in the 21st century.

To understand future SLR effects on anchialine ecosystems, groundwater must be accounted for in models. As sea level rises, the groundwater table will be forced up through the porous bedrock, increasing flood inundation in coastal zones beyond what would be predicted when considering ocean levels alone, especially in inland areas (Bjerklie, Mullaney, Stone, Skinner, & Ramlow, 2012; Rotzoll & Fletcher, 2013). Changes in coastal flooding due to elevated groundwater will have a direct effect on anchialine habitat migration (Marrack, 2016; Moritsch et al., 2014). For example, as sea level rises, some pool habitats will eventually be lost by overland connection to the ocean. Yet, many pool habitats are located far enough inland that they will not connect overland to the ocean, even in extreme storm conditions. With SLR, increased flooding from groundwater will cause existing pool habitats to expand and new pools to emerge in low-lying areas where the aquifer becomes higher than the ground surface. In areas with subterranean connectivity, hypogeal species will move into these new habitats quickly establishing communities in some areas while they are lost in others.

As new coastal habitat is created due to SLR, the quality of these habitats will be determined by the level of local stressors, including detrimental land-use practices, groundwater pollution, and dispersal of introduced species. Coastal development has led to destruction of pool habitats and may alter the connectivity of subterranean habitat (Brock & Kam, 1997). Although few studies have directly examined the effects of groundwater pollution on anchialine systems, the detrimental effects of nitrogen and phosphorus loading, pharmaceuticals, pesticides, and heavy metals have been well documented in fresh and marine aquatic ecosystems worldwide (Carpenter et al., 1998; Erisman et al., 2013; Islam & Tanaka, 2004; Laws, 2017; Vitousek et al., 1997). One study on anchialine caves in the Caribbean and Yucatan, found that groundwater pollution from deep well injections of sewage resulted in bacterial growth and declines in oxygen levels (Iliffe, Jickells & Brewer, 1984). With SLR, groundwater tables will interact with sewage disposal systems more frequently, potentially altering groundwater fed habitats. Introduced species are another conservation concern for anchialine habitats. In particular, non-native fishes have had a dramatic impact on anchialine biodiversity in both the Atlantic (Iliffe, 2002) and Pacific regions (Brock & Maciolek, 1997; Nico & Walsh, 2011). Surveys of over 400 pools in Hawaiʻi show that introduced predatory fishes (poeciliids and tilapia) have a strong negative effect on the occurrence of endemic species in anchialine pools (Marrack, Beavers & O'Grady, 2015). In pools with introduced poeciliids, the dominant grazing shrimp *Halocaridina rubra* and predatory shrimp *Metabetaeus lohena* changed their behaviour and retreated out of pools during the day into the subsurface aquifer (Capps et al., 2009; Carey et al., 2010; Dudley, MacKenzie, Sakihara, Riney, & Ostertag, 2017). In exclusion experiments, decreased grazing pressure from *H. rubra*, such as might occur when introduced fish are present, led to increased epilithon biomass (Sakihara, Dudley, MacKenzie, & Beets, 2015) which could increase rates of pond infilling. Rising sea levels and the resulting increase in groundwater height will facilitate dispersal of invasive species to previously isolated habitats. Conservation plans that include efforts to limit existing stressors such as groundwater pollution, development, and introduced species will bolster the resilience of ecosystems as they respond to climate change.

The goal of this project was to predict the effects of future flooding on anchialine pool habitats by integrating models of coastal groundwater and future ocean levels to identify areas where management and conservation efforts are needed to preserve these important ecosystems. Datasets of anchialine pool condition and stressors along the western coastline of the island of Hawaiʻi were combined and updated. Then high-resolution geospatial models were generated to examine how anchialine pool location, density, and risk factors are likely to change over the next 60 years in this region. The objectives of this study were: (i) to determine time periods when current pools will merge with the nearshore marine environment, (ii) to predict when and where new pools will emerge under future conditions, and (iii) to assess the level of risk due to non-native fish, cesspool contamination, ocean inundation, and land protection status for current and future pools. Methods used for these predictions incorporated field surveys of anchialine pools, *in situ* measurements of local groundwater levels, and statistical analysis of flood frequencies observed in tide gauges combined with regionally adjusted scenario-based SLR projections of mean sea level. Projections of both flood frequency and magnitude were used to determine the location of future habitat and risks for those habitats. From the anchialine pool ecosystem perspective, more frequent minor flooding that might be considered “nuisance flooding” in an area with human infrastructure is an opportunity for new pool habitats to form. However, extreme flooding might negatively impact pools due to increased dispersal of non-native fishes. Effects of both minor flooding and extreme flooding on pool habitats were examined. Understanding both opportunities and risks is expected to improve outcomes for anchialine ecosystem management under future sea level scenarios.

2 Methods

2.1 Study Site

The study region stretching from Kawaihae to Kailua-Kona, on the Island of Hawai‘i, (West Hawai‘i) represents one of the highest concentrations of anchialine pool habitats in the Hawaiian island chain and possibly in the world (Brock & Kam, 1997; Figure 1). Pools in this area range in salinity from 1 to 28 ppt, show daily tidal fluctuations, and can be over 400 m inland from the Mean High Water line on shore (Brock & Kam, 1997; Marrack et al., 2015). Hawaiian anchialine pool habitats support a unique community of flora and fauna including the endemic red shrimp *Halocaridina rubra* and *Metabetaus lohena.* Endangered species such as the two shrimps *Procaris hawaiana* and *Vetericaris chaceorum*, the damselfly *Megalagrion xanthomelas*, and the Hawaiian wetland bird *Himantopus mexicanus knudseni*, along with other rare aquatic species, also rely on these habitats (Brock & Kam 1997; Maciolek & Brock, 1974; Sakihara, 2012; US Fish and Wildlife Service, 2017). On this arid leeward coastline, rainfall ranges from 21 to 72 cm of rain a year (Giambelluca et al., 2013). Therefore, pools provide essential access to groundwater for native plants, terrestrial fauna, and indigenous communities. The integrity of anchialine pool ecosystems is threatened by non-native fishes, changes in land-use that contribute to habitat loss, reductions or impairments of fresh water quantity and quality, overgrowth by introduced vegetation, and rising sea levels (Brock & Kam, 1997; Capps et al., 2009; Carey et al., 2010; Marrack, 2016). Currently, land-use within the study area is a mix of private housing developments, tourist resorts, conservation areas owned by the State of Hawaiʻi or other entities, and Kaloko-Honokōhau National Historical Park. The range of land ownership represents a diverse assemblage of resource managers with potentially disparate objectives. The northern and central portion of the study area is designated the National Oceanic and Atmospheric Administration (NOAA) Habitat Blueprint and Sentinel Site of West Hawaiʻi (NOAA, 2016). The southern portion includes the town of Kailua-Kona, the second largest urban area on Hawaiʻi Island (Figure 1).

2.2 Flooding Analysis

Elevated sea levels result from the complex interplay of a spectrum of oceanic, atmospheric, and terrestrial processes (Table 1). The total water level (TWL) spectrum can be divided into three principal components: (i) fluctuations at the highest frequencies associated with local wave runup (e.g., setup plus swash); (ii) fluctuations across a broad range of frequencies from local storm surge through to regional natural variability associated with patterns of atmospheric and oceanic circulation; and (iii) fluctuations at the lowest frequencies associated with regional and global changes in absolute Mean Sea Level (MSL) and vertical land motion. Traditionally, the combination of components (ii) and (iii) are referred to as the Still Water Level (SWL). Here, predictions focus on SWL, with weather-related components associated with tropical and extra-tropical cyclones and climate-related components associated with seasonal to inter-decadal variability (ii) treated separately from trends associated with the MSL (iii).

Coastal erosion and storm wave run-up (i) were not included in the analyses because they are not expected to significantly affect pool habitats. In West Hawai‘i, anchialine pools exist in basalt bedrock, therefore erosion of nearshore sediments are relatively fixed and will not affect pool formation or loss. Anchialine pools are far enough from the shoreline that run-up from storm waves is extremely rare. Empirical observations made during this study support this suggestion. Furthermore, projections of future wave and wind conditions for the United States and United States-Affiliated Pacific Islands by Storlazzi, Shope, Erikson, Hegermiller, and Barnard (2015) indicate that little to no change is expected for wave conditions reaching the study area in the foreseeable future.

To evaluate how coastal flooding (expressed as changes in SWL) might affect anchialine pool ecosystems in West Hawai‘i, regionally adjusted mean SLR projections from Sweet et al. (2017) were combined with flood frequency estimates derived from statistical analysis of observed water levels at local tide gauges (Marra & Genz, 2018). Joining emissions-dependent probabilistic approaches and discrete scenario-based methods, Sweet et al. (2017), identify six representative global MSL rise scenarios ranging from a best-case (Low) scenario of 0.3, through Intermediate-Low (0.5 m), Intermediate (1.0 m), Intermediate-High (1.5 m) and High (2.0 m) scenarios, to a worst-case (Extreme) scenario of 2.5 m by 2100. The amount of relative sea-level change that occurs regionally under each global MSL rise scenario at a given tide gauge location is adjusted to reflect contributions from (a) climate-related processes affecting regional sea surface height and vertical land motion, and (b) non-climatic background relative sea level changes, primarily from vertical land motion but also including any related sea surface height changes. Using this analysis applied to the Kawaihae tide gauge, values associated with the Intermediate-Low (0.5m), Intermediate (1.0m), and Intermediate-High (1.5m) scenarios established plausible ranges (high, medium, low) of SWL at different time periods from 2015 to 2080.

To formulate flood frequency estimates, two basic types of flood frequency analysis were conducted as part of this study: (i) analyses of flood extremes derived from a Generalized Extreme Value (GEV) distribution; and (ii) analyses of minor flood frequencies derived from a normal distribution. Flood extremes are expected to disperse introduced species between pools. As inland areas become flooded more frequently during minor events, there is the potential for new anchialine habitat to form.

2.2.1 Analyses of flood extremes

For the flood extremes analyses, three separate approaches were used in order to address recognized limitations with respect to the calculation of exceedance probabilities of extreme water levels from tide station records (e.g. Coles, 2001; FEMA, 2005; Haigh et al., 2014; McInnes, Macadam, Hubbert, & O'Grady, 2009; Thompson, Bernier, & Chan, 2009). These limitations centre on the issue of how well any given tide station record is truly representative of a region; for example, are station records of sufficient length to accurately capture low probability events attributable to tropical cyclones? The range of plausible results that were generated from the three separate approaches formed the basis for selecting a set of scenarios used in this risk-based model.

Extreme value analysis (EVA) was the first approach to assess flood extremes. It focuses on characterizing the upper tail of a distribution, and is commonly used to estimate extreme sea levels from tide gauge records (e.g. Coles, 2001; FEMA, 2005; Stephens, 2012; Tebaldi, Strauss & Zervas, 2012; Zervas, 2013). Much of the attention with respect to future estimates of extreme sea levels has focused solely on accounting for SLR. A commonly used method involves generating the stationary extremes distribution using direct forms of EVA, and then creating a future estimate of extreme levels by simply adding back in the historically observed trend and / or SLR scenarios (e.g. Tebaldi et al., 2012; Zervas, 2005; Zervas, 2013). Sea level height from the Kawaihae tide gauge was used for this analysis. The time series, consisting of hourly observations over 29 years, was downloaded from the University of Hawai‘i Sea Level Center fast delivery database. The time series extended to January 2018 and was not corrected for the inverse barometric effect. The detrended annual maxima water levels relative to Mean Higher High Water (MHHW) were analysed using the Annual Maxima Method (AMM) of the GEV. The results were a range of return-interval estimates (e.g. 5-year, 25-year, and 50-year) for SWL at the Kawaihae tide gauge.

The second approach to assess flood extremes used a Regional Frequency Analysis (RFA). A common approach in hydrology, it is increasingly applied to tide gauge analyses by using results from a set of tide gauges to minimize bias due to record length (Bardet, Duluc, Rebour, & L’her, 2011; Barnardara, Andreewsky & Benoit, 2011; Hall et al., 2016; Hosking & Wallis, 1997). In RFA, data from different tide gauges are combined into regions with the assumption that the frequency distribution at each gauge is similar. An “H” score determines the measure of heterogeneity and whether the regions can be sufficiently considered homogeneous. An H score with a value >2 is considered heterogeneous (Hosking & Wallis, 1997). Once the gauges are selected, a local scaling factor (“index event’) is used to standardize the data from different gauges so that they can be combined and analysed using EVA. Based on the H score (H=0.78), the stations were considered homogeneous and used in RFA (Table 2). In this case, the index event for each station is the mean of the observed annual maximum values. Each time series was divided by its index event and combined into one time series. The time series was then analysed using a stationary AMM of GEV. This approach was used to generate another estimate of extreme sea levels along the West Hawai‘i coast.

The third approach to assess flood extremes used a time varying approach to EVA as employed by Mendez, Menéndez, Luceño, and Losada (2007), Menéndez, Mendez and Losada (2009), and Menéndez and Woodworth (2010), among others. Here the GEV model is fitted to the monthly tide station maxima so as to decipher long-term tidal cycles, intra-annual seasonal cycles, and covariability with climate patterns as well as trends. This approach was applied only to the Kawaihae tide station data to generate a third estimate of sea level extremes (SWL). Using the monthly maxima without the trend removed, the extreme signal was decomposed into the seasonal cycle, perigean and nodal (tidal) cycles, and the long-term trend (AppendixFig1). The change in extremes due to climate variability was also assessed, using the Pacific Decadal Oscillation (PDO) as a covariate in the extremes model.

2.2.2 Analyses of minor flood frequencies

One particularly important consequence from rising sea levels is the increased frequency of coastal flooding due to storms, tides, and other climatic forcings. As the gap between mean sea level and a flood threshold decreases, smaller storm surges and the highest tides will exceed specific flood levels. Thus, what were relatively rare events will quickly become relatively common (Sweet & Marra, 2014; Sweet & Marra, 2015). These relatively frequent flood events are not considered part of the extremes found in the upper tail of a probability density function (PDF) and as a result, potential changes in minor flooding need to be analysed differently. Similar to Sweet, Park, Marra, Zervas and Gill (2014) and Sweet and Park (2014), the number of days in a year that the daily maximum SWL exceeded a minor flood threshold was calculated for a range of regionally adjusted SLR projections. These calculations were based on an analysis of flood frequencies derived from an empirical kernel distribution of water levels at the Kawaihae tide gauge. The minor flood threshold varied in increments of 10 cm starting at MHHW and ending at MHHW + 2.6 m. Regionally adjusted scenario-based SLR projections from Sweet et al. (2017) were used to project the annual number of days that the SWL exceeded a given flooding threshold (Appendix Figure 2).

Finally, for the purpose of the anchialine pool analyses, minor and extreme flooding projections were categorized as frequent, semi-frequent, infrequent and rare flooding events. Frequent flooding was defined as flooding that occurs daily to every other day. Semi-frequent flooding will occur on a weekly to monthly basis. Infrequent flooding might happen one to several times a year. Rare flooding was defined as flooding that occurs once in multiple decades. The rare flooding elevations were derived from EVA while all other categories of flooding were obtained from the normal distribution (Marra & Genz, 2018). For each time period (Current/2015, 2030, 2040, 2050, and 2080), Low, Medium, and High scenarios were established (Low: ~1 to 2 year event, Medium: ~25 to 50 year event, High: greater than ~100 year event). For GIS analysis, ocean levels were referenced to Mean Sea Level (MSL) which is 0.37m below MHHW at the Kawaihae tide gauge (NOAA, 2016).

2.3 Groundwater Level Measurements and Model

To more accurately predict the location of future anchialine pool habitats, groundwater levels were collected and incorporated into the SLR models. Based on widespread field observations of daily tidal fluctuations in groundwater levels within wells and anchialine pools, it is assumed that there is high connectivity between the ocean and groundwater across the study site (Marrack, 2015; Oki, 1999). In unconfined coastal aquifers such as in West Hawai‘i, the groundwater table is elevated above mean sea level sloping up and away from the shoreline, and typically moves in response to changes in ocean level (Oki, 1999). Because groundwater may exacerbate inundation as sea levels rise, previous work has included groundwater elevations above sea level in models of sea-level change (Bjerklie et al., 2012; Marrack, 2015; Rotzoll & Fletcher 2013). The methods used to incorporate groundwater into SLR models were modified from these previous studies.

Theoretically, in a homogeneous unconfined coastal aquifer with constant recharge from an inland source, the groundwater level should be a function of the square root of distance from the coast (Glover, 1959). Previous work in West Hawai‘i showed that the relationship between average groundwater height in metres above MSL (H_{GW}) and distance from shore in metres (d) could be calculated as $H_{GW} = 0.00989d^{1/2} + 0.16734$ (R=0.93; Marrack, 2015). To confirm this relationship across a larger geographic area, groundwater elevations above sea level were measured within 12 additional anchialine pools, fishponds and wells in the study area (Figure 1). Water level loggers (In-Situ Rugged Troll 100) collected data at 15 minute intervals for over a year at each location starting in August of 2015. At each level logger position, semi-permanent benchmarks were established by the NOAA Geodetic Survey using CHC X90-OPUS (GPS) receivers during September 2015 and July 2016. These surveyed control points were used to calculate the mean groundwater level over sea level as well as examine the effect of tides on groundwater heights with high vertical resolution (5 cm). Mean groundwater levels from the 12 loggers along with the previous measurements from an additional nine groundwater sites (USGS sites in Figure 1) were used to recalculate the equation for H_{GW}.

Geospatial models representing the increase of groundwater heights with distance from shore were developed based on the updated equation for H_{GW}. First a raster representing the Euclidean distance from shoreline (2-m resolution) was created. Then mean groundwater height above MSL was calculated by applying the groundwater height equation to each pixel within the Euclidean distance raster. A tidal efficiency component was then added to the groundwater raster to incorporate tidal effects on groundwater heights. Tidal effects decay with distance inland from shore and can be represented by a tidal efficiency ratio, which is the ratio of mean daily groundwater tidal range at a site to mean daily ocean tidal range (Todd, 1980). The ratio is 1 at the shoreline decreasing to 0 inland where there is no tidal effect. For this study, raster surfaces representing tidal influence during MHHW (0.37 m, Kawaihae tide gauge) were combined with the raster of groundwater heights above MSL to create the final groundwater models. Groundwater models were created for each SWL scenario using the unique shoreline (MSL) predicted for that specific ocean water level. Additionally, groundwater elevations were calibrated to future ocean heights by adding the expect elevation increase (SWL) to current MSL.

2.4 Overview of flood mapping methods

Using the spatial models for SLR and groundwater levels described above, geospatial data were created to visualize potential impacts to anchialine pools under future flooding scenarios. Under each scenario, the inundation of existing pools as well as the size, location, and number of new pools that will emerge on the landscape were mapped. Additionally, flooding scenarios were combined with current pool locations, non-native fish distribution, land use, and density of proximal cesspools to determine the effect of these factors on anchialine habitats under future sea level changes.

2.5 Mapping and modelling pools

To determine future pool locations and flood extent for various scenarios, 1 m resolution spatial grids were created that combined a SWL "bathtub" mapping approach in areas adjacent to the ocean with additional inland flooding based on groundwater models. Therefore, water levels used in flood models included SWL (regional SLR, oceanographic processes, tides, and climate variability) and groundwater levels. Locations were identified as flooded when ocean or groundwater elevations were greater than the elevation of current topography. Topographic elevation data were derived from the US Army Corps of Engineers 2016 LiDAR data release. Digital Elevation Models (DEMs) were built in LAStools (2014) with 1 m grids using the lowest elevation recorded in each grid. For the LIDAR topographic data, Horizontal Positional Accuracy was compiled to meet 1 m at 95% confidence level and Vertical Positional Accuracy of 19.6 cm at a 95% confidence level (10 cm Root Mean Square Error).

2.5.1 Current Anchialine Pools: Current anchialine pools were mapped with a Trimble GeoXT Global Positioning System between 2011 and 2016 (Marrack et al., 2015). A subset of pools on private properties, for which landowner support for access could not be obtained, were digitized from Quickbird 2006 satellite imagery.

2.5.2 Future Anchialine Pools: Observations of current pools that go dry daily at a low tide show that endemic shrimp and other pool species will emerge from the subterranean aquifer to graze on the pool substrate during higher tides (Marrack, pers. obs.). Therefore, water bodies that hold water at least every other day and are not attached overland to the ocean will likely fulfill the function of anchialine pools or wetlands in the porous basalt landscape of West Hawai‘i. Future pools were thus defined as inland water features created at SWL frequency scenarios that flood a minimum of 185 days a year, roughly equivalent to the flood frequency of Mean Higher High Water. The Medium SLR scenario was used. In the Geographical Information System (GIS; ArcGIS 10.13), future pools were identified as flood polygons that: (i) did not intersect with the predicted ocean surface of a SWL scenario; (ii) did not fall within a 13 m shoreline buffer at a SWL scenario; (iii) did not intersect with any polygon for a water body (fishpond or vegetated wetland) that is connected overland to the ocean; and (iv) did not intersect with any paved or similarly developed land use type as defined by visual inspection of aerial imagery and C-CAP layers (NOAA, 2011). Due to the high uncertainty in flood frequency estimates between the scenarios for 2100, future pools were only projected for 2030, 2040, 2050, and 2080.

2.5.3 Risks to Anchialine Pools: At each time period (current, 2030, 2040, 2050, and 2080), individual pools were ranked in terms of their risks from invasion by non-native fishes, overland connections to the ocean, habitat loss through development, and contamination by cesspools. These risks were determined in a GIS using pool locations, frequency of flooding layers, and other spatial data.

The non-native fishes tilapia and poeciliids are an important factor known to alter pool ecosystems and drive native fauna out of anchialine habitats (Brock & Kam, 1997; Capps et al., 2009; Chai, Cuddihy & Stone, 1989; Englund, 1999). Previous extreme tide events that provided surface connections between individual pools have facilitated dispersal of non-native fish into pools where they were previously absent (Figure 2). For accessible pools, the presence or absence of non-native fishes (tilapia and/or poeciliids) were recorded at the time of the surveys or were confirmed by property owners or land managers. If the non-native fish status of a pool was unknown it was indicated as unknown in the attribute table. Then in a GIS analysis, if an annual flood frequency layer connected a pool that previously had no fish to another pool containing non-native fish, this overland connection was considered a risk potential for introduced fishes to disperse. Both pools were then ranked as highly likely to contain non-native fishes.

Infrequent overland connection to the ocean is not considered a large risk for pool ecosystems due to persistent groundwater flow regulating salinity; however, frequent connection indicates pools may soon become part of the nearshore marine environment and cease to exist as anchialine habitat. Pools were assigned as high risk for ocean flooding if they connected to the ocean with the semi-frequent (weekly to monthly) flooding frequency layers (or within 13 m of connection with the ocean). Those pools that connected overland to the ocean with the infrequent (annual) flood frequency layers (or within 13 m of the connection with the ocean) were assigned a lower risk for ocean flooding.

Pools that intersected land that was proposed for future development may be at risk; however, this information also provides an opportunity to influence that development to minimize impact. Using the County of Hawai‘i ’s General Plan Land Use Pattern Allocation Guide (2015), pools that intersected with planned conservation or open space areas were assigned low risk status, pools that intersect with areas proposed for low density development were assigned medium risk status, and pools that intersected with areas proposed for medium-high density development, urban expansion, or industrial use were assigned high risk for development.

Cesspools are a common wastewater disposal method in Hawaiʻi and contaminate coastal aquatic and nearshore marine ecosystems with elevated nutrients, bacteria, and other contaminants (Abaya et al., 2018; Yoshioka, Kim, Tracy, Most, & Harvell, 2016). Because groundwater flows through anchialine pools, those adjacent to cesspools have a higher likelihood of contamination. To map the potential of this contamination to anchialine pool systems, the State of Hawaiʻi wastewater risk score attribute for On-Site Sewage Disposal Systems (OSDS) was used (Whittier & El Kadi, 2014). The risk score represents proximity to coast and stream, flood potential, soil type and permeability and OSDS density. In GIS, a buffer around each OSDS with a radius equal to the risk score squared was created. For instance, a risk score of 3 would have a circular buffer of radius 9 m. Pools located near a "Low" risk cesspool (0-5 OSDS score) were then assigned low risk status, pools located near a "Medium" risk cesspool (6-15 OSDS score) were assigned medium risk status, and pools located near a “High” risk cesspool (>15 OSDS score) were assigned high risk status. This was determined for each flood frequency scenario.

3 Results

3.1 Flood analyses

Using three approaches to estimate extreme water levels and bracketing the results in a risk-based construct, Extreme Value Return Intervals of 0.3 m, 0.4 m, and 0.5 m (above MHHW) were determined to represent low, medium, and high scenarios respectively (Table 3). In the assessment of extreme SWL, the results from the RFA analysis and the analysis from Kawaihae tide gauge were quite similar. For example, the 2-yr return level (also referred to as 2-yr storm: the probability a water level can reach this elevation once in 2 years) at Kawaihae of 0.3 m above MHHW was similar to the 2-yr return level (0.31 m) with the RFA. The 100-yr storm for Kawaihae was 0.42 m compared to the RFA of 0.50 m. Because the results were relatively close and multiple tide gauges are probably a better indicator of potential exposure than relying solely on the results from one tide gauge, the RFA results were used for scenarios. What is particularly noteworthy is that in all cases the maximum difference between a 2-yr storm and a 100-yr storm is quite small and in the 20 cm range.

When all factors are considered - flood extremes, future regional sea levels, and possible contributions attributable to climate variability - changes in the projected SWL (m relative to MHHW) range from 0.5 to 0.8 m by 2030, from 0.6 to1.0 m by 2040, from 0.6 to 1.2 m by 2050, and from 0.9 to 1.9 m by 2080. The magnitude of sea-level change over the next 30 years is relatively small and the values derived from different scenarios are similar regardless of which GMSL scenario is selected (Table 3). However, by 2080, scenario projections differ by 1 metre.

Flood frequency analysis projects that water level elevations, which are currently reached only during extreme events, will begin to occur on a much more frequent basis. For example, in 2030, areas at or above 1 m over MSL will likely flood four or less days a year (Table 4). By 2050, these areas will flood six to 252 days a year depending on which scenario is selected. By 2080, these areas will be flooding 123 to 365 days a year. Assuming new anchialine pools will form in areas that begin to flood daily to every other day, the elevation thresholds used to map new pools were 0.6 m above MSL in 2030, 0.7 m in 2040, 0.8 m in 2050 and 1.3 m in 2080, the frequent flooding values for the Medium scenarios in Table 4.

3.2 Groundwater level measurements and analysis

Data showed that as expected, mean groundwater levels are elevated above MSL and that these heights increase with distance from shore (Figure 3). For loggers located between 70 to 430 m from shore, mean groundwater elevations ranged from 0.0 to 0.38 m above MSL. The pool located furthest inland (1290 m from shore) had a mean elevation of 0.7 m over MSL. Based on the groundwater height measurements in West Hawai‘i, the equation describing mean groundwater elevation over MSL (H_{GW}) as a function of distance from shore (d) was calculated as $H_{GW}= (0.010883d^{1/2} + 0.15234)$ ($R_2 = 0.8$). The data and resulting curve support previous observations from the Kona area (Figure 3)**.**

3.3 Current and future pools

A total of 509 pools were identified along the 40 km of coastline between Kawaihae Harbour to the southern end of Kailua-Kona through intensive field surveys and discussions with landowners. As sea levels rise, analysis predicts that many of the existing pools will merge with the marine nearshore environment over time and cease to be anchialine habitats. By 2080, only 100 (loss of 80%) of the original pools were predicted to remain (Figure 4a). However, new pools were predicted to emerge inland in low-lying undeveloped area (Figure 4a, Figure 5). Our models predicted that by 2030 in West Hawai‘i, 847 pools will exist with pool numbers increasing to more than 1000 by 2080. Likewise, the surface area of anchialine pool habitat is likely to expand from 121,750 m^2 in 2018 to 344,785 m^2 by 2080 (Figure 4b), an increase by a factor of nearly 2.

Pools are currently distributed throughout West Hawai‘i with concentrations typically ranging from 0 to 20 pools within a 100 m radius (Figures 5 and 6a). Several locations in State and Federally protected lands contain higher pool densities. As sea levels rise, pool densities are predicted to increase in many areas. The areas with the highest concentrations in 2018 will continue to support the greatest density of pools in 2030, 2040, 2050 and 2080 (Figures 6b,c,d,e).

In 2018, introduced fish were present in 31% of pools. As new pools were predicted to form, the existing pools became the source for introduced fish to disperse into new habitat at high water levels (Figure 5). Between 2030 to 2080, introduced fishes were predicted to disperse into 42 to 47% of pools (Figure 7a). The rate of dispersal of fishes into new pools will be somewhat offset by the loss of existing pools.

In 2018, the risk of ocean inundation was very low for anchialine pools; however, the threat of ocean flooding is predicted to increase under future sea level scenarios. By 2030, 10% might flood on a monthly basis, increasing up to 23% of pools by 2040 (Figure 7b). By 2080, 61% of pools may flood on a monthly basis. However, the wide uncertainty of flooding in 2080 between the high and low scenarios make these estimates tentative (Table 3; Figure 5d). The uncertainty between high and low scenarios in 2100 was so great, predictions of pool locations and risks were not included in the analyses.

Based on our models using current land-use plans and cesspool distribution, development and cesspool risks are quite low for anchialine pools for all scenarios (Figure 7c and d). High-density development plans threaten only 3 to 4% of future pools in 2030, 2040 and 2050. In 2080, 9% of pools are under high risk for development. Currently, 3% of anchialine pools are at a moderate risk from cesspool contamination. Future cesspool risk remains at moderate levels for 6 to 8 % of total pools across time periods examined.

4 Discussion

Based on the geospatial models developed in this study, anchialine pool density and location, as well as risks to pools, will change over the following decades in West Hawaiʻi due to SLR. By 2080, approximately 80% of the current pools will merge with the nearshore marine environment and cease to be anchialine habitat. However, many new anchialine habitats will emerge inland in low-lying areas. Aside from direct pool destruction due to increased ocean inundation, the greatest threat to new pool habitats appears to be the dispersal of introduced fishes during infrequent periods of extremely high water levels. Currently 31% of pools contain tilapia and/or poeciliids. Between 2030 and 2080, introduced fishes are predicted to disperse into 42 to 47% of pools. Previous work has shown that introduced fishes are one of the greatest threats to pool ecosystem health (Brock & Kam, 1997; Chai et al., 1989; Marrack et al., 2015). Current management actions to remove fishes from anchialine habitats is key for protecting the quality of habitats now and into the future.

Efforts to protect critical habitats will need to include assessment of other risks in some locations. Based on current land use plans in West Hawaiʻi, a small percentage of future anchialine habitats (3-9%) are faced with the risks associated with medium to high-density urban development. Future planning should account for the fact that pavement and urban landscapes will prevent inland migration of these ecosystems. In the past, development has also led to pool infilling, lack of buffers around pool habitats, non-point source runoff into groundwater, increases in human access, and introduction of non-native species (Brock & Kam, 1997). Similarly, contamination from cesspools threatens up to 3% of pools based on the cesspool density data used here, which underestimates groundwater contamination because urban run-off, septic tanks, and injection wells for sewage treatment plants also contribute to groundwater in West Hawaiʻi (Hoover & Gold, 2006). Plans for future development along this coastline indicate rapid potential growth in some areas (County of Hawai‘i, 2015). Risks to anchialine pools could be substantially reduced by thoughtful landscape planning, sustainable water extraction, and sewage treatment designs that protect these habitats from the issues that development may pose.

It is also essential to recognize that risk factors often act synergistically to impair aquatic habitats. In pools where non-native fishes are coupled with increased nutrient loads from contaminated groundwater, epilithon biomass appears to be highest, and this may drive pool infilling (Dalton et al., 2013). Infilling rates are also increased by accumulation of organic matter from native and introduced plants which grow around the edges of pools that are situated on older lava flows (Brock & Kam, 1997). Additionally, leaf litter subsidies from both native and introduced tree species appear to alter food web dynamics and, in some cases, increase dissolved inorganic nutrient levels (Dudley et al., 2017; Nelson-Kaula, Ostertag, Hughes, & Dudley, 2016). Studies have not examined if vegetation around anchialine pools may grow more rapidly in areas with sewage enriched groundwater. Ultimately, interaction effects may be complex and are important for pool managers to consider when prioritizing conservation actions.

Conservation planning and management can improve coastal habitat quality in the future, especially if it is informed by regional projections of SLR and if flood models are appropriate for the ecosystem of interest. In this study, average groundwater levels in most anchialine pools were observed to be 0.2 to 0.4 m but as high as 0.7 m over MSL. Recent studies have shown that SLR driven groundwater inundation is likely to account for substantial amounts of flooding in many areas with unconstrained aquifers including Waikiki, Hawai‘i (Rotzall & Fletcher, 2013), Connecticut (Bjerklie et al., 2012), and in some coastal areas in California (Hoover, Odigie, Swarzenski, & Barnard, 2017). Because anchialine systems are composed of groundwater that connects to the marine environment through permeable rock, it is essential that SLR models aimed at predicting the migration and flooding of these habitats should include groundwater elevation. It is important to note that the models used in this study as well as the other studies cited above are based on current groundwater conditions and do not take account of factors that can influence the water table including changes in rainfall patterns, aquifer geology, and changes in groundwater inputs or withdrawal (Rotzall & Fletcher, 2013). On the western side of Hawai‘i Island, Frazier and Giambelluca (2017) documented significant long-term declines in annual and dry season rainfall between 1920 and 2012, and these trends coincide with long-term declines in base flow (Bassiouni & Oki, 2013). These factors are dynamic and may be considered in future models.

To determine the distribution and emergence of new anchialine pool habitats, it was also essential to focus on flood frequency models. New habitats emerge when water is pooling in low-lying areas on a daily basis not during rare extreme water levels. Storm wave run-up and erosion during extreme events are important factors in SLR models for shoreline ecosystems composed of unconsolidated sediments such as beaches or wetlands (Vitousek et al., 2017). However, these factors are less important for modelling future anchialine habitat locations, because anchialine ecosystems are typically found in karst or basalt bedrock and are set back from the shoreline. For anchialine pools, extreme water levels are considered a key factor for dispersing introduced species such as invasive fishes. The extreme sea level model used for this study incorporated regional sea-level rise, tidal fluctuations, oceanographic processes, storm surge and groundwater heights above sea level, but did not include wave run-up or tsunamis. Wave run-up during extreme events could disperse introduced species beyond what is predicted in this study. Interestingly, although a 2011 tsunami originating in Japan caused considerable coastal damage in West Hawai‘i, there is no evidence that the high waters dispersed introduced fishes into new pools. It would be valuable to predict introduced species dispersal using dynamic models of extreme water level such as those discussed in Passeri et al. (2015) and see how results compare to the modified bathtub approach used in this study. Ultimately, efforts to model SLR effects on the distribution and function of rocky, groundwater-fed ecosystems such as anchialine pools should consider incorporating both flood frequency and flood extreme predictions.

One aspect of SLR that was not examined in this study was that increasing intrusion of marine water will change the salinity of existing coastal groundwater habitats. Similar to the aytid shrimp *H. rubra*, which is found in salinities from 1 to 34 ppt, many anchialine species of shrimp and other taxa are found within a broad range of salinities (DeGrave, Cai & Anker, 2008; Iliffe, 2000), and will likely be able to move inland as new habitat emerges (Moritsch et al., 2014). However, some anchialine species, such as remipedes, are distributed below the halocline found in anchialine caves, and their dispersal will be restricted by their salinity tolerance (Moritsch et al., 2014). Likewise, vegetation that is associated with anchialine systems will be affected by increased salinity. Research on barrier islands on the east coast of North America indicate that critical dune and maritime forest habitats will shift in response to changes in vadose zone thickness and groundwater salinity (Masterson et al., 2014). Groundwater-dependent vegetation will likely shift with anchialine pools as well. The biotic communities in future anchialine habitats will be determined in part by the species specific tolerance levels to salinity and other abiotic factors.

To facilitate effective planning and management actions at the local level, the data generated through this study were developed in cooperation with planners, natural resource managers, cultural practitioners, and coastal community members and provided to the public in an online tool (maps.coastalresilience.org/hawaii). Planners and coastal land managers were also trained to use the tool. Users are able to examine pool locations, risks to pool habitats, flood maps of various scenarios, and associated summary statistics at the regional and specific site scale. Access to technical information on methods and GIS data are available for users through the portal. The predictions generated are being used by managers, planners, and the public to reduce coastal vulnerability and identify actions to conserve new habitat under future sea level scenarios. A next step should be expanding the geographic extent of these risk analyses to assist management of other anchialine pool systems both in Hawaiʻi and across the globe.

The approach presented here would be useful for examining the effects of SLR on anchialine pool complexes documented elsewhere including the Sinai Peninsula (Por & Tsurnamal, 1973), Indonesia (Becking et al., 2011), the Ryukyu Archipelago in Japan (Weese, Fujita, Hidaka, & Santos, 2013), Bermuda and the Bahamas (Iliffe & Kornicker, 2009), as well as across the Hawaiʻi, Fiji, Funafuti, Tuvalu, Philippine, Tokelau and Loyalty archipelagos (Holthuis, 1973; Wear & Holthius, 1977). For the extensive anchialine cave habitats such as those existing in Eastern Europe (Zaksek, Sket, & Trontelj, 2007), Australia (Boulton, Humphreys & Eberhard 2003), and the Yucatan and Caribbean (Iliffe & Kornicker, 2009), subsurface rock porosity and cave morphology would be necessary components to include in habitat models. For species with restricted salinity tolerances such as remipedes, models that incorporate salinity profiles would be useful.

Worldwide, coastal ecosystems are at risk from local and global stressors, some of which can be locally managed to improve the habitat suitability of these systems for endemic species. By evaluating the loss and emergence of anchialine ecosystems, as well as their future risks, a more complete picture of threats and opportunities emerges. The outputs of this study and the related tool that depicts future sea level scenario impacts on anchialine ecosystems can inform natural resource managers, planners, and decision-makers to justify and prioritize conservation and development mitigation actions. These actions should include: (i) removing introduced fishes, especially in areas that will be a source for future pools; (ii) reducing groundwater contamination and ensuring adequate groundwater flow for endemic species in anchialine systems; and (iii) restricting development in coastal zones where anchialine pool habitats will emerge under future sea levels. As in the geologic past, coastal ecosystems are expected to persist under sea level rise if they are allowed to shift inland. Ideally, planning, policy, and management actions aimed at conserving anchialine systems will track the real-world progression of threats at the local scale while incorporating updates to sea-level change predictions. Continued research and monitoring of anchialine systems will allow both refinement and validation of risk assessment models so as to best protect these significant global ecosystems in a changing climate.

Acknowledgements

Funding: NOAA/National Center for Coastal Ocean Science NA15NOS4780170 (David Kidwell).
Project: Doug Harper, Ed Carlson (NOAA), Ross Winans; Laura Flessner, Zach Ferdana, Julia Rose, Cecile Walsh (TNC). Community Support: Peter Hackstedde, Mike and Diane O’Toole, A.K. Shingle, Ku‘ulei Keakealani, Brad Romine, Kevin Sullivan, Bethany Morrison, Dena Sedar, Pii Laeha, Reggie Lee, Jenny Mitchell.

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TABLES

Table 1. Spatial and temporal scales of geophysical processes affecting ocean water levels. The processes highlighted in blue contribute to the Still Water Level (SWL) component of ocean water levels. Modified from Sweet et al. (2017).

Physical Process	Spatial Scale			Temporal Scale	Potential Magnitude (yearly)
	Global	Regional	Local		
Wind Waves (e.g., dynamical effects, runup)			x	secs to mins	< 10 m
Tsunami		x	x	mins to hours	< 10's of m
Storm Surge (e.g., tropical storms or nor'easters)		x	x	mins to days	< 15 m
Tides			x	hours	< 15 m
Seasonal Cycles		x	x	months	< 0.5 m
Ocean/Atmospheric Variability (e.g., ENSO processes)		x	x	months to years	< 0.5 m
Ocean Eddies and Planetary Waves		x	x	months to years	< 0.5 m
Ocean Gyre and Over-turning Variability		x	x	years to decades	< 0.5 m
Land Ice Melt/Discharge	x	x	x	years to centuries	mm's to cm's
Thermal Expansion	x	x	x	years to centuries	mm's to cm's
Vertical Land Motion		x	x	minutes to centuries	mm's to m's

Table 2. Tide Gauge stations used in the Still Water Level analysis. Hourly time series were obtained from the University of Hawai‘i Sea Level Center fast delivery database.

Station	# Years	First Year	Last Year*

HONOLULU	113	1905	2018
NAWILIWI	34	1954	2018
KAHULUI	68	1950	2018
HILO	91	1927	2018
KAWAIHAE	29	1989	2018

*January is the only month from 2018 included in this analysis

Table 3: Potential magnitude of the SWL in West Hawai‘i in metres above Mean Higher High Water (MHHW) and Mean Sea Level (MSL) for a range of flood scenarios for the time periods 2030, 2040, 2050, and 2080. In terms of flood frequency (or return intervals) the LOW, MEDIUM, and HIGH scenarios correspond to roughly once every 1-2 years, once every 25-50 years, and once every 100 plus years. The sea-level rise (SLR) trend is from Sweet et al. (2017). Climate Variability represents the Pacific Decadal Oscillation component.

Scenarios		Extreme Value Return Level (m)	SLR trend (m)	Climate Variability (m)	Projected SWL Value (m) MHHW	Projected SWL Value (m) MSL
2030	LOW	0.3	0.2	0	0.5	0.9
	HIGH	0.5	0.28	0.05	0.8	1.2
2040	LOW	0.3	0.27	0	0.6	0.9
	MEDIUM	0.4	0.35	0.05	0.8	1.2
	HIGH	0.5	0.43	0.05	1.0	1.4
2050	LOW	0.3	0.34	0	0.6	1.0
	MEDIUM	0.4	0.48	0.05	0.9	1.3
	HIGH	0.5	0.62	0.05	1.2	1.5
2080	LOW	0.3	0.56	0	0.9	1.2
	MEDIUM	0.4	0.95	0.05	1.4	1.8
	HIGH	0.5	1.36	0.05	1.9	2.3

Table 4: Potential changes in frequency of ocean flooding for elevations above Mean Sea Level (MSL) in West Hawai‘i. Days per year an elevation threshold is exceeded are listed for a range of scenarios (Low, Medium, High) for the time periods 2030, 2040, 2050, and 2080. Elevation thresholds are listed in the top row in 0.1 m increments starting at Mean Higher High Water (0.4 m). The flood frequency categories are highlighted by color with frequent flooding depicted in dark blue, semi-frequent in light blue, infrequent in yellow, and rare flooding in red. Rare flooding values are from the extreme analysis (Table 3).

Ht above MSL (m)		0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	Extremes (m)
2030	LOW	347	288	188	85	22	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9
	HIGH	364	353	303	210	103	30	4	0	0	0	0	0	0	0	0	0	0	0	0	1.2
2040	LOW	361	334	261	154	61	12	1	0	0	0	0	0	0	0	0	0	0	0	0	0.9
	MEDIUM	365	360	329	252	143	54	10	0	0	0	0	0	0	0	0	0	0	0	0	1.2
	HIGH	365	365	361	334	261	154	61	12	1	0	0	0	0	0	0	0	0	0	0	1.4
2050	LOW	364	357	317	232	123	41	6	0	0	0	0	0	0	0	0	0	0	0	0	1.0
	MEDIUM	365	365	363	343	279	176	77	18	1	0	0	0	0	0	0	0	0	0	0	1.3
	HIGH	365	365	365	365	360	329	252	143	54	10	0	0	0	0	0	0	0	0	0	1.5
2080	LOW	365	365	364	357	317	232	123	41	6	0	0	0	0	0	0	0	0	0	0	1.2
	MEDIUM	365	365	365	365	365	365	364	359	323	242	133	47	8	0	0	0	0	0	0	1.8
	HIGH	365	365	365	365	365	365	365	365	365	365	365	363	347	288	188	85	22	2	0	2.3

- Elevations that experience flooding daily to every other day (FREQUENT).
- Elevations that experience flooding once a week to once a month (SEMI-FREQUENT).
- Elevations that experience flooding once to several times a year (INFREQUENT).
- Elevations that flood in extreme SWL events (Once per decade).

Figure Captions:

Figure 1: Study location on the Island of Hawai‘i in the state of Hawai'i. The locations of groundwater level loggers are indicated with black symbols, including those deployed between 2015 to 2017 for this study (n=12) as well as USGS loggers (n=9) used in a previous study by Marrack (2015). Federal and State conservation lands are shaded green.

Figure 2. Anchialine pool risks (a) before and (b) after SLR. (a) Anchialine pools are composed of brackish groundwater and support endemic fauna such as *Halocaridina rubra* shrimp. Non-native fishes (Tilapia species and poeciliids) cause shifts in pool biota due to predation on the dominant grazer *H. rubra.* Risks to anchialine pools from SLR include ocean inundation of pools (1), dispersal of non-native fishes during high water levels (2), and groundwater inundation of cesspools (4). New pools will emerge in low-lying areas (3) as groundwater floods previously dry areas on a daily basis.

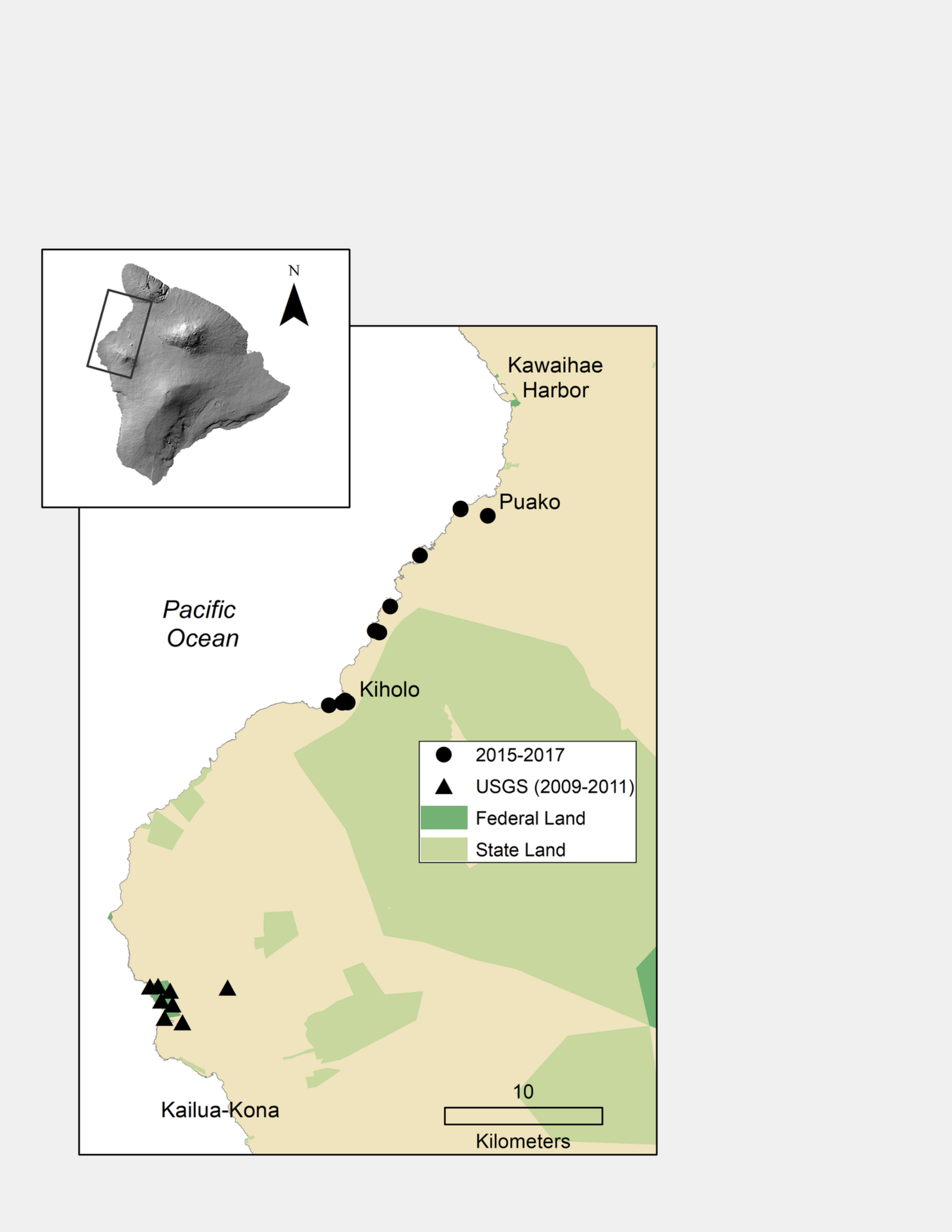
Figure 3: Mean groundwater elevations above Mean Sea Level as a function of distance from shore (m). Data from 12 groundwater level logger sites (circle) are plotted along with 9 groundwater level sites monitored by the USGS from 2009-2010 (triangle). The top curve represents the function calculated using all 21 data points (R^2 = 0.8). The bottom dashed curve represents the function calculated by Marrack (2015) using the USGS data from 2009-2010.

Figure 4: Summary statistics for all pools in West Hawai‘i: (a) Total number and surface area of anchialine pools predicted for future time periods. (b)Total surface area of pools is shown in 1000s of m^2. Original pools were surveyed in 2018.

Figure 5: Maps of ocean and groundwater inundation for various sea level rise scenarios at Kiholo Bay: (a) Current daily flood conditions with anchialine pools highlighted in yellow (no non-native fish) and red (with non-native fish). High and low sea level scenarios indicate uncertainty. Note the Hawaiian fishpond that is connected overland to the ocean and is therefore not an anchialine pool; (b) Flooding predicted to occur daily by 2040. Pools have enlarged and new pools have formed; (c) Flooding that is expected to occur only a few times a year by 2040; (d) Flooding expected to occur daily by 2080. There is higher uncertainty in the extent of sea level rise by 2080 as indicated by flood layers.

Figure 6: Anchialine pool density in West Hawai‘i from Puako to Kailua-Kona for (a) existing during 2018, and predicted for (b) 2030, (c) 2040, (d) 2050, and (e.) 2080. Visualization represents point density of pools within a 100 m radius.

Figure 7: Exposure to all risk factors for current and future anchialine pools. Risks include: a) introduced fishes, b) ocean inundation, c) development, and d) proximity of cesspools. Risk from introduced fishes is categorized as unknown, with fish or with no fish. Ocean inundation is categorized as inundation on an annual basis, monthly basis, or not inundated. Development and cesspool risks are categorized as high, medium and low.



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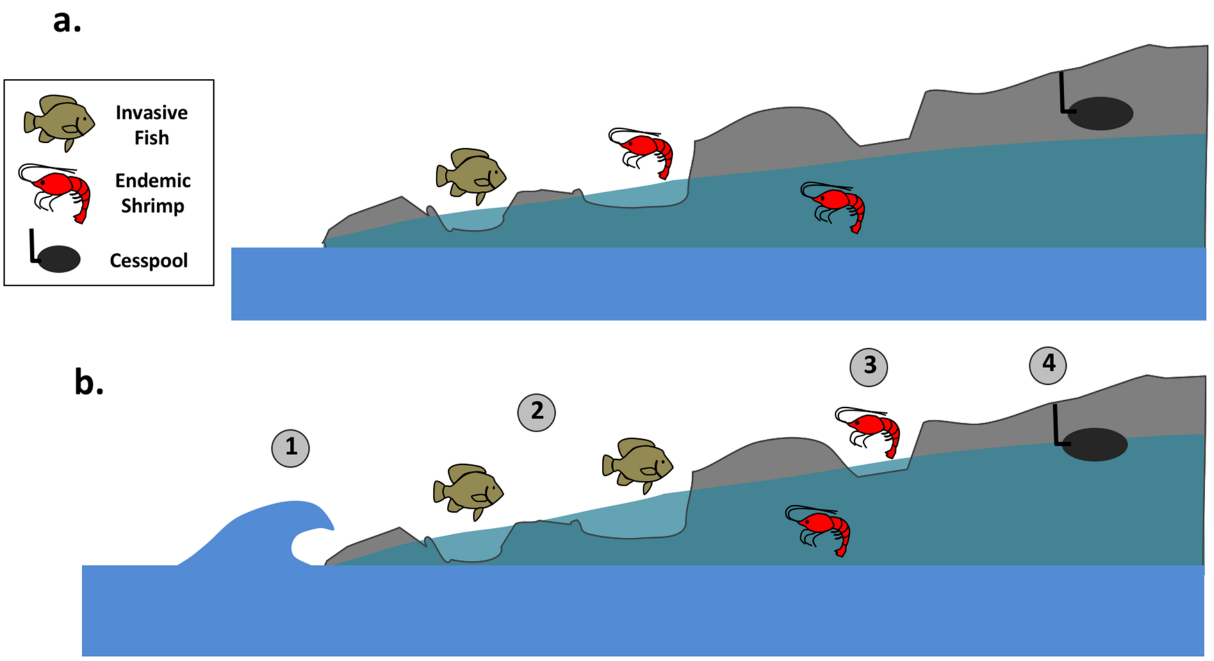

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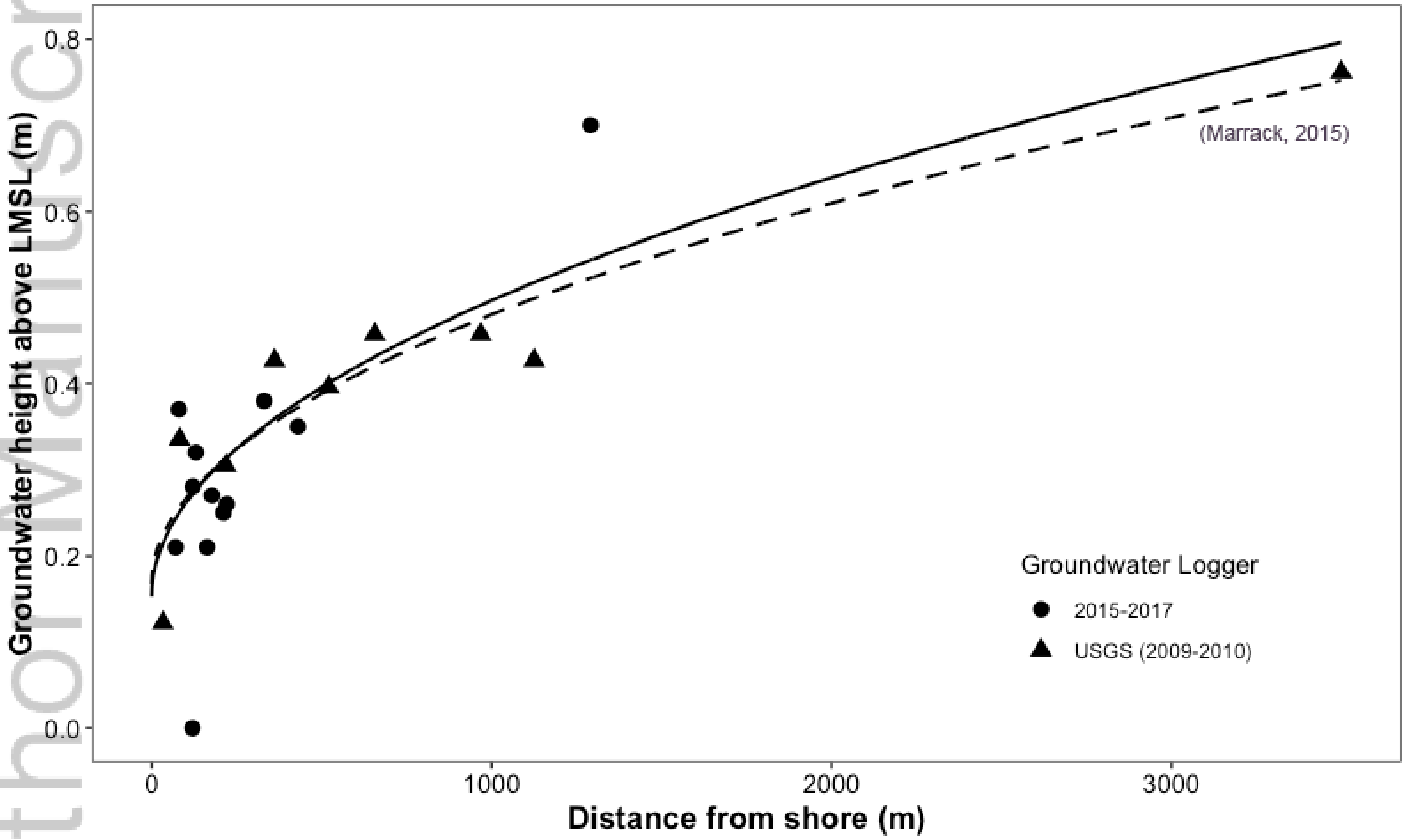

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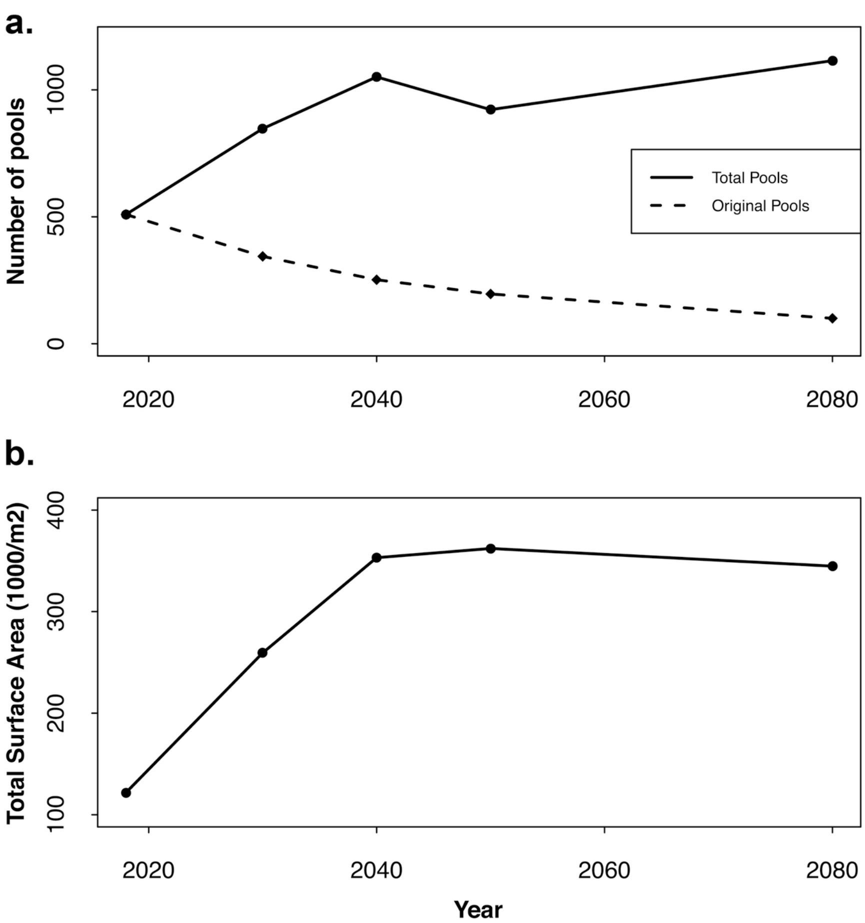

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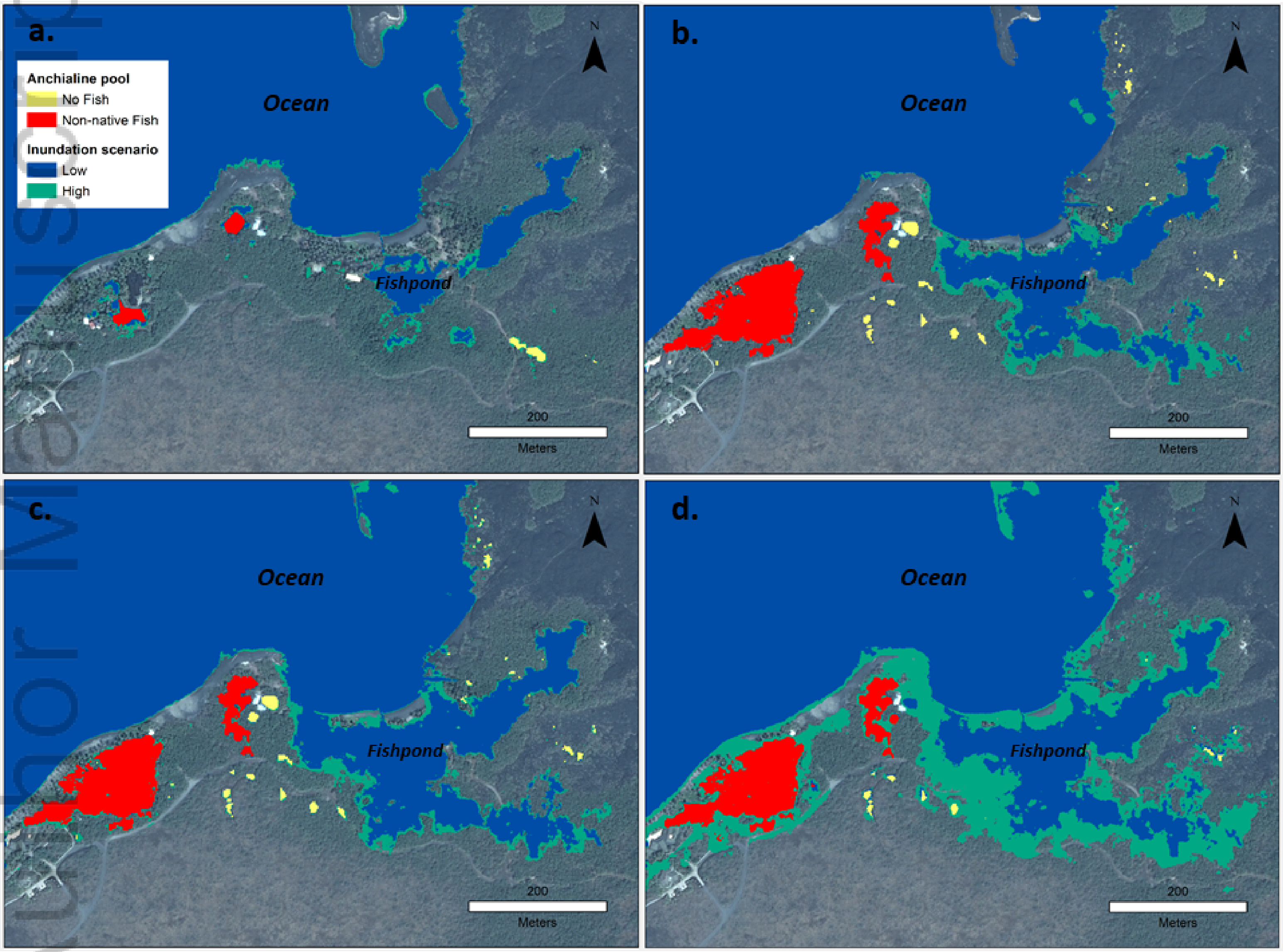

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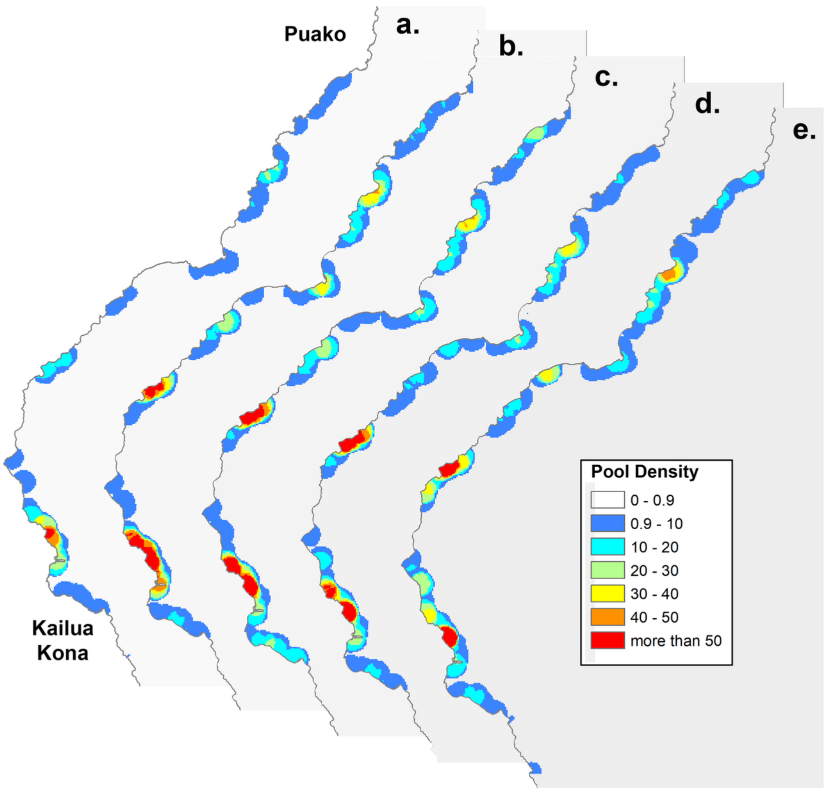

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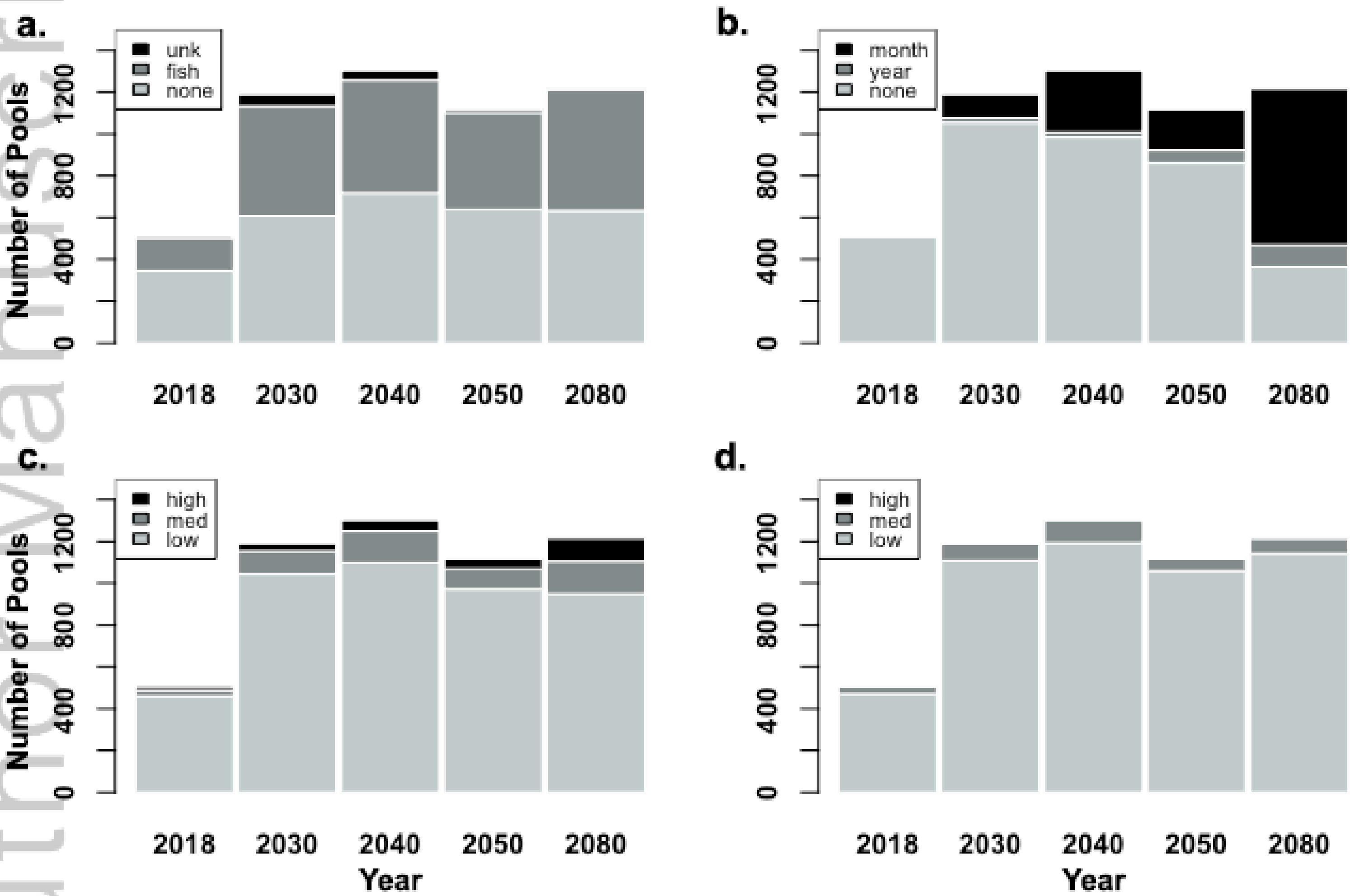

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