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Synthesis

Biocultural values of groundwater dependent ecosystems in Kona, Hawai'i

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ABSTRACT. Groundwater dependent ecosystems (GDEs) are increasingly recognized as important conservation targets with linked ecological and social value. However, the social uses and values of GDEs have received relatively little research attention in the peer-reviewed literature, precluding their greater inclusion in policy and management decisions. To help fill this gap, we provide a case study from Kona, Hawai'i, where multiple types of GDEs are abundant, to illustrate the diversity of social uses and values of GDEs. To explore these uses and values, we combined a literature review, archival analysis, and key-informant interviews with resource managers and lineal descendants connected to three prominent GDEs: Indigenous aquaculture systems, anchialine pools, and nearshore ecosystems. Interviews focused on current and historical uses and values of GDEs, contemporary management challenges and strategies, and desired visions for the future. Interviewees expressed a range of uses and values associated with GDEs, which we categorized using a Hawai'i-based cultural ecosystem service framework focused on social connections, physical and mental health, spirituality, and knowledge. Importantly, results suggest that the historical value of these systems directly informs current social value, and that restoration efforts are largely carried out through biocultural approaches, which emphasize the mutually reinforcing restoration of ecology and culture. We found that interviewees seek to restore ecosystem functions, cultural practice, and connection to place, and in some cases, local food production. Achieving these goals requires addressing multiple and interacting threats to these systems including invasive species, land-based sources of pollution, groundwater pumping, and climate change. Importantly, effective and equitable restoration also rests on recognition and amplification of Indigenous rights, knowledge, practice, and governance. These results provide important lessons for land and water management and policy in Hawai'i as well as other islands and coastal areas where GDEs have important linked social and ecological value.

Key Words: *anchialine pools; biocultural restoration; cultural ecosystem services; loko i'a; social-ecological systems; submarine groundwater discharge; water resources*

E ui aku ana au ia oe, Aia i hea ka Wai a Kane?
Aia i lalo, i ka honua, i ka Wai hu,
I ka wai kau a Kane me Kanaloa
He waipuna, he wai e inu,
He wai e mana, he wai e ola,
E ola no, ea

One question I ask of you:
Where flows the water of Kane?
Deep in the ground, in the gushing spring,
In the ducts of Kane and [Kana]loa
A well spring of water, to quaff,
A water of magic power The water of life!
Life indeed, o give us life!

This stanza is part of the longer "*Wai a Kāne*" (water of Kāne) *oli* (chant) that describes the sources of *wai* (water) throughout the Hawaiian Islands as translated by Emerson (1909:258-259). We highlight this stanza describing groundwater in aquifers and springs because this is the primary water source in Kona. The chant describes the connections between water and Kāne, one of four major *akua* (deities) in Kānaka ʻŌiwi (Native Hawaiian) cosmologies, who, as ancestor to all living beings, provides fresh water, sunlight, and all life substances (Mitchell 2001; Hawaiian language translations here and throughout this text from Pukui and Elbert 1986, see glossary in Appendix 3). *Oli* along with *mele* (songs) and *moʻolelo* (legends) are important repositories of Indigenous knowledge that have been passed down in oral and written form (Kealiikanakaoleohaililani et al. 2020). This stanza also makes reference to Kanaloa (translated by Emerson as Loa), another major deity of the ocean, expansiveness, and the underworld. Together, Kāne and Kanaloa are known water finders, and this chant references their ability to locate water sources. This stanza demonstrates the knowledge of hydrogeology that allowed Kānaka ʻŌiwi to describe unseen water flowing deep underground, the spiritual reverence for water as a source of life, and the dedication to commit this knowledge to memory through chant, such that many generations came to learn these details about the water of Kāne.

INTRODUCTION

Efforts to holistically manage groundwater highlight the need to protect groundwater dependent ecosystems (GDEs) for their social and ecological uses and values (Kløve et al. 2011, Wachniew et al. 2014, Esteban and Dinar 2016, Rohde et al. 2019, Elshall et al. 2020). Found worldwide, GDEs are ecosystems that are fed by groundwater, and include ecosystems above (e.g., wetlands, estuaries, springs/seeps, rivers/streams) and within subterranean zones (e.g., aquifers, caves and hyporheic zones; Eamus and Froend 2006, Humphreys 2006). GDEs often support high endemic biodiversity (Boulton 2020, Cantonati et al. 2020), can serve as important sites for food and water supplies (Murray et

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al. 2006, Burnett et al. 2017), and frequently have high social and economic value (Moosdorf and Oehler 2017, Burnett et al. 2018, Boulton 2020).

Despite their recognized value, academic research on and formal conservation of GDEs lags behind research and conservation efforts focused on ecosystems with substantial surface water input (e.g., streams; Mammola et al. 2019). Moreover, the majority of peer-reviewed GDE research focuses on hydrological and ecological characteristics (Eamus and Froend 2006, Kløve et al. 2011, Adams et al. 2015, Rohde et al. 2019), rather than their social value and characteristics. There are examples of studies on ecosystem services and the economic value of GDEs (Murray et al. 2006, Duarte et al. 2010, Tomlinson and Boulton 2010, CGIAR 2015, Burnett et al. 2017), but there have been far fewer studies focused on the social and cultural values of GDEs, particularly on how these values relate to GDE ecological structure and function (Boulton 2020). A recent review of the societal values of submarine groundwater discharge (SGD) highlights global examples of the social uses and values of SGD for drinking, hygiene, agriculture, fishing, culture, tourism, and navigation (Moosdorf and Oehler 2017). Through this review of primarily anecdotal evidence, the authors conclude that there is a need for dedicated research on human dimensions of SGD and the GDEs it supports: "because global change will strongly affect this water resource we should assess and understand that value, before the phenomenon will disappear at many locations due to terrestrial groundwater extraction or sea level increase" (Moosdorf and Oehler 2017:338). The need to better characterize the social values of GDEs (or the ways that these systems are important to people) also echoes broader calls to more thoroughly characterize the diverse values of ecosystems in decision making for more equitable and effective conservation outcomes (Pascua et al. 2017, Chan et al. 2020, Mandle et al. 2020).

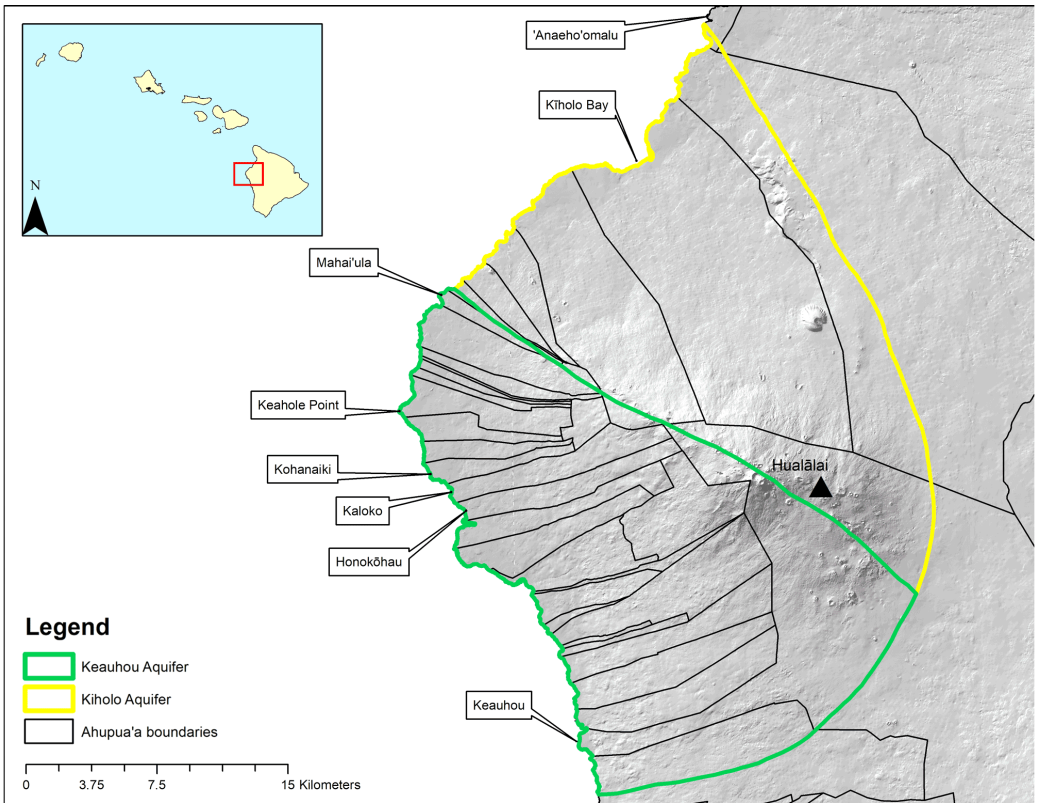
Concern for the protection of GDEs and their linked ecological and social value is particularly strong in the Pacific where GDEs are prominent and are important places of Indigenous knowledge and practice (Pukui 1949, Macpherson and Macpherson 1990, Adler and Ranney 2018, Mead 2018, Brosnan et al. 2019, Boulton 2020). In these contexts, many GDEs can be understood through the framework of social-ecological systems or integrated, complex systems that include humans as part of nature (Berkes and Folke 1998).

The region of Kona, on Hawai'i Island (Fig. 1), provides a model system to address the linked social and ecological values of GDEs as its unique hydrologic, geologic, and social conditions support a high diversity and abundance of culturally and ecologically valuable GDEs, including *loko i'a* (Indigenous aquaculture systems), *loko wai kai* (anchialine pools), and *muliwai* (estuarine systems that extend to nearshore fisheries; Brock and Kam 1997, Maly 1998, Maly and Maly 2003, Duarte et al. 2010, Yamamoto et al. 2015, Adler and Ranney 2018, Wada et al. 2020; see Figs. 2 and 3). Notably, 600 of the 700 known anchialine pools in the Hawaiian archipelago are found along the Kona coast (Yamamoto et al. 2015), and Hawai'i Island contains 80% of known anchialine pools worldwide (Christen et al. 2005). Historically, in part from a paucity of surface water features and low rainfall on this arid leeward coast, GDEs were a primary source of water and food for coastal communities in Kona, and these systems continue to have important cultural, social, and ecological value today (Adler and Ranney 2018, Maly and Maly 2003, Maly 2007). For example, *loko i'a* aquaculture systems have been described as important sites of food production (Kamakau 1976, Winter et al. 2020a), and there is widespread interest in the restoration of these and other systems through biocultural approaches, which focus on the mutually reinforcing restoration of ecology, cultural knowledge and practice (Kimmerer 2011, Kurashima et al. 2017, Sterling et al. 2017, Adler and Ranney 2018, Morishige et al. 2018, Kealiikanakaoleohaililani et al. 2020, Winter et al. 2020b).

Drawing from Indigenous management principles, the Hawai'i State Water Code is among the first to encode holistic water management into law (Sproat 2015). Specifically, the public trust doctrine described by the Hawai'i Supreme Court as, "the right of the people to have the waters protected for their use [which] demands adequate provision for traditional and customary Hawaiian rights, wildlife, maintenance of ecological balance and scenic beauty, and the preservation and enhancement of the waters" (HRS 174C-2), aims to protect the multiple ecological and social uses of water including as used in aquifers, springs, and streams. However, the implementation of the public trust doctrine has lagged behind, in part because the inclusion of ecological and social values of water remains insufficient (Sproat 2015). In this context, Kona has emerged as a hotspot for conflicts around GDEs, including a recent petition filed by the National Park Service to the Commission on Water Resources Management (CWRM) to designate the Keauhou aquifer as a Ground Water Management Area (GWMA), implicating greater regulation and permitting requirements in order to better protect water flow and quality, including the protection of ecologically and socially important GDEs in the area (U.S. National Park Service 2013).

Although the Keauhou petition was not successful in designating the aquifer as a GWMA, the petition helped to elevate the importance of GDEs to the public trust doctrine, and resulted in a directive for CWRM to work with local communities, Kaloko-Honokōhau National Historical Park, and researchers to improve understanding of the linked social and ecological uses and values of GDEs and how changes in water quality and quantity could affect these uses and values (Adler and Ranney 2018). This article responds to this need to improve understanding of the linked hydrological, ecological, and social values of GDEs and associated knowledge systems through a literature review and key-informant interviews with resource managers and lineal descendants (descendants of the original Indigenous tenants; Pascua et al. 2017). We focus on the following questions: (i) In what ways are GDEs used, valued, and cared for in Kona currently and historically?; (ii) What are the major perceived threats to these systems?; (iii) What are resource managers' and lineal descendents' visions for future use and management of these systems? In so doing, we document some of the importance of these systems for the people and ecology of Kona, providing an important case study of the linked social and ecological uses and values for GDEs for island and coastal communities that responds to broader calls for the recognition and elevation of Indigenous and local knowledge in natural resource management (Berkes et al. 2000, Kimmerer 2011, Winter et al. 2020b, Gadgil et al. 2021, Lander and Mallory 2021, Kamelamela et al. 2022).

Fig. 1. Study area in Kona Hawai'i, including the Kīholo and Keauhou aquifers, which together encompass the Hualālai aquifer, extending from the northern boundary of Anaeho'omalu *ahupua'a* (Indigenous political-ecological land division) to the southern boundary of Keauhou *ahupua'a*. This includes two distinct regions, the Kekaha wai 'Ole (land without water) region, which encompasses the *ahupua'a* from Pu'uanahulu to Keahuolū, where no surface rivers are found and where the highest number of anchialine pools in the world exist, and the Kona Kai 'Opua (refers to the billowing cloud formation which occurs over and is reflected in the calm sea) region which extends from the *ahupua'a* of Lanihau to Pu'u o Hau (found just south of Keauhou).



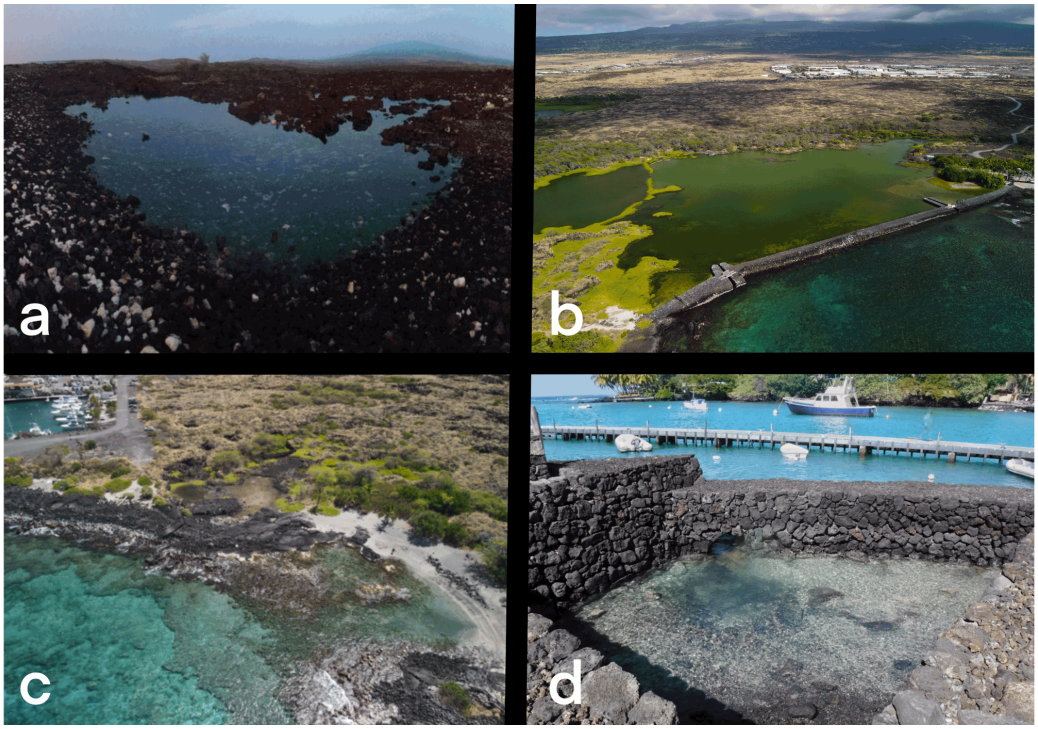
BACKGROUND

This study focuses on GDEs associated with the Keauhou and Kīholo aquifers on the leeward Kona coast of Hawai'i Island, the youngest emergent island of the Hawaiian archipelago (Fig. 1). The aquifers associated with these watersheds are highly permeable and are composed of young vesicular basaltic bedrock, lava tubes, clinker zones, and downslope flow between lava flow sheets (Peterson et al. 2009). The arid leeward coast receives 200–750 mm of annual rainfall (Giambelluca et al. 2013), and the majority of groundwater recharge within these aquifer systems occurs on mountain slopes, with virtually all freshwater fluxes from the land to sea occurring as SGD rather than surface flow (Peterson et al. 2009).

GDEs on this coast are central to Kona's history and culture as primary sources of water for drinking, bathing, agriculture, and spiritual practice, and described in many *mo'olelo* and historical accounts (see Table 1). Many *mo'olelo* and historical accounts, including those of GDEs, are documented in *nūpepa* (Hawaiian language newspapers), the world's largest Indigenous archive, printed from 1834 through 1948 (Kihe 1869-1870, 'Ī'ī 1923-1924, Institute of Hawaiian Language Research and Translation 2018). Within two prominent newspaper series translated by the University of Hawai'i at Mānoa Institute of Hawaiian Language Research and Translation, 19 of 38 article topics described Kona GDEs and their uses and values (detailed in Table 1; Kihe 1869-1870, 'Ī'ī 1923-1924). For example, two of these articles described the largest *loko i'a* (recorded in the *nūpepa* as 3 miles long and 1.5 miles wide), Pā'aiea, as the favorite *loko i'a* of Kamehameha I (Kihe 1869-1870), the first *ali'i* (member of the governing class) said to unite the eight main Hawaiian islands under his rule (Stokes 1932), and founder of the Hawaiian Kingdom in 1810 (Beamer and Duarte 2009). The articles describe a *mo'olelo* associated with the destruction of Pā'aiea *loko i'a* by the Hu'ehu'e lava flow of 1800, and how this lava flow was attributed to the wrath of Pele (*akua* of volcanoes), who was denied a share of fish by Kamehameha's *konohiki* (resource manager; see below for expanded translation; Kihe 1869-1870, Fujii et al. 1995). Two of these articles reference the *mo'olelo*, "the breadfruit roasting girls," which describes the source of this lava flow that destroyed Pā'aiea and how those who heeded Pele's requests for fish and other offerings were spared (Kihe 1869-1870, Fujii et al. 1995; Table 1).

Though impacted by colonization and associated economic and political changes that occurred since 1778, the social uses and

Fig. 2. (a) A *loko wai kai* (brackish anchialine pool) on the Kona coast. *Loko wai kai* are brackish water bodies fed by groundwater discharge and tidally driven marine water inundation. These pools have no surface connection to the ocean. Notable anchialine pool species include the anchialine pool shrimp called *ʻōpaeʻula* (*Halocaridina rubra*), and an endemic damselfly (*Megalagrion xanthomelas*). (b): Kaloko Loko iʻa (Indigenous Hawaiian aquaculture system) at Kaloko *ahupuaʻa* within Kaloko Honōkohau National Historical Park. Taking advantage of natural springs and spawning cycles, a sluice gate is used to allow smaller fish to enter while keeping larger fish contained for easy harvesting. Loko iʻa aquaculture predominantly cultured fish including *ʻamaʻama* (*Mugil cephalus*), *āholehole* (*Kuhlia sandvicensis*), and *awa* (*Chanos chanos*), though many other species were cultivated. (c): *Muliwai*, brackish water occurs in the nearshore submarine groundwater discharge (SGD) influenced reef at Alula Bay in the *ahupuaʻa* of Kealakehe. SGD seeps from the basal lens are fresh to brackish water, often high in nutrients and lower in temperature and salinity than the surrounding coastal water. These seeps play a key role in nearshore reef dynamics. Some anchialine pools are seen inland of the bay. (d) Kuhalalua spring, birthplace of Kauikeaouli, Kamehameha III, born 11 August 1813, though he chose to celebrate his birthday as 17 March 1814. An important historical groundwater dependent ecosystems (GDEs) that demonstrates ties between GDEs and the history of Hawaiʻi. Photos b and c by Duke Malczon, photo d by Rebecca Miller.



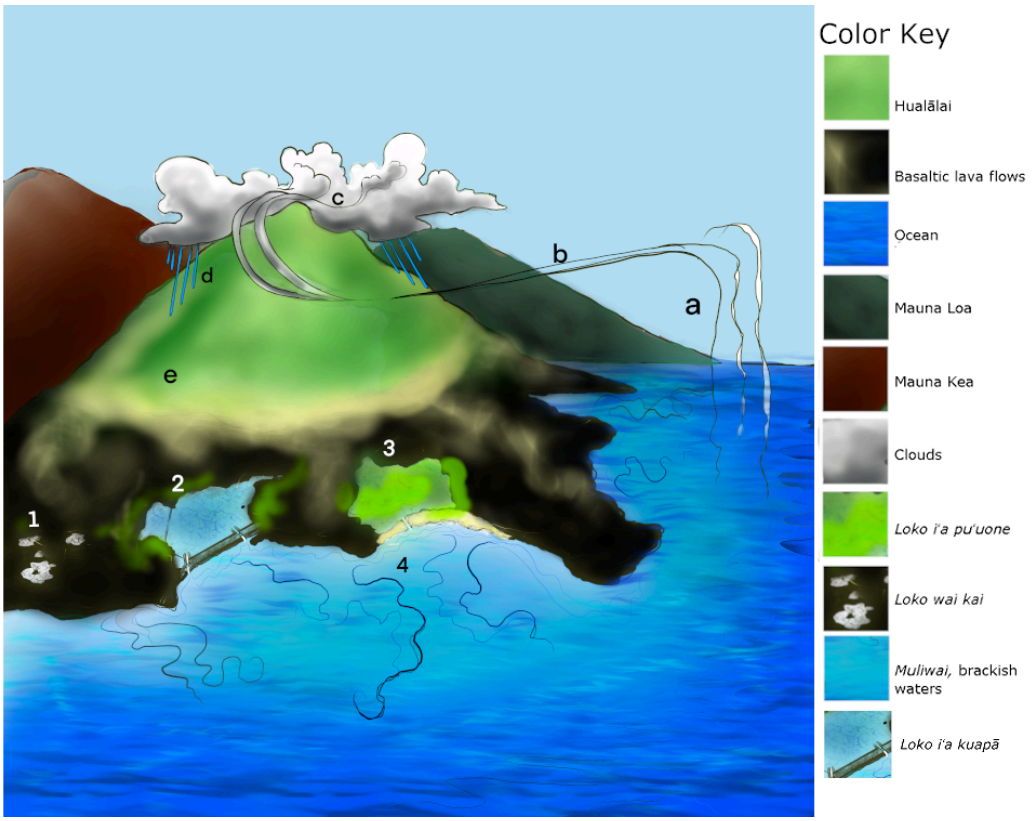
values associated with GDEs and other Kānaka ʻŌiwi social-ecological systems remain important today (Abbott 1992, Fujii et al. 1995, Osorio 2002, 2010, Howes and Osorio 2010, Winter et al. 2020a). This includes deeply held Kānaka ʻŌiwi values including *pono* (righteousness, balance), *hoʻomana* (creating, spirituality), *mālama* (to care for), *kuleana* (honored responsibility), and *aloha* (love), which have recently been discussed in the context of relational values (Gould et. al 2019) or the "preferences, principles, and virtues associated with relationships" (Chan et al. 2016:1462). Relatedly, GDEs continue to provide high social value in the sense of continued importance to people for their contribution to individual and community well-being (Gould et al. 2020).

In line with the continued social and ecological importance of GDEs, there has also been a resurgence in GDE stewardship, particularly since the 1970s, including the publication of the "Spirit of Kaloko Honōkohau," a study submitted to the U.S. Congress in 1974 as part of a petition to designate Kaloko Honōkohau as a National Historical Park (Honokōhau Study Advisory Commission 1974). Since the time when Kaloko Honōkohau was designated, community-led efforts worked to restore social-ecological systems along the coast, providing important social and ecological benefits (e.g., Public Access Shoreline v. City Planning Commission 1995, U.S. National Park Service 2009; "Hui Aloha Kīholo" 2020, https://www.huialohakiholo.org; KUA Hawaii 2016, http://kuahawaii.org/kaʻupulehu-try-wait-faqs/; see Appendix 1.1.3 for further discussion of GDE political history). We describe three types of coastal GDEs in Kona, recognizing that there are other types of GDEs that are important and that these categories are overlapping rather than discrete (see Appendix 1 for additional description on GDEs).

Anchialine pools, *loko wai kai*

Globally, anchialine pools are widely distributed among porous substrates adjacent to the ocean, occurring wherever the underlying water table emerges through to expose fresh or

Fig. 3. Island hydrogeology and groundwater dependent ecosystems (GDEs) represent a continuum of water flow from (a) evaporation over the ocean, (b) movement of moist air inland, (c) cloud formation, and (d) orographic rainfall, through (e) geological formations to create a subterranean gradient of fresh, brackish, and saline water, which flows into diverse types of GDEs (1. *loko wai kai*, 2. *Loko iʻa kuapā*, 3. *Loko iʻa puʻu one*), and then move as submarine groundwater discharge (SGD) to the ultimate receiving waters in nearshore settings to create (4) *muliwai*, estuarine conditions of mixing fresh to brackish submarine groundwater discharge and receiving saline ocean water. Inspired by a figure from Wyban 1992.



brackish groundwater at the surface (Brock and Kam 1997, Weijerman et al. 2014, Yamamoto et al. 2015, Seidel et al. 2016). Anchialine pools have diverse ecological characteristics that vary substantially across pools, including salinity, temperature, light intensity, tidal mixing, and geologic structure; these characteristics can vary across gradients from high to low elevation, and from surface to subsurface pools, which can extend deep into underground cave systems (Brock and Kam 1997, Marrack 2014, Seidel et al. 2016). Tidal inundation and evaporation in coastal pools can result in salinities above usual seawater salinities of 33 parts per thousand (ppt), whereas inland pools can have salinities as low as 3 ppt (Seidel et al. 2016). Recognizing the hydrologic and biological diversity of these ecosystems, there are a variety of Hawaiian names reflecting distinct social uses and values, including: *loko wai kai* (mixing fresh and saltwater pond), *wai ʻōpae* (waters containing *ʻōpae* shrimp), *loko wai* (freshwater pond), *ana wai* (water cave), *hāpuna* (source water, spring, or pool), *kiʻo wai* (pool of water), *kumu wai* (source or spring water), *luawai* (well), *māpuna* (spring water), *kāheka* (tide pools with groundwater influence), and *wai puna* (spring water; Pukui and Elbert 1986, Maly 1998, Maly and Maly 2003).

Anchialine pools are used and valued within Hawaiian social-ecological systems for drinking, bathing, agriculture, refrigeration, spirituality, and healing, as well as for their unique ecology for aquaculture, collecting, and fishing (Brock and Kam 1997, Maly and Maly 2003, Adler and Ranney 2018). The Kekaha Wai ʻOle region (Fig. 1) is particularly noted for high numbers of *wai ʻōpae*, pools where *ʻōpae ʻula* (Hawaiian anchialine pool shrimp, *Halocaridina rubra*) were widely collected for use in offshore *ʻōpelu* (*Decapturus* spp.) fishing (Maly 1998, Maly and Maly 2003), as well as for deep sea fishing for *aku* (*Katsuwonus pelamis*) and *ʻahi* (*Thunnus albacares*; Maly 1998). A prominent Kanaka ʻŌiwi contributor to the Hawaiian language *nūpepa* from 1928 to 1930, John Kaʻelemakule Sr., lineal descendant of Kekaha Wai ʻOle, noted that in his lifetime, there was an industry in which dried *ʻōpelu* was shipped from Kona's fisheries to be sold in Honolulu (Maly 1998), pointing also to the market value of anchialine pools during this period. Although *wai ʻōpae* is an important name for most of the pools in Kona, in which the *ʻōpae ʻula* are found, not all pools naturally contain *ʻōpae* (shrimp). For this reason we use *loko wai kai* to refer broadly to anchialine pools, which John Kaʻelemakule Sr. used to describe the mixed fresh and saltwater within the land and the pools of the Kekaha Wai ʻOle

Table 1. Groundwater dependent ecosystems (GDEs) uses and values from two Hawaiian *nupepā* (newspaper) series: Na Hoonanea o ka Manawa by Isaac W. H. Kihe, and Na Hunahuna No Ka Moolelo Hawaii by John Papa ʻĪʻi, were translated by the University of Hawaiʻi Institute of Hawaiian Language Research and Translation (ʻĪʻī 1923–1924, Kihe 1869–1870, Institute of Hawaiian Language Research and Technology 2018). Nine of the total 38 articles in the two Hawaiian *nupepā* series describe *loko wai kai* (anchialine pools), five describe *muliwai* (nearshore brackish-marine ecosystems), and five describe *loko iʻa* (Indigenous aquaculture systems). Select translations from this series and detailed translation methodology can be found at, http://ikewai.org/hawaiian-language-translation-methodology/.

Title of Article	Location/Ahupuaʻa	GDE	Uses and values
Keāhole Point	Keāhole point (to Upolu)	Nearshore	Fishing
The Spring of Wāwāloli	Oʻoma and Kalaloa	Anchialine pool	Bathing; drinking; fishing; romance
The Cave of Laʻina	Kaloko	Anchialine pool	*Kapa* (fabric) making
Puʻuokaloa	Kealakehe and Keaholū	Water basins	Agriculture; drought resilience
The Water of Kahinihiniʻula	Kaloko and Honokōhau	Anchialine pool	Bathing; ancestral connections
Keʻelehuluhulu	Mahaiʻula; Kaʻelehuluhulu	Anchialine pool	Navigation
The Water of Kāne	Kaʻūpūlehu	Coastal spring	Drinking; spiritual
Luahine Wai	Kīholo, Laemanō	Anchialine pool	Sacred water; ritual; bathing for *aliʻi*; beauty
The Pond of Kīholo	Kīholo	Fish pond	Ancestral connections; education
The Pond of Wainanaliʻi	Puʻuanahulu	Fish pond	Fishing
The Three Waters	Puʻuanahulu	Fish pond	Fishing; *ʻōpae* (for fishing); birthing
The Other Celebrated Places of Puʻuanahulu	Puʻuanahulu	Spring	Drinking; drought resilience
The Pond of Paʻaiea	Mahaiʻula, Wāwāloli, ʻOʻoma	Pond	*ʻAku* (*Katsuwonus pelamis*) harvesting, memorials
A Cave Called Mākālei	Makalawena, Kūkiʻo	Cave pool	Drinking during drought; ice water
A Story About Nanaikahaluʻu	Kalaloa	Cave pool	Drinking
Leaving Lahaina	Keōpū, Lanihau	Spring	Bathing; landmark; navigation
Much Famine in Kailua	Keōpū	Spring	Bathing; landmark; navigation
Fortifying the King's Residence at Kamakahonu	Lanihau	Spring	Bathing for *aliʻi*; landmark; navigation
Resuming the Previous Discussion	Lanihau	Pond	Bathing; landmark; navigation

region. See Appendix 1.1.1 for further discussion of anchialine pool biology.

Nearshore brackish-marine ecosystems, *muliwai*

Nearshore marine waters are inundated with fresh to brackish groundwater where SGD springs release diurnal fresh pulses to nearshore reefs, creating intermittent estuarine, or *muliwai*, conditions (Duarte et al. 2006, Johnson et al. 2008, Kaleris 2006, Knee et al. 2010, Peterson et al. 2009). Pulses of SGD create *muliwai* waters that are cooler, and more nutrient-rich than nearshore waters without SGD-influence (Kaleris 2006, Johnson et al. 2008, Knee et al. 2010, Beusen et al. 2013). *Muliwai* in Kona extends from within the subterranean estuary, where mixing, biological transformation, and GDE species like *ʻōpae ʻula* range from within the aquifer itself, to estuarine tide pool systems, and nearshore reef ecosystems fed by SGD. *Muliwai* is populated by species that are physiologically able to thrive under conditions of sedimentation and oscillating estuarine and marine salinity (Christen et al. 2005, Taniguchi et al. 2017; Appendix 1, Table 1).

Nearshore *muliwai*-dependent and opportunistic *muliwai* inhabitants include invertebrates such as *wana* (urchins), *ʻōpae* (shrimps), *pūpū* (snails), and *limu* (edible macroalgae), which provide important minerals and variety for local diets (Titcomb et al. 1978, Abbott 1984, 1992). *Limu* and invertebrates also have high spiritual and cultural value for ceremonies, making tools and implements, costumes and instruments for *hula* (dance), and for *lāʻau lapaʻau* (Hawaiian herbal medicine; Titcomb et al. 1978, Abbott 1984, 1992). Some *muliwai*-associated edible and medicinal *limu* are *limu pālahalaha* (*Ulva lactuca*), *limu ʻeleʻele* (*Ulva prolifera*), limu manauea (*Gracilaria coronopifolia*), and *ogo* (locally adopted Japanese term for *Gracilaria parvispora*; Abbott 1947, 1992, Glenn et al. 1999, Amato et al. 2016). Some edible fish associated with *muliwai* are: *ōʻio* (*Albula virgata* and *Albula glossodonta*), *moi* (*Polydactylus sexfilis*), *awa* (*Chanos chanos*), *weke* (*Mulloidichthys* spp.), *āholehole* (*Kuhlia sandvicensis* and *Kuhlia xenura*), *pāpio* (young *Caranx ignobilis* and *C. melampygus*), *ʻamaʻama* (*Mugil cephalus*), and *awaʻaua* (*Elops hawaiensis*; Keala 2007). Spiritual practices associated with nearshore reefs include placing offerings at *kūʻula* (fishing shrines) and *koʻa* (fishing markers where wild fish are fed and cultivated; Maly and Maly 2003). See Appendix 1.1.2 for further discussion of *muliwai* biology.

Indigenous aquaculture systems: *loko iʻa*

Kānaka ʻŌiwi aquaculture practices include harvesting from and management of existing anchialine pools, but also aquaculture systems that are engineered by enclosing nearshore *muliwai* or otherwise modifying and stocking natural embayments and brackish pools with desirable species (Kikuchi 1976, Abbott 1992). A 1901 inventory for the Hawaiian archipelago recorded 360 existing *loko iʻa*, 99 of which were active and producing an estimated 486,000 lbs of *ʻamaʻama* and 194,000 lbs of *awa* annually (Cobb 1905). *Loko iʻa* conditions of shallow (less than six feet deep) embayments create areas of still water and ample sunlight, which cultivate "pastures" of microbenthos for grazing by herbivorous fish, primarily *ʻamaʻama* (mullet) and *awa* (milkfish; Abbott 1947; Appendix 1.1.3). *Loko iʻa* are also important sites of *limu* collection (Abbott 1992). By enclosing natural springs with rock walls, or by physically altering,

managing, and stocking naturally occurring anchialine pools with desirable species (Kikuchi 1976, Maly 2003), *loko iʻa* historically contributed food supplies that supported the existence of the *koa* (warrior class), which functioned as an army for the *aliʻi* (governing class), and contributed to substantial food production systems that sustained high human populations in pre-European-contact Hawaiʻi (Kurashima et al. 2019).

Loko iʻa are described by Winter et al. (2020a) as an important example of trophic engineering, a type of "ecomimicry" in Kānaka ʻŌiwi social-ecological systems designed to use and expand natural processes such as transitional zones of groundwater and seawater to maximize food production and ecosystem services. Functioning *loko iʻa* increase sediment and nutrient retention, which, while undoubtedly altering natural flow patterns, provides important ecosystem services to nearshore reefs by reducing sediment and nutrient loads from upstream agricultural and residential development (Winter et al. 2020a, Wyban 2020).

*Loko iʻa kuap*ā, the walled aquaculture systems, are special places for *aliʻi*, in that historically the *aliʻi* were able to produce fish for the royal court and their warriors (Maly and Maly 2003). *Loko iʻa* are important spiritual places where offerings to *akua* (deities) are made and *iwi* (cherished remains) are placed (Maly and Maly 2003). Additional guardian *moʻo* (water spirits) are believed to protect *loko iʻa* from pollution and overharvesting (Kikuchi 1976). *Konohiki* (resource managers) also acted as guardians who managed not only *loko iʻa*, but all *ahupuaʻa* (political-ecological land divisions) resources, including through implementation of *kapu* (laws holding spiritual repercussions; Maly 1998). In addition to the common translation of *konohiki* as resource manager, the term has also been interpreted as *kono* (ability) and *hiki* (to invite), meaning that the *konohiki* invited sustainable resource abundance (Andrade 2008). See Appendix 1.1.3 for further discussion of *loko iʻa* biology, and Appendix 1 1.2 for a discussion of invasive species impacts.

Many social, economic, and political factors led to continued declines in *loko iʻa* production and maintenance through the 20th century, including shifting economic conditions with colonization and the illegal overthrow of the Hawaiian Kingdom in 1893, disease and population decline, privatization and development of coastal areas, and lack of management leading to overgrowth by invasive mangrove and other plant species and sediment accumulation (Wyban 2020). Today restoration of *loko iʻa* is prominent throughout Hawaiʻi with over 40 *loko iʻa* and 100 *loko iʻa* owners represented in the Hui Mālama Loko Iʻa network, a network of fishpond practitioners founded in 2004 and founded by the nonprofit KUA, Kuaʻāina Ulu ʻAuamo (http://kuahawaii.org/huimalamalokoia/; Wyban 2020).

METHODS

To deepen understanding of GDE uses, values, and management strategies and challenges from the perspective of those connected to these systems today, we conducted 19 key informant interviews with GDE resource managers and lineal descendants with genealogical and ancestral connections to the GDE locations. Of our 19 interviewees, 16 are in formal GDE resource management positions within the study region, and 10 identified as Kānaka ʻŌiwi, including six lineal descendants of the Kona region (see Table 2 for description of interviewees). Three of the interviewees were both resource managers and lineal descendants of the Kona region. Of the nine interviewees who did not identify as Kānaka ʻŌiwi, all had been employed in Kona for over five years, and five for over 10 years. Where interviewees are not identified in results as lineal descendents or Kanaka ʻŌiwi, the interviewee did not self-identify as either.

Initial interviewees were met through the first two authors' attendance of the Adaptive Management Symposium on Ground Water Dependent Ecosystems at Kaloko-Honokōhau National Historic Park (Adler and Ranney 2018). We then identified other interviewees through snowball sampling (Creswell and Creswell 2018) and personal and professional connections in Kona. We did not speak with all resource managers in the region, nor did we speak with all knowledgeable lineal descendants; we instead focused on representation from *ahupuaʻa* throughout the region (Fig. 1). Semi-structured interviews focused on the historical and current uses and values of GDEs, current management strategies and perceived challenges, as well as desired futures (see Appendix 4 for interview questions).

In the context of this study, we use the term values to refer to the ways that GDEs are perceived as important and/or as providing (often reciprocal) benefits for individuals and communities, including how GDEs support appropriate human-environment relationships (Tadaki et al. 2017). In the results section we report the number of interviewees who brought up the importance of various uses and values, but these are not meant to suggest that those that did not explicitly bring them up did not find them important. Interviews were conducted at GDE sites relevant to each interviewee, which helped to facilitate conversations and understanding. The first author and primary interviewer of this study is not Kānaka ʻŌiwi, but was raised in Kona, and participated in GDE workdays and cultural events throughout her life. The fourth author is a lineal and cultural descendant of Kona, and the other authors are interdisciplinary researchers focused on the ecological and social dimensions of social-ecological systems in Hawaiʻi.

Following University of Hawaiʻi Human Subjects Review protocol, interviews were kept anonymous by only identifying quotes and information by location with permission from interviewees. Interviews were recorded, transcribed, and analyzed by major themes of this study: uses and values, management strategies and challenges, threats to GDEs, and visions for the future. Because many of the uses and values discussed were cultural or biocultural values, we used a Hawaiʻi-based cultural ecosystem service framework to categorize responses in this category (Pascua et al. 2017). This framework was developed with several communities in Hawaiʻi, including a community in Kona, and has been applied to several contexts including land use planning in Kona (Bremer et al. 2018a) and the cultural value of Indigenous agriculture in Heʻeia, Oʻahu (Bremer et al. 2018b). However, Pascua et al. (2017) emphasizes that the categories are overlapping and not meant to be prescriptive or comprehensive, but adapted to various contexts. The four main categories in the framework are: *ʻike* (knowledge); *pilina kānaka* (social connections); *mana* (spirituality); and *ola mau* (physical and mental well-being).

We engaged in an iterative research process where transcripts and the manuscript were returned to interviewees for comments and

Table 2. List of interviewees including lineal descendents of Kona families and resource managers. Institutional review board protocol for this study prevents us from releasing the names of our interviewees in this study. Some interviewees preferred for their positions and associated *ahupuaʻa* to remain anonymous; others preferred to be identified. Six interviewees were lineal descendents, three of those were also resource managers. In total 16 were resource managers. In addition to the three lineal descendant resource managers, four resource managers were Kānaka ʻOiwi but did not identify as lineal descendents of Kona.

	Interviewee, time in resource management (if known)	Organization(s)	*Ahupuaʻa*
1	Lineal descendant	Kaʻūpūlehu marine advisory council	Kūkiʻo; Kaʻūpūlehu; Kīholo; Puʻuwaʻwaʻa
2	Lineal Descendant	Anonymous	Kealakehe; Kāloko; Honōkohau; Kukiʻo
3	Lineal descendant; cultural practitioner	West Hawaiʻi Civic Center	Mahaiula; Makalawena; Keahuolū
4	Lineal descendant and resource manager, 52 years	Kohanaiki	Kohanaiki; Oʻoma; Kaloko; Hōnokohau
5	Lineal descendant and resource manager, 16 years	The Kohala center	Kahaluʻu; Keauhou
6	Lineal descendant and resource manager, 16 years	Anonymous	Broad Kona
7	Resource manager, 5 years	Kaloko Honōkohau National Historical Park	Kaloko; Hōnokohau
8	Resource manager, 4 years	Hawaii State Parks	Mahaiʻula; Kaulana; Holualoa
9	Resource manager, 13 years	The Nature Conservancy	Kīholo
10	Kanaka ʻŌiwi Resource Manager, 18 years	Anonymous	Anonymous
11	Resource Manager, 16 years	Anonymous	Anonymous
12	Kanaka ʻŌiwi Resource manager, lifetime Kona resident	Kohanaiki	Kohanaiki; Oʻoma
13	Kanaka ʻŌiwi Resource Manager, 38 years	Anonymous	Keahuolū
14	Kanaka ʻŌiwi Resource Manager, 8 years, lifetime Kona resident	Anonymous	Keahuolū
15	Hydrologist, 24 years	Kona Coast Waterkeepers Alliance; Former Chair County of Hawaii Environmental Management Commission	Broad Kona; Kahaluʻu
16	Resource manager, 13 years	Anonymous	Kīholo
17	Resource manager, 20 years	Anonymous	Broad Kona
18	Resource Manager, 16 years	The Natural Energy Laboratory of Hawaii Authority	Oʻoma I & II
19	Resource Manager, 6 years	The Natural Energy Laboratory of Hawaii Authority	Oʻoma I & II

clarification. We also presented the work at several local events including the Hawaiʻi Conservation Conference and Hanauma Bay speakers series, always asking for permission and input before and after presentations. We circulated the manuscript to interviewees throughout the editing process, and iterated upon comments and revisions from each interviewee over email or phone.

RESULTS

Uses and values of GDEs in Kona

> *I think about the anchialine pools and the significance of the anchialine pools and how, if you have anchialine pools in your ahupuaʻa, especially in a place like North Kona, Kekaha Wai ʻOle,… you're considered very wealthy.*
> - Kanaka ʻŌiwi resource manager (see Table 3.4.1 for expanded quote)

All interviewees emphasized the historical importance of GDEs as important water and food sources and as central to Kona politics and culture. The continued high social and cultural value of these systems is, in part, related to their storied history, as many GDEs feature prominently in *moʻolelo* and other accounts (Table 1). Interviewees pointed to the historical importance of anchialine pools and springs as a source of drinking water as a defining characteristic of Kona. Although anchialine pools and groundwater springs are not used as primary drinking water sources today, recognition of the historical importance of the pools and springs supports connection to *kūpuna* (ancestors) and to ancestral knowledge and practice. Given the high social and cultural value of these systems and recognition of their historical importance, restoration activities are primarily carried out through a biocultural approach (Kimmerer 2011, Morishige et al. 2018). Though not the most prominent of values discussed, interviewees also pointed to the financial value of GDEs as increasing property value and appeal of resorts through both aesthetics and by providing a "license to operate" through GDE preservation agreements with local communities.

The *ʻōpae ʻula* (the Hawaiian anchialine pool shrimp) helps to illustrate the biocultural importance of GDEs as well as the connections between their historical and current uses and values in biocultural restoration (Fig. 4). *ʻŌpae ʻula* are considered an important biocultural indicator of healthy anchialine pools, as stated by one Kanaka ʻŌiwi resource manager, "Anchialine pools have a lot of different purposes and one of the major purposes is to supply, to be home for *ʻōpae ʻula*... So once we see an abundance of *ʻōpae ʻula* come back, that's when we can begin thinking of the reinstatement of practices again." Interviewees explained that *ʻōpae ʻula* are desirable because they help maintain ecological balance by grazing algae and detritus, stirring up settled sediment, and increasing water flow from springs. Interviewees also

Table 3. Examples of groundwater dependent ecosystem (GDE) values associated with cultural ecosystem services categories, and examples of relevant quotes from interviews. The GDE values from interviews are coded with the Pascua et al. (2017) cultural ecosystem services framework. See Appendix 1 for additional quotes. Format adapted from Bremer et al. (2018b).

3.1 *ʻIke*: Knowledge	
3.1.1. *Ma ka hana ka ʻike*: Learn place based practices by actually doing them (Interviews mentioned: 13)	
Opportunities to engage in *loko iʻa* restoration and management; fishing practices; learning about *ʻōpelu* fishing practice associated with anchialine pools; learning *makaloa* weaving and associated history; participating in and learning about ecological restoration and management practices; practice of place-based *ʻoli* (chants) and *hula* (dance)	"By learning more they [volunteers and educational participants] are connected to it, because they keep coming back, you know they really want to keep contributing and they believe in the project, they believe in the vision of what this place is transforming into. People really want a place where they can be active in contributing to something and I think this is the perfect site for that."
3.1.2. *Nānā i ke kumu*: Observe familiar natural processes and seasonal occurrences (Interviews mentioned: 13)	
Observation of GDE biota; observation of spring flow and water quality; seasonal observations; recognition of connectivity between GDEs and other parts of the *ahupuaʻa*; observing connections across the hydraulic system (rain, evaporation, spring flow); observing and recognizing *ʻōpae ʻula* biology and ecology	"The *ʻaina* [land] has created that opportunity, and to be privileged to be there and to witness these things happen is so magical ... the importance of the water, you know the fresh water that comes out, like we spoke earlier about this pond area right here, is a good example, you know it's a nursery area. You look in there there's all the *pua* [juvenile fish and other organisms], you know, all the babies that grow up in a really safe environment over there. You know, the coolness, you're walking around and you can feel the freshwater on your feet, the cold sand coming up but it creates an environment that the *pua* feel safe. And this has been going on for generations. Who knows how long it's been going on. When we look at our home and that's why when you find the *pua* in places like this you know it's a safe place for kids, it's protected from whatever that may be threatening. So it's important for this, for our kids, our other *ʻohana*, the ocean dwellers, the fresh water that's coming out in different areas, I don't know if we did any studies, but if you just look at what's there it kind of tells me something."
3.1.3 *Hālau ʻike*: Diverse formal and informal learning (Interviews mentioned: 15)	
Living classroom for *ʻāina*-based, cultural, historical, and scientific learning; community workday education; learning of moʻolelo and history; knowledge sharing through Hui Mālama Loko iʻa network; learning family histories; shared knowledge of place names and events	"It's also the cultural programs, it's also providing time and space for the families to share their knowledge. It's time for community. We host a lot of school groups so every month we have about 3 to 5 school groups come here for field trips where we're hosting kids and we have a curriculum that we teach them place based outdoor education activities. So all of that combined I really think there's this beautiful, it's like a space where all of those things can happen."
3.2. *Mana*: Spiritual landscapes	
3.2.1 *Hoʻomana/Mauli Ola*: Spiritual beliefs and practices that allow people to interact with the mana of the landscape (Interviews mentioned: 6)	
Physical, mental, and cultural connections with GDEs; GDE knowledge and practices contribute to cultural identity; increased awareness of sacred sites; fulfilling a sense of *kuleana* (responsibility); connecting to ancestors through shared practice and place	"So, to be in that space at that time with an individual or a group is really special to see, you know? And you watch them. It's just like magic that happens, you look at them and some of the kids, they can be *kolohe* [mischievous] as *kolohe* can be, they doing like that, but yet they reflect that they enjoyed that time over there doing these things. So, I don't know how you put that down but it's, you're looking at like 38 years of memories of blessings that come, that the *ʻaina* has created that opportunity, and to be privileged to be there and to witness these things happen is so magical."
3.2.2. *Wahi Pana*: Existence of and access to storied landscapes and associated place-based practices (Interviews mentioned: 11)	
Recognition of *one hānau* (birth sites) and *iwi* (treasured remains) associated with GDEs; Learning names of storied landscapes and meanings of place and GDE process names; Opportunities to access and engage in cultural practice with GDEs	"There's three translations of Kīholo, the last one being the one that's tied to fresh water. One translation for Kīholo is a fish hook and it was a fish hook that was huge, it was about 2 feet long by a foot and a half wide and it was made of wood and then it had a bone tip. So a fish hook that large would catch sharks so Kīholo is a fish hook to catch sharks and there's a lot of legends, a lot of moʻolelo about mano here. The point on the south end is Ka Lae Mano so shark action is definitely something present here. The second translation of Kīholo was a huge net that they would use to corral the fish in from the outer bay and they would use canoes. The net was about 125 feet long and they would bring the fish into the shallows for harvest. And the third translation of Kīholo, *holo* means flowing water and *kī* is an emphasizer, like a lot. Much. So Kīholo means a lot of flowing water. "
3.2.3. *Hōʻailona*: Presence of environmental signs/indicators and the ability to recognize them (Interviews mentioned: 14)	
Recognition of GDE associated organisms; recognition of indicator organisms; management of GDEs based on environmental indicators	"Anchialine pools have a lot of different purposes and one of the major purposes is to supply, to be home for *ʻōpae ʻula*, and not all of our ponds have *ʻōpae ʻula* right now. So once we see an abundance of *ʻōpae ʻula* come back that's when we can begin thinking of the practice, the reinstatement of practices again. There's other species too that are in there that are indicators, but what it really comes down to is the *ʻōpae*. When the *ʻōpae* are happy, we're happy. The *ʻōpae* are happy if they're in the pools."
3.2.4. *I ka ʻōlelo nō ke ola, i ka ʻōlelo nō ka make*: Presence of place-based Hawaiian terms/names describing the environment (Interviews mentioned: 10)	
Presence of GDE specific names; learning GDE specific terms and practices	"We have one [pond] that is unique to this place, and that is the *loko ʻauʻau*. When we used to go down [to that place] my mother needed a private place to bathe, so my father built it for her. That is one thing I never heard of anywhere else, is the name *loko ʻauʻau* [bathing ponds]."

(con'd)

3.3. *Pilina Kānaka*: Social Interactions	
3.3.1 *Hoʻolako*: Perpetuation of practices/skills that allow individuals to provide for their families (Interviews mentioned: 16)	
Producing food and other products through fishing, *loko iʻa* aquaculture, limu gathering, *ʻōpelu* fishing; gathering of resources; taking part in resource management; perpetuating cultural practices	"In terms of feeding people from within the pond we harvest, we have some invertebrates that we also harvest like Samoan crabs. Out on the reef, I mean Kīholo was a fishing village and it continues to be a source of food for the community. So, all of the families of Kīholo are fishermen so we go out on the reefs and we fish and we eat it and it's delicious. People come to Kīholo to fish."
3.3.2. *ʻIke aku, ʻike mai*: Opportunities to share traditional/local values and knowledge (Interviews mentioned: 12)	
Youth education; tourism; employee education at resort properties; resident and resident guest education; walking tours; intergenerational learning	"If we can continue to educate the kids, the ponds will be there, the necessity of it, it's a matter of keeping interest of the children now who are going to be the future caretakers in future generations and it's a matter of just getting a few of them interested in it, knowing the need, the purpose and the value of these areas. For them to have just a want to take care of it and a want to have it for their future generations. I believe and I hope that it will continue for generations to come."
3.3.3. *Kōkua aku, kōkua mai*: Presence of strong social ties/social networks (Interviews mentioned: 14)	
Networking of GDE managers through Hui Mālama Loko Iʻa-network; community building through community workdays; common challenges and values amongst GDE communities; expanding social networks; shared work; community bonding; therapy; exchange of goods and work; connections to other social networks; *lawaiʻa* (fishing) camps bring children and practitioners together	"So I think that is the community aspect. There were a lot of people here today that have been coming every month for years and years and years. And that's kind of amazing to me that people will give their Saturday and keep coming back. You know, it's not easy work, but they really love this place and to me that's a sign of success and it's positive that people feel invested in this."
3.4. *Ola Mau*: Physical and Mental Well-being	
3.4.1 *Lako*/*Momona*: Availability and access to subsistence resources rich enough for people to thrive (Interviews mentioned: 8)	
Access to resources including; fish, limu, invertebrates, fresh water, unobstructed hydrogeologic dynamics, cloud formation, and precipitation	"I think about the anchialine pools and the significance of the anchialine pools and how, if you have anchialine pools in your *ahupuaʻa*, especially in a place like North Kona, Kekaha Wai ʻOle, you're considered very wealthy, because you have access to water, you have access to a refrigerator, and you have the source for your *ʻōpelu* fishing. *ʻŌpelu*, the source for the people in this region."
3.4.2. *Hoʻoikaika kino*: Opportunities for an active lifestyle to support the physical demands of specialized practices (Interviews mentioned: 8)	
Opportunities to build strength, dexterity, and ability through physical work; benefits of being outdoors while doing work for self and family; appreciation and patience for work and results	"What I see is a lot of the kids and groups that have been here, some of the ways that she embraces them and how she nurtures them and how she helps them grow. So, when you take care of her like the anchialine ponds, you know, and the *wai* [water] that comes up in there [the bay] and you look at how it's going there, how they grow. It gives them an opportunity in a non-threatening, non-judgmental space to be who they are. So they go in there and it then allows them to drop some of the barriers, the fences that they create in their lives because of some of the trauma that they experience. And to be vulnerable in a space like that and to be able to give and when they are able to give and contribute that is when they are more open to receive. And that's when that feeling happens."
3.4.3 *ʻOihana*: Opportunities for engaging in family roles and occupations (Interviews mentioned: 11)	
Occupations as: resource managers, cultural practitioners, cultural advisors; roles within *loko iʻa* production and management, science, environmental monitoring, education, cultural practice; lessons gained through working with GDEs applied to other occupations	"And I think what it also does is when they begin to understand it more they begin to realize that whether you use it in your job or just your personal life, when you begin to do things that are *pono* in different environments because you understand that it also nurtures you. It spiritually nurtures you because you begin to understand this, everything and the interconnectedness and stuff. You know, everything. Just in their own personal lives I think that it will help heal some of the past and cultural stuff that has happened in the past."
3.4.4. *Moʻokūʻauhau*/*Noho Papa*: Opportunities for multigenerational presence on and interaction with lands that foster security and sense of place (Interviews mentioned: 14)	
GDEs act as a physical and mental sanctuary; therapy through physical work; pride; accomplishment; purpose; connection with *ʻohana* (family); *mālama* (to care for); *kuleana* (responsibility); programs for youth; lineal descendant involvement, community workdays, cultural events	"I'm going to be sharing the importance of place [with children GDE education participants], the importance of knowing your history, the importance of knowing your genealogy, because in many ways land and people are connected. The land needs the people or the people need the land to be able to know your genealogy and your connection to your lands, and knowing the genealogy of the lands is really important, because then from there you can go and you can do further study about where your *kūpuna* were from. That's why I stress genealogy and the connection that our ancestors and that we have with the land. From there, once you know where your ancestors were from, who they were, from there if you want to take your interests even further you can go study about that *ahupuaʻa* with all the knowledge that is out there today."

emphasized the role of *ʻōpae ʻula* as central to Indigenous fishing practices.

Those working with anchialine pools (n = 15) expressed strong interest in restoring anchialine pools and *ʻōpae ʻula* populations for both ecological and cultural benefits, while some (n = 5) seek to support Hawaiian *ʻōpelu* fishing practices in the future by maintaining healthy *ʻōpae ʻula* populations (Fig. 4).

***ʻIke*: knowledge**

To look at how water moves in the different wai [water] from the mauka [mountains] to makai [sea]; how the cloud patterns in Kahaluʻu move, and what captures it in the forest; the drip systems that start the process of creating water for Hawaiʻi, it is not rivers or streams, it is all underground systems; so, we have a huge amount of water here.

Fig. 4. ʻŌpae ʻula (*Halocaridina rubra*), the anchialine pool shrimp, and associated values that span all four social-ecological service categories.

- Kanaka ʻŌiwi resource manager and lineal descendant of Kona

Interviewees emphasized that GDEs are valued places that cultivate ʻ*ike* (knowledge) through facilitating *kilo* (observation) practices, which facilitates inter-generational biocultural knowledge, provides educational opportunities to learn by doing, and creates networks of knowledge sharing (Table 3.1). Interviewees discussed GDEs as sites important for perpetuating knowledge of Indigenous practices associated with cultivating, fishing for, and collecting fish, plant, *limu*, and invertebrate species (Table 3.1.1). In the words of a *loko iʻa* resource manager and Hawaiʻi Island resident, "To bring back the health and abundance of Kīholo fishpond to feed the community once again ... We feel that's very significant, work in the pond, learn from the pond, and eat from the pond. It sustains and grows them, it makes that connection even more visceral" (See Appendix I.2 for expanded quote).

Alongside harvesting, GDEs provide opportunities to learn Indigenous food preparation practices and other uses of GDE materials, including weaving of GDE-associated plant species such as *makaloa* (*Cyperus laevigatus*), into mats and other products. Three interviewees referred to John Kaʻelemakule Sr.'s recording that *makaloa* was harvested from remnants of the *loko iʻa* of Paʻaiea, at Kaʻelehuluhulu and used to decorate the town church through 1928 (also documented in Maly 1998). *Makaloa* harvesting, in turn, is thought by resource managers to reciprocally benefit the plant and pond system by thinning leaves through careful harvest.

The majority (n = 10) of interviewees also specifically mentioned GDEs as important sites for observation of seasonal changes and natural phenomena, including flows of water from the uplands to the sea, and observing and recognizing GDE plants (e.g., *limu*) and animals (e.g., ʻ*ōpae* ʻ*ula;* Table 3.1.2). One resource manager and Hawaiʻi Island resident explained:

> *I like to think of the groundwater as almost the blood that keeps the pond alive, it's coming in through lava tubes and veins through the watershed, it enters the fishpond, and then I like to think of the tides as the heartbeat, because it's moving that fresh water around.* (See expanded quote in Appendix I.2).

Interviewees emphasized that *kilo* observations are important for management of GDEs, but also have value for broader society in understanding links between people and the environment. For instance, a Kanaka ʻŌiwi resource manager stated the following:

> *We have to look beyond jobs just in natural resource and conservation, but also begin to bring up the awareness of our kids so they can have jobs like in the planning department, they have a deeper insight into how everything fits in and how what they do, how that will impact the source.*

Many interviewees (n = 10) discussed GDEs and other native ecosystems as valuable outdoor classroom spaces for STEAM (science, technology, engineering, art, and math) education, as explained by a Kanaka ʻŌiwi resource manager and lineal descendant:

> *Our keiki [children], once we train them, can interact with the beachgoers and share knowledge of the place. This kind of experience provides them [experiential opportunities to develop] different skills, public speaking skills, confidence, transferable personal skills. That is as important as teaching them how to collect water quality data from a YSI unit.*

Interviewees also highlighted how GDEs have also helped to create community knowledge-sharing networks (Table 3.1.3). Most interviewees (n = 15) are members of a network of *loko iʻa* and anchialine pool resource managers and practitioners for collaboration, education, and development of best practices amongst GDE knowledge experts ("Hui Mālama Loko Iʻa," 2014). Beyond this group, called Hui Mālama Loko Iʻa, interviewees attested to eight cases in Kona where resource managers and lineal descendants work together to share knowledge that is relevant to management decisions for the regions they care for in various capacities, from informal advising to formal committee participation. Interviewees (n = 8) emphasized that these relationships are seen as central to understanding change over time and are based on reciprocal knowledge sharing of historical conditions, stories, and management and discussion of present conditions and challenges. Some interviewees (n = 7) highlighted formal committees of lineal descendants and cultural practitioners who advise on GDEs

restoration, maintenance, and education. In other cases (n = 2), GDEs have been dedicated to lineal descendants in honor of the *ʻike* imparted by these individuals for the preservation and management of these systems, and memorial plaques and museums at these sites help to perpetuate this history.

***Mana*: spiritual connections**

> *For me, it's a really sacred relationship with Keahuolū... And you know the ahupuaʻa, it's a relationship that you have with her and like with any relationship it's only over time that you gain deeper and deeper understanding.*
> -Kanaka ʻŌiwi resource manager

GDEs are seen as important places to cultivate spiritual beliefs and practices, which supports relationships to place and past and future generations (Table 3.2). Another Kanaka ʻŌiwi resource manager explained, "When you begin to do things that are *pono* [righteous] in different environments because you understand that it also nurtures you. It spiritually nurtures you because you begin to understand this, everything and the interconnectedness."

Many interviewees (n = 11) highlighted GDEs as *wahi pana*, or storied landscapes, by referring to the importance of place-specific practices and histories associated with these landscapes (Table 3.2.2). For example, nearly half of interviewees (n = 7) pointed to how GDEs in Kona are woven into the history of lava flows and interactions with the volcano *akua*, Pele. Interviewees (n = 10) highlighted that GDEs are intricately linked to the history of human settlement and political power as some *loko iʻa* were status symbols of *aliʻi* that were transferred with transitions of power. Several lineal descendents (n = 2) and Kānaka ʻŌiwi resource managers (n = 2) explained that the history of these places contributes to their *mana*, and this knowledge is imparted from generation to generation. Interviewees also referenced spiritual importance of GDEs as important sites for *iwi* (treasured remains; n = 5), *one hānau* (birth sites; n = 1), and physical links to family genealogies and practices (n = 3; Table 3.2.2). Five interviewees described GDEs and other ecosystems as spaces where Kānaka ʻŌiwi can reconnect with their genealogy and practices, especially those who have lost connections with their family history and culture. As stated by a Kanaka ʻŌiwi lineal descendant and genealogist:

> *The land needs the people, or the people need the land. To be able to know your genealogy and your connection to your lands, and knowing the genealogy of the lands is really important, because then from there you can go and you can do further study about where your kūpuna [ancestors] were from.*

Most interviewees (n = 11), however, cautioned that some sacred spaces and GDEs should not be accessible to everyone. For example, some GDEs are considered *huna* (hidden, sacred) and may have specific cultural protocols for visiting or access may be restricted altogether, whereas other GDEs are more suitable for community workdays and broader education and outreach. Today, appropriate use of each GDE must be considered on a case by case basis, and should be revisited and revised as needed based on changing environmental and social conditions, similarly to historical decision making under the *konohiki* and the *kapu* system. Interviewees (n = 8) emphasized that proper cultural protocol should be followed to respect these spaces and the *mana* associated with them.

GDEs are also sites with prominent biocultural indicators, such as the return of the *ʻōpae ʻula* as described above (Table 3.2.3), as well as with place-based Hawaiian names that help perpetuate connection and relationship to place (Table 3.2.4). Interviewees expressed a strong personal connection to the state and existence of *ʻōpae ʻula* within GDEs, and a spiritual connection through shared space and practice to past and future generations of GDE stewards who valued and fostered generations of *ʻōpae ʻula*.

***Pilina Kānaka*: social interactions**

> *It [working in the loko iʻa] feeds us spiritually and emotionally, it brings us together as a community. Many of these people I work with down here at Kīholo have become some of my closest friends. So, feed can mean many things.*
> - Resource manager, Hawaiʻi Island resident

GDEs are highly valued as places that support social interactions, connections, and networks (Table 3.3). Although there is interest in GDE restoration for subsistence, such as *loko iʻa*, restoration of *ʻōpelu* fishing with recovering *ʻōpae ʻula* populations, and thriving nearshore systems (Table 3.3.1), interviewees emphasized the importance of thinking about the multiple ways that taking care of GDEs "feeds," including through fostering community connections to each other and to place (Table 3.3.2 and 3.3.3).

Many interviewees discussed the historical context of GDEs in the context of their importance for social connections (Table 3.3.2). For example, several (n = 5) interviewees mentioned how the Kona trail system connects upland and lowland communities in Kona, such that *mauka* (upland) communities have relied on *makai* (lowland) communities and the GDEs they steward for subsistence through the act of *mālama* (where people care for each other) through sharing resources. GDEs remained important places for gathering even after drinking water wells replaced GDEs as primary water sources. For example, a Kanaka ʻŌiwi lineal descendant explained that when she was young, even though they lived *mauka*, they would *holoholo* (journey) to the coast to valued GDEs: "even though they were remote places, they had a strong emotional attachment, and in those days, there were fish galore." She went on to explain how important these sites are for perpetuating intergenerational social connections and knowledge systems:

> *So that is, I think, the value in the insistence on perpetuating this knowledge. You are not thinking in terms of years, you are thinking in terms of generations... to mālama [care for], is ... sustaining, not only the physical nature of water flow and our places in the hydrological cycle, but our relationship to the elements in the hydrologic cycle, including each other.*

GDEs continue to be highly valued as places of social connections across generations. In the words of one lineal descendant, "Kīholo is one of those places that I feel contributed to my sense of identity and connection to where I am from because of the memories I made there with my friends and family." Another Kanaka ʻŌiwi resource manager emphasized the need to perpetuate these connections: "it's a matter of keeping interest of the children now who are going to be the future caretakers in future generations and it's a matter of just getting a few of them interested in it, knowing the need, the purpose and the value of these areas."

Many interviewees who manage GDEs (n = 8) hold regular community workdays to restore GDE ecology and practice, which maintain and strengthen social ties (Table 3.3.3). All emphasized the positive impacts of building a community that cares about GDEs, as well as the satisfaction gained by work day participants from seeing the progress of restoration. Being a part of something bigger and a part of a positive change was a common theme with interviewees who worked with volunteers, as stated by one resource manager: "it's not easy work but they really love this place and to me that's a sign of success and it's positive that people feel invested in this."

***Ola mau*: well-being**

> *It [interacting with GDEs] gives them [*Kānaka ʻŌiwi *and other youth] an opportunity in a non-threatening, non-judgmental space to be who they are … it then allows them to drop some of the barriers, the fences that they create in their lives because of some of the trauma that they experience.*
> - Kanaka ʻŌiwi Resource Manager who works with Kānaka ʻŌiwi and youth programs

GDEs are highly valued for their role in individual, family, and community mental and physical well-being (Table 3.4). There is interest in some places in restoring food systems, largely for their potential to improve physical and mental well-being in the community (Table. 3.4.1). As explained by one interviewee, "the goal is to eventually have this [*loko iʻa*] be a place where we can harvest fish for the community." Beyond any actual food produced, there was also a strong sense that engaging in GDE restoration and practice provides important mental and physical health and healing benefits (Table 3.4.2). In the words of one Kanaka ʻŌiwi resource manager,

> *They have to get in there and begin to contribute. When they're healing the ʻāina [land] they're healing themselves. So, as we go I don't think that we should be doing it for them, we should be doing it with them. It's an opportunity that we have there. It's important that we make the effort to try to get the kids in here to do this, to work towards them. For them to experience the blessings and see the outcomes.*

The majority of resource manager interviewees (n = 12) attested to GDEs contributing to well-being through emotionally and physically satisfying employment in GDE biocultural restoration (Table 3.4.3). Positive experiences associated with employment in GDE restoration include: seeing visible and measurable progress in ecological restoration work, seeing enthusiasm and understanding from participants, especially *keiki* (children), and seeing mental and emotional progress in at-risk-youth participants. Many also expressed excitement in being a part of the Hui Mālama Loko Iʻa network and seeing community-wide benefits ranging from eradicating invasive species to improved historical understanding derived from knowledge sharing there (Table 3.3.2 and 3.3.3). One Kanaka ʻŌiwi lineal descendant and resource manager explained that his ancestor approved a private license to operate for a luxury resort within their ancestral *ahupuaʻa* so that their descendants could be employed and continue living in the region.

Another aspect of *ola mau* is food sovereignty and sustainability. Some interviewees (n = 5) look to a time when the food production function and populations of food species of GDEs are more fully restored, including harvesting in *loko iʻa*, *ʻōpelu fishing*, *limu* and invertebrate gathering, and nearshore fisheries. Even partial restoration of *loko iʻa* production contributes to enriched individual experiences with GDEs, especially where some harvests are restored.

As discussed in relation to *mana*, some GDEs continue to be used for healing today, in part because of their multigenerational and historical significance (Table 3.4.4). For example, one interviewee spoke of a basal spring that was historically important during times of drought, and has been and continues to be important for self-care and well-being today. Another interviewee explained that while their partner was battling cancer they would visit an anchialine pool, not only to bathe in the pool for pain relief and healing, but also as a special place to spend healing time as a family.

Perceived current threats to GDEs and management responses

Major perceived threats to GDEs mentioned by interviewees include invasive species (n = 18), sea level rise (n = 18), nutrient pollution (n = 16), tsunami damage (n = 13), degradation associated with overuse and increased access (n = 12), reduced groundwater flow (n = 10), over pumping of groundwater resources (n = 9), and direct displacement by urban development (n = 7; Table 4).

Invasive species (Table 4.1 and 4.2)

Management efforts first focus on the most proximate threats to GDEs, one of which is invasive species. Within GDEs, invasive species compete with natives for space and resources, and alter the structure and function of the ecosystem. For *loko iʻa* and anchialine pools management efforts are focused primarily on the removal of invasive fish, invasive terrestrial plants, sediment build up, and algal biomass (see Appendix I, Table 2 for a list of invasive species in GDE systems). In particular, removing invasive guppies (*Gambusia affinis* and *Poecilia reticulata*) in anchialine pools is a primary management goal because they are predators of native *ʻōpae ʻula* and disrupt the natural function of these systems (Havird et al. 2013); accordingly, removing them using various approaches including carbon dioxide treatment is a primary management goal. Note that sedimentation occurs naturally in pools, but more rapidly without *ʻōpae ʻula* because of their role as detritivores and movement through water channels between the aquifer and surface pools. With invasive guppy removal in anchialine pools, improved water flow and water quality has been observed and is attributed both to direct removal activities as well as to the return of *ʻōpae ʻula*, which continue to remove sediment and algae and increase water flow through their role as detritivores and movement through subterranean spring channels. See Appendix 1.2 for further discussion of invasive species within GDEs. Both anchialine pool (n = 15) and *loko iʻa* managers (n = 2) also described removal of invasive terrestrial plants, primarily *Paspalum vaginatum* and *Batis maritima*, which overgrow and disrupt GDE ecosystem functioning. These same resource managers (n = 17) described that sediment and excess algae removal to prevent subsidence over time in anchialine pool and *loko iʻa* systems is achieved through manual removal and the use of sediment pumps.

Table 4. Groundwater dependent ecosystem (GDE) threats, negative impacts, and mitigation techniques from interviews. Counts reflect the number of interviews in which the threat and the mitigation techniques were mentioned. GDEs affected reflect the GDEs reported to be affected in interviews.

Threat	Negative impacts	Mitigation techniques	GDEs affected	Interviews Mentioned
4.1 Invasive guppies (invasive poeciliids (*Gambusia affinis* and *Poecilia reticulata*)	Consumption of native *ʻōpae ʻula*; increased sedimentation; competition with other native species; decreased water quality	Eradication using CO_2 treatment; hand removal; education to prevent new introductions	Anchialine Pools	18/19
4.2. Invasive vegetation (Seashore paspalum; pickle-weed; *kiawe*)	Increased leaf fall; increased sedimentation; reduction in water flow; reduction in native fish reproduction	Hand removal; community workdays; herbicides; heat treatment	Anchialine pools; *loko iʻa*; nearshore ecosystems	12/19
4.3 Tsunami damage	Filling of springs; pools with sediment and debris; introduction of species; physical damage	Physical restoration; sediment removal; maintenance of physical barriers	Anchialine pools; *loko iʻa*; nearshore	13/19
4.4. Sea level rise	Changes in tidal height; height of groundwater lens; locations of springs and ponds; changes potentially too fast or far for biota to adjust and move without assistance; inundation of cesspools/septic/sewage infrastructure	Using sea level rise maps to prioritize conservation and management; native plantings; anticipation of changes; preventative mitigation for sewage systems	Anchialine pools; *loko iʻa*; nearshore	18/19
4.5. Reduced groundwater flow	Irreversible decreases to watershed integrity through land use, compaction of the aquifer, reduced porosity, disruption of water flow through lava tubes and pores	Further hydrologic understanding of the watershed and inter-connectedness of water resources	Anchialine pools; *loko iʻa*; nearshore	10/19
4.6. Over pumping; decreases in water availability	Declines in water flow; alteration of salinity within GDEs; changes outside native species salinity tolerances and subsequent declines in these species	Designation as watershed management area; understanding relevant salinities and flow volumes to maintain GDEs	Anchialine pools; *loko iʻa*; nearshore	9/19
4.7. Nutrient pollution	Algal blooms; declines in native species; declines in water quality; increased invasive species and sedimentation	Improve sewage treatment; reverse osmosis and improved septic systems with no leakage	Anchialine pools; *loko iʻa*; nearshore	16/19
4.8 Overuse; increased access	Declines in water quality; introduction of invasive species; erosion of physical features; microbial introductions; trash pollution; human waste pollution; trampling; impacts on Kānaka ʻŌiwi practices	Increased education; reinstatement of *konohiki* monitoring systems; decreased access for unprotected systems; signage; seasonal or weekly closures for public systems	Anchialine pools; *loko iʻa*; nearshore	12/19

Resource managers (n = 17) highlighted the value of knowledge sharing networks to address GDE management techniques and collaborative approaches. Hui Mālama Loko Iʻa, in particular, has provided an important network for shared information and resources to respond to the threats within anchialine pools and *loko iʻa*, such as sharing strategies and lessons learned in managing invasive guppies and sediment removal techniques.

Tsunami damage and sea level rise (Table 4.3 and 4.4)

Most resource managers (n = 9) noted the devastating effects of a 2012 tsunami, including through deposition of sedimentation and rocks, facilitation of the spread of invasive species, and structural damage. Responses to tsunami damage included physical restoration, barrier construction, and sediment and species removal. Even more so than just tsunamis, most interviewees (n = 15) pointed to sea level rise as an important threat and that tsunamis are a preview for what would come with sea level rise (confirmed by predictions of shifting of pools inland and loss of some pools; Marrack 2014, 2016). Twelve resource managers attested to using the Pacific Islands Ocean Observing System sea level rise prediction tool to plan restoration efforts (Hawaiʻi Climate Change Mitigation and Adaptation Commission 2021). Others acknowledged that GDEs will be so heavily impacted by sea level rise that some anchialine pools may cease to exist, while new GDES are likely to be created inland.

Groundwater quality and quantity (Table 4.5, 4.6, and 4.7)

Interviewees also pointed to the threat of declining SGD quality and quantity, related primarily to land-use change, wastewater management, and increases in groundwater pumping (Table 4.5 and 4.6). One lineal descendant and resource manager explained that she could feel and taste the change in Kona's nearshore water quality during her lifetime, and that Kānaka ʻŌiwi now preferred to swim and fish in the more pristine southern Kaʻū region. Another lineal descendant expressed that the water temperatures along the coast have increased and that the quality has decreased in the nearshore with loss of freshwater springs, especially with dredging of Honokōhau Harbor. Interviewees also linked declining groundwater quality to declines in coral cover in the Keauhou aquifer, and bleaching on nearshore reefs associated with both the Keauhou and Kīholo aquifers. These changes were largely attributed to land-use change (e.g., urban development) and wastewater management issues, as described by one lineal descendant resource manager: "Water runs to the ocean from *mauka* to *makai*, but all the *mauka* lands have cesspools."

A lineal descendant noted declines in culturally valued *limu*, and associated this change with declines in SGD quality and quantity: "I know Keauhou had the *ʻeleʻele*, [*Ulva prolifera*] I know that part is true and the *kūpuna* said they used to gather from that side, because we did, too, but it's not there anymore ... it needs more cold water." Others noted increases in algal growth as an indicator of increased nutrients or loss of herbivores within the ecosystem.

Urban development (Table 4.8)
Interviewees (n = 8) expressed regret at the loss of anchialine pools and spring resources associated with grading and filling of coastal lands for urban development, especially the loss of large anchialine pools within Lanihau *ahupua'a* for the development of the Old Kona Airport. One resource manager and Hawai'i Island resident highlighted how today informed and involved GDE communities have come forward to prevent development from impacting anchialine pool water sources:

> *So at Waikoloa they wanted to expand a huge development and basically wipe out a bunch of anchialine pools... The call went out to our Hui Loko network to all of our agencies that we need advocates at these meetings to say, one, you can't just bulldoze anchialine pools, they're valuable resources that should be protected.* (See expanded quote in Appendix 2).

Others (n = 9) described the benefit of public-private partnerships and development agreements that protect GDE resources in perpetuity.

Overuse and increased access (Table 4.9)
Interviewees identified social media, geotagging, and tourism publications as sources of increased visitation to certain GDE systems (particularly small, vulnerable anchialine pools). Access roads and trails were also noted to increase the number of visitors to remote GDEs. Increased visitation, without education and personal connection, is seen as a major source of degradation of these systems, as explained by one Kanaka ʻŌiwi interviewee:

> *As with most of Hawai'i, our sacred and/or special places see more people, exposure, commodification, and at times, destruction. In today's society of social media and Instagram celebrities, I see instances where people are willing to go to the extremes in order to 'get the shot' that will get them the most 'likes' even if they may not be aware of the negative impact they may be having on these places or people.*

For example, in response to perceived insufficient staffing at state parks to educate visitors and enforce camping rules at Kīholo, the community, including lineal descendants responded by forming Hui Aloha Kīholo, a nonprofit management entity that monitors and protects natural and cultural resources, engages with and educates visitors, maintains the State Park reserve and manages camping. The Kīholo bay area is now jointly managed by the Division of State Parks and Hui Aloha Kīholo, which has improved many of the issues with visitor volume and misuse in this region.

Desired futures of GDEs

> *We also need to understand that the process is very important. If the process is not pono [correct and proper] then the outcome is never pono.*
> - Kanaka ʻŌiwi Resource Manager

All interviewees expressed a desire for GDE ecological function to be restored and maintained for future generations, along with continuing to perpetuate the history, practices, and social identity associated with these systems. Accordingly, many interviewees advocate a biocultural restoration and management approach. For some resource managers (n = 4), a key goal of restoration is to restore food production associated with these systems, whereas a larger number (n = 9) explicitly discussed restoring GDE-related Kānaka ʻŌiwi practices and language. Restored cultural practice is seen as a critical indicator of long-term restoration success, as one lineal descendant explained: "I always think about the practices that were passed on and where we are today, the gap that, for whatever reason there's a gap, and we're trying to re-establish the practice again." Interviewees also discussed the importance of *mālama* (to care for), *kuleana* (honored responsibility), and *pono* (righteousness) as critical Kānaka ʻŌiwi values for biocultural restoration of GDEs.

There was also a strong sense of the importance of *kūpuna* (elder and ancestral) knowledge in informing management today. In the words of one Kanaka ʻŌiwi lineal descendent: "To learn the history, and to know that it's not just an anchialine pool. There is a history to it, and if the *kūpuna* said so that is what it is." Many interviewees (n = 8) also explicitly discussed the importance of GDEs for Kānaka ʻŌiwi children through providing opportunities for (re)connection to genealogy and history, for healing multigenerational trauma, and for reinstating cultural practices, Indigenous management practices, and balance in the ecology of these systems.

Interviewees generally advocated for adaptive management that integrates ancestral knowledge with modern management and technology to best care for these systems and associated knowledge and practices from the mindset of multigenerational preservation. One Kānaka ʻŌiwi resource manager pointed to a balance between technology and preservation: "We like the technology and we want to use it as much as possible to inform management decisions, just as long as we don't push the boundaries to where it affects the integrity of the practice or the place. That's something that we feel really strongly about."

Interviewees (n = 10) expressed a desire to move toward a more holistic and thoughtful multigenerational planning and nearly all interviewees (n = 17) expressed some desire to look to the *konohiki* system of management, especially the inclusion of knowledgeable resident caretakers, to improve management of GDEs today. On defining *konohiki* as a system of resource management a Kanaka ʻŌiwi resource manager explained the following:

> *... resources, that again is a really Western term when we look at it... science uses it a lot but when you look at it from a Hawaiian perspective that is our sources, our sources of who we are, so, because, you're related because there's a kinship connection to these sources. It's like other things, that's stewardship. That feels good like you're a good steward, but really it's a kinship.* (See expanded quote Appendix 2).

There was also a strong sense that GDEs are part of a broader connected *ahupua'a* system and that restoring and amplifying this relationship with the broader system is key. The importance of this relationship was expressed by a Kanaka ʻŌiwi resource manager who had worked in the area for 30+ years:

> *At first you just see the ahupua'a and you're trying to understand the ahupua'a, but somewhere along the line the ahupua'a is teaching you.* (See expanded quote in Appendix 2).

Perceived policy solutions to achieve these visions include limiting visitation to allow for "resting" of GDEs and creating a fee-based or tax-based system to fund docents for education and GDE maintenance. Additionally, interviewees (n = 5) suggested increasing setback laws to prevent additional development along the shoreline, which would protect existing GDEs and allow space for creation of new GDEs inland as expected with rising sea levels. Some resource managers (n = 6) asked for ingenuity in funding and policy that would allow them to efficiently enact GDE protections, for example, by allowing rapid responses to limit nearshore access during coral spawning. Other interviewees (n = 6) also highlighted desired improvements in GDE protection including impartial, high-quality environmental impact statements.

In addition to local-level interventions to achieve the aforementioned visions, interviewees emphasized the need for broader aquifer-wide interventions to prevent declines in SGD quality and quantity, particularly in the context of threats derived from climate change and future development. In particular, many interviewees (n = 14) pointed to the impacts of septic and cesspool systems on groundwater quality, and advocated for improvements in sewage treatment, while some (n = 2) advocated strongly for reverse osmosis sewage treatment and recycling of water.

DISCUSSION

This study highlights the ways people use, value, and care for GDEs in Kona, and provides insights into how Indigenous knowledge and practice informs sustainable land and groundwater management in Hawai'i and other coastal regions. In doing so, we help to address the critical need highlighted by Moosdorf and Oehler (2017) to better document the human uses and values associated with SGD and GDEs in order to better inform decisions that influence the health and abundance of these systems. Interviews also provide critical insight on steps and actions needed to support GDE stewards in protecting and restoring valued GDEs.

Though GDEs support the Kona economy through management jobs and increasing tourism and property value, our findings suggest that the most important current values of GDEs may be biocultural values well-aligned with the Hawai'i-based cultural ecosystem services framework developed by Pascua et al. (2017). Similar to conclusions about the cultural benefits of Indigenous wetland agriculture in He'eia, O'ahu (Bremer et al. 2018b) using Pascua et al. (2017)'s framework, our findings also point to the importance of the process of restoration as fundamental to the benefits and values perceived today. This study is not a comprehensive record of values associated with GDEs in Kona, but does serve to elevate the human dimensions of GDEs, which have not been widely explored in the broader literature (Murray et al. 2006, Duarte et al. 2010, Moosdorf et al. 2015, Burnett et al. 2017), and has been identified as a key research need for groundwater management in Kona and in Hawai'i more broadly (Adler and Ranney 2018).

In line with the biocultural value of these systems, we found that the place-based history and historical uses of GDEs play an important role in influencing the current cultural (e.g., through customary rights and natural heritage) and economic (e.g., through tourism and employment) values of these systems. For example, the storied history of Kuhalalua spring in Keauhou as the birthplace of Kamehameha III elevates its cultural importance today because this spring is maintained for cultural value and as the site of Kamehameha III's annual birthday celebration (Fig. 2d). Likewise, accounts of GDEs once providing abundant food sources for previous generations motivates restoration today, despite acknowledgement that restoring actual food systems may be far into the future.

In the context of GDEs, many of which once were vital to the people of Kona for drinking water and food production, managers generally recognize that restoration success does not rest in necessarily reviving all historical uses, but in the process of restoration that builds and re-establishes relationships between people, place, ancestral knowledge, and practice, and amplifies Kānaka 'Ōiwi deeply held relational values around caring for land, including *mālama, kuleana* and *pono* (Gould et al. 2019). This echoes broader efforts to employ biocultural approaches to conservation, which have accelerated around Hawai'i and beyond and which emphasize the reciprocal restoration of ecology and culture (Gavin et al. 2015, Sterling et al. 2017, Bremer et al. 2018a, 2018b, Morishige et al. 2018, Burnett et al. 2019, Chang et al. 2019, Winter et al. 2020a, Sato et al. 2021), and which highlight the role of the sacred in Indigenous conservation approaches (Kealiikanakaoleohaililani et al. 2018, 2020).

Supporting biocultural restoration of GDEs also requires shifting decision-making power to local resource managers and exploring models of community-based governance and Indigenous knowledge-based management of these systems. This has been similarly demonstrated for other systems in Kona (Kurashima et al. 2017, 2018, Bremer et al. 2018b, Sato et al. 2021, Kamelamela et al. 2022). For instance, biocultural restoration of dryland forest systems was shown to increase purpose and meaning in human relationships to place (Sato et al. 2021). Similarly, community-led restoration and Indigenous consensus-driven and place-based stewardship were shown to provide reciprocal benefits in restoring ecological function and Indigenous practice while building trust between community partners, articulating concepts of Indigenous and local knowledge-based restoration, (re) connection of Indigenous people to their land, and in addressing historical legacies of cultural and ecological degradation (Kamelamela et al. 2022). Community and Indigenous knowledge-based subsistence fishing and forest management areas and biocultural restoration offer potential adaptable models that may help to elevate Indigenous knowledge and local management systems broadly (Berkes 2004, Ostrom 2009, Vaughan 2018, Kamelamela et al. 2022; KUA Hawai'i 2016, http://kuahawaii.org/ka'upulehu-try-wait-faqs/).

GDEs also face important challenges that on-site resource managers do not have direct control over, such as climate change and wastewater and watershed management. For example, sea level rise is projected to eliminate or severely alter some GDEs (by suppressing and otherwise altering SGD spring flow, and by submerging nearshore anchialine pools and *loko i'a*), while also potentially creating new springs and pools inland (Marrack 2014, 2016). Tools like the Nature Conservancy's sea level rise projection tool showing the impacts of sea level rise on Kona's GDEs allow resource managers to prioritize restoration accordingly (Hawai'i Climate Change Mitigation and Adaptation Commission 2021). Interviews also highlighted desired improvements in GDE

protections reflecting challenges outside of their control, including faster permitting for management response to emergency situations, impartial, high-quality environmental impact statements for development, increased shoreline setbacks, and time-wise resting or rotational closures of resources from human use.

In addition to climate change, interviewees pointed to the need for groundwater, wastewater, and watershed policy and management to more directly consider GDEs. Groundwater pumping for drinking water use and irrigation, for example, can result in a direct trade-off to GDEs through reduced flow and increased salinity (Burnett et al. 2020), though in cases where SGD is elevated in nutrients and other pollutants from wastewater and land management, even sustained flow can have adverse effects (Dailer et al. 2012a, 2012b, Delevaux et al. 2019, Wada et al. 2021). Hawai'i legislation requires upgrades of cesspool systems to septic or sewer systems, but legal compliance will likely be influenced by the upfront and long-term costs compared with available incentives. Upland of urban areas, there is additionally increasing attention to the role of watershed management in sustainable groundwater supplies (Bremer et al. 2021), as well as elevated efforts to reduce unnecessary human use of water and promote water conservation practice (Hawai'i Fresh Water Initiative 2015). Decision support modeling, such as that done by Wada et al. (2021), which identified land-use and wastewater management related impacts to GDEs and associated costs and benefits, could usefully link model outputs to potential outcomes for GDE biocultural values presented here for more informed policy decisions.

Outcomes of the aforementioned recent symposium on adaptive management of groundwater dependent ecosystems at Kaloko-Honokōhau National Historical Park held by the Commission on Water Resources Management (the state water regulator) pointed to the importance of establishing relevant social-ecological indicators of healthy GDEs as a way to assess the impacts of water use and development on these important public trust resources (Adler and Ranney 2018). Recent work on biocultural indicators demonstrates the importance of developing indicators embedded in local conceptualizations and definition of resilience (Sterling et al. 2017, Dacks et al. 2019, Ingram et al. 2020). The uses and values illuminated here can provide important guidance of developing biocultural indicators that truly shed light on the social-ecological health of the system. Our study points to important biocultural indicators of recovering GDEs, including the presence of *'ōpae 'ula* in anchialine pool systems, and continued or restored Indigenous practices, such as the feeding of *ko'a* or harvest of GDE species. Using *kilo* observational practices to guide management decisions is also an important biocultural indicator (Morishige et al. 2018), as are the temperature, taste, and smell of water. Future research could further develop these indicators and inform decision making by evaluating the effects of current and future water quality and quantity related to wastewater management, water use, forest conservation, development, and climate change.

For more effective groundwater management and protection of these ecosystems, GDEs and GDE practices across multiple disciplines (i.e., Kānaka 'Ōiwi cultural practice, ecology, biology, conservation, social science, and economics) and scales (i.e., individual ecosystems, regional, *ahupua'a*, island, state, and worldwide) should be tied to GDE hydrogeologic connectivity, and should continue to address newly identified gaps in knowledge. Individual GDE-dependent species likely have specific needs for qualities and quantities of groundwater that may be adversely impacted by changing land use, groundwater pumping, or polluting groundwater. Finally, there is a need for better understanding of the required quality and quantity of groundwater required for cultural practices, to ensure that these practices can be perpetuated. Biocultural restoration of thriving GDE social-ecological systems depends on proactive and constant evolution of the integration of Indigenous people, knowledge, and practices, with science, technology, and policy.

CONCLUSION

The Indigenous people of Kona have a long history of resilience and adaptation that is instrumental in successfully facing challenges in GDE management (McMillen et al. 2017). Today, a growing number of leaders, including lineal descendants, Kānaka 'Ōiwi scholars and resource managers, and *kama'āina* (people born of this land) of other ethic backgrounds have elevated the value and importance of GDEs and have clearly articulated visions for a more sustainable future. In the face of urban development, wastewater management, sea level rise, invasive species, and other challenges, the Kona community is at the forefront of combining Indigenous knowledge and resource management practices with contemporary technology for GDE biocultural restoration. Supporting local resource managers and lineal descendants in achieving these goals through re-orienting governance and funding toward community-based management will be critical to the long-term ecological and social health of these important systems. Incorporation of GDE values and Indigenous practices into stewardship and restoration decisions and policy is critical to protect GDE systems in Kona and throughout Hawai'i, and further contributes to the broader movement to elevate Indigenous rights, knowledge, values, and practice into the continued stewardship and restoration of social-ecological systems worldwide.

Responses to this article can be read online at:
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Author Contributions:

VG, LB, and KB contributed to research conceptualization and study design. VG and LB designed the study method and interview questions and conducted interviews. VG led the manuscript effort. NL, CS, LB, and KB assisted in writing, reviewing and editing the manuscript.

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Data Availability:

The data that support the findings of this study are available on request from the corresponding author, VG. None of the data are publicly available as institutional review board interviewee privacy agreements require that interview transcripts and participant information remain private. Ethical approval for this research study was granted by the University of Hawaii Human Studies program, which determined that this study is exempt from federal regulations pertaining to the protection of human research participants. Largely, data/code sharing is not applicable to this article because no data/code were analyzed in this study beyond interview transcripts and value coding worksheets.

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A1. Appendix 1: Background

A 1.1 GDE Biodiversity

Diverse species are supported by groundwater dependent ecosystems (GDEs) in Kona (A1 Table 1). Native wetland birds rely on *loko wai kai* (anchialine pools) and *loko iʻa* (Indigenous aquaculture systems) for nesting habitat, including the endemic *ʻalae* (*Fulica alai*) and endangered *aeʻo* (*Himantopus mexicanus*; Christen et al. 2005). GDEs broadly, from anchialine pools to *loko iʻa*, *muliwai* on nearshore reefs influenced by submarine groundwater discharge springs, and subterranean aquifers themselves, support diverse native and introduced organisms. This includes terrestrial plants with water and nutrient sources, such as trees like the Polynesian introduced *hau* (*Hibiscus tiliaceus*), endemic *loʻulu* (*Pritchardia spp.*), grasses (*Ruppia maritima* and others), sedges including *makaloa* (*Cyperus laevigatus*), and succulents like indigenous *ʻākulikuli* (*Sesuvium portulacas*). GDEs also broadly support vertebrate and invertebrate species; for instance, some species of fish and invertebrates have GDE-dependent larval stages that move across salinity gradients into various GDEs to complete their life history, while other euryhaline species opportunistically use GDEs to gain refuge from predation, and still others move into GDEs to feed on GDE species (Titcomb et al. 1978, Havird et al. 2015, Marrack et al. 2015, Peyton et al. 2016, Smith and Parrish 2002). Low-salinity tolerant macro and microalgae grow in exclusion from grazers in geologically protected GDEs (Littler and Littler 2006), while taking advantage of groundwater derived nutrients (Abbott 1947). The habitat range of some invertebrates, including endemic shrimp species, spans nearshore, estuarine, and anchialine systems (Titcomb et al. 1978, Yamamoto et al. 2015). See A1 Table 3 for examples of GDE species salinity tolerances. Surprisingly few Hawaiian species have published salinity tolerances and defined groundwater chemistry and quantity needs.

A1.1.1. *Loko wai kai* (anchialine pool) biological diversity:

Diverse assemblages of organisms are found in anchialine pools, including crustaceans, fishes, mollusks, isopods, amphipods, decapod crabs and alpheids, a hydroid, sponges, polychaetes, tunicates, insects, algae, and aquatic macrophytes (Brock 1977, Brock and Kam 1997, Yamamoto et al. 2015). Eight species of anchialine pool shrimps are found in Hawaiʻi's anchialine pools, all of which are listed as endangered species candidates except *ʻōpae ʻula* (*Halocaridina rubra*), and five of which are endemic (*Halocaridina rubra*, *Halocardidina palahemo*, *Procaris hawaiana*, *Palaemonella burnsi*, and *Vetericaris chaceoru*; Christen et al. 2005, Yamamoto et al. 2015). Of the five endemics, *V. chaceorum* and *H. palahemo* are recorded to exist in a single pool each, both of which lie outside the southern boundary of the study site for this research (Christen et al. 2005). Of the eight anchialine pool shrimp species found in Hawaiʻi, four are recorded for the Kona region (Christen et al. 2005). The endemic *ʻʻōpae ʻula*, *Halocaridina rubra*, are the most abundant in Kona's anchialine pool systems and play a key role in ecological functioning by consuming algae and detritus (Seidel et al. 2016). *ʻʻōpae ʻula* have been recorded in the stomach contents of nearshore fish species including *ʻuʻu* (*Myripristis spp.*), suggesting that *ʻuʻu* travel into groundwater-fed spaces to feed on *ʻʻōpae ʻula* which are swept out by outgoing tides (Yamamoto et al. 2015). The indigenous *Metabetaeus lohena* is a predator of *H. rubra*, and the indigenous *ʻōpaeʻhuna* (*Palaemon debilis)*, all of which are found in anchialine pools (Brock and Kam 1997). The rare endemic, *Palaemonella burnsi* is found in this region, within Kaloko Pond in Kaloko-Honōkohau National Historic Park (Brock and Kam 1997).

Some of Kona's pools contain characteristic cyanobacterial carbonate producing mats or crusts comprised of a matrix of living organisms including; cyanobacteria (including *Lyngbya, Schizothrix, Scytonema* and *Oscillatoria spp.*), chlorophytes (*Rhizoclonium sp*. and *Cladophora spp.*), the marine plant *Ruppia maritima,* bacteria, diatoms, and protozoans (Brock and Kam 1997). West Hawai'i anchialine pools are known for characteristic orange to yellow cyano-bacterial mats which form a white precipitate of silicon, magnesium, calcium and phosphorus on the pond floor (Brock and Kam 1997). Common molluscs found in Kona's anchialine pools include *Theodoxus cariosa*, *Melania sp.*, and *Assiminea nitida* (Brock and Kam 1997). The macroalgae, *Ahnfeltiopsis concinna*, has also been recorded within anchialine pools (Brock and Kam 1997).

A few endemic damselfly species, including the endangered species candidate *Megalagrion xanthomelas,* rely on anchialine pools for specific salinities for reproduction (Seidel et al. 2016). The indigenous dragonfly *Pantala flavescens* is also present in Kona's anchialine pools (Seidel et al. 2016). The endemic, brackish water tolerant, *'o'opu 'akupa*, or sandwich island sleeper goby (*Elotris sandwichensis*) are found in Kona's anchialine pools (Brock 1977). Common anchialine pool fish species include *āholehole* (*Kuhlia sandvicensis*), *'ama'ama* (*Mugil cephalus*), *uouoa* (*Neomyxus chaptalii*), *'o'opu* (*Eleotris sandwichensis*), 'o'opu nākea (*Awaous stamineus*), *kūpīpī* (*Abdeufduf sordidus*), *manini* (*Acanthrurus trigostegus*), and *weke'ā* (*Mulloidichthys flavolineatus*; Brock 1977).

A1.1.2. *Muliwai* (nearshore reefs) biological diversity

SGD seeps in nearshore ecosystems deliver cool, fresh, nutrient rich fluxes of water to nearshore reefs and create zones of high productivity as phytoplankton (Delevaux et al. 2018) and macroalgae (Amato et al. 2016) acquire otherwise limiting nutrients from groundwater sources. Some euryhaline fish species require fresh or brackish water to complete their life histories, while others are tolerant of brackish water and benefit from predation and protection in these productive, turbid, and, often, calmer, nearshore ecosystems which provide food and protection from wave action and larger predators (Smith and Parrish 2002). As the Kona coast is devoid of riverine inputs these species must rely on SGD for habitat in this region. A survey of juvenile fish and larvae often associated with these kinds of estuarine regions in Hawai'i found fish species associated with estuarine waters include; *weke* (*Mulloidichthys flavolineatus)*, *'oi'o* (*Albula virgata)*, *moi* (*Polydactylus sexfilis*), *uouoa* (*Neomyxus leuciscus*), *manini* (*Acanthurus trigostegus*), *mā'i'i'i* (*Acanthurus nigrofuscus*), *kala* (*Naso unicornis*), *'iao* (*Atherinomorus insularum*), *'Ulua* (*Caranx ignobilis, C. melampygus, and C. sexfasciatus*), *lai* (*Scomberoides lysan*), *awa'awa* (*Chanos chanos*), *kākū* (*Sphyraena barracuda*) introduced sardine (*Herklot sichthys quadrimaculatus*), *'o'opu* (*Eleotris sandwicensis*), *nehu* (*Encrasicholina purpurea*), *iheihe* (*Hemiramphus depauperatus* and *Hyporhampus acutus*), *āholehole* (*Kuhlia xenura* and *K. sandvicensis*), and *'o'opu hue* (*Arothron hispidus*); shrimp species (*Macrobrachium grandimanus*, *Palaemon pacificus*, and *Palaemon debilis*) and one crab species (*Portunus sanguinolentus*; Peyton et al. 2016). *'Ulua* (*Caranx ignobilis* and *Caranx melamypygus*) opportunistically inhabit Hawaiian estuarine regions as nursery and hunting habitat (Smith and Parrish 2002). Sediment and low salinity in estuarine regions can prevent coral growth and lead to proliferation of sediment and low salinity adapted species, such as worms and shelled animals, and fish that feed in soft sediment such as rays and flatfishes (Christen et al. 2005), as well as sediment- adapted marine plant species, such as the indigenous seagrass, *Halophila decipiens* (Fonesca 1989) and proliferation and even blooms of macroalgal species including *Gracilaria spp.*, *Hypnea spp.*, *Cladophora spp.*, and *Ulva spp.* (Abbott 1947, Amato et al. 2016).

Speciation within Hawaiian GDEs has led to the evolution of endemic species which rely on groundwater inputs for survival, for example, the endemic *āholehole* species, *Kuhlia xenura,* is a nocturnal planktivore whose young are found in shallow coastal estuarine waters and tide pools (Christen et al. 2005, Yamamoto et al. 2015). This differentiates the endemic *K. xenura* from the indigenous *K. sandvichensis*, which prefers higher salinity (Christen et al. 2005). The authors expect this is true for more endemic Hawaiian species and varieties of vertebrates, invertebrates, and macroalgae, as the topic has not been thoroughly examined.

A1.1.3 *Loko iʻa* (indigenous aquaculture system) biological diversity

Under Kānaka ʻŌiwi (Native Hawaiian) management, *loko iʻa* aquaculture was carried out in virtually any sizeable body of water, including naturally occurring anchialine pools and modified natural embayments, as these were stocked, collected from, and maintained with desirable species specific to each *loko iʻa (*Kikuchi 1976). *Loko iʻa kuapā*, or walled aquaculture systems, have a permeable barrier made of stone to impound water from springs as well as the nearshore (Kikuchi, 1976). *Loko iʻa kuapā* walls were built to be permeable to allow water flow and tidal exchange while dampening wave action, thereby creating large areas of calm, shallow, water with ample sunlight for algal growth (Kikuchi, 1976). Intentionally positioned *mākāhā* (sluice gates) allowed for tidal exchange and control of the movement of fish in and out of the pond (Kikuchi, 1976, Winter et al. 2020a).

Other groundwater dependent components of *loko iʻa* aquaculture systems included stocked anchialine pools, including *kiʻo pua*, small fingerling holding ponds, *loko wai kai*, anchialine pools (often stocked with *ʻoʻopu* and *ʻōpae*), and *wai ʻōpae*, pools that were important habitat for *ʻʻōpae ʻula* (Kikuchi 1976, Maly and Maly 2003, Mackenzie 2015). *Loko wai kai* were used as *loko iʻa* to grow *āholehole*, Hawaiian flagtail (*Kuhlia xenura*) and big eyed mullet (*Kuhlia xenura*), *'o'opu* (various gobies including *Elotris sandwichensis*), *amaʻama* (*Mugil cephalus*), *awa* (*Elops machnata*), and *awa'awa* (*Chanos chanos;* Kikuchi 1976). *Loko puʻuone* are natural estuarine habitats that have no surface connection to the sea due to formation of a sand and loose coral berm (the *puʻuone,* or sand berm), formed from either sea level changes or wave action, fish grown in puʻuone were considered a savory, highly prized delicacy (Kikuchi 1976). *Loko kuapā*, walled fishponds, were purposefully engineered to be permeable to allow water flow while dampening wave action and allowing control of fish movement in and out of the pond through the *mākāhā*, or sluice gates (Kikuchi 1976).

Kānaka ʻŌiwi observed that freshwater associated species thrive naturally in SGD and riverine influenced *muliwai*, and engineered *loko iʻa* to enhance productivity in these natural systems. The foundation for this productivity is the growth of algae and microbenthos, with most algae growing in the more marine influenced region (*limu pālahalaha*, or *Ulva lactuca*, *Erythrotrichia carnea*, *Centroceras clavulatum*, and *Ceramium spp.*), while some fresh-water species are restricted to spring fed inlets (*Spirogyra* and desmids), brackish tolerant species are found throughout the aquaculture system (*Cladophora spp., Polysiphonia spp.* and *limu ʻeleʻele*, *Ulva prolifera*) and abundant epiphytic diatoms which form a thick mat mixed with small algae and animal larval stages (Abbott 1947). A study of *loko iʻa* food chains for key harvested species (*amaʻama* and *awa*) found that *amaʻama* feed primarily on littoral diatoms and cyanobacteria, while *ʻawaʻawa* feed on unicellular algae as juveniles and filamentous algae as they mature (Hiatt 1947). Overall, both species subsist largely on diatoms (including *Navicula*, Cymbella*, Pleurosigma*, *Amphora*, *Melosira*, *Mastogloia*, *Coscinodiscus*, *Nitzchia*, *Surirella*, and *Hyalodiscus*) and blue green algae (*Oscillatoria*, *Merismopedia*, and *Microcystis*), with smaller portions of the diet comprised of filamentous algae (*Cladophora spp., Ulva prolifera, Vaucheria,*

Spirogyra, Polysiphonia, Acrochaetium), plant fragments (*Batis maritima*), and other microorganisms (Hiatt 1947).

A1.2 Invasive species and GDEs

Within anchialine pools, invasive guppies or poeciliids (*Gambusia affinis* and *Poecilia reticulata*) are a primary cause of declining water quality and dramatic decreases in *ʻōpae ʻula* populations (Havird et al. 2013, Marrack et al. 2015), tilapia also impact a number of anchialine pools and *loko iʻa* by predating native species and increasing nutrient concentrations (Adler and Ranney 2018). Tilapia can also become invasive in nearshore regions, so special care has been taken not to release this species from *loko iʻa* to adjacent nearshore systems ("Adler and Ranney 2018," http://files.hawaii.gov/dlnr/cwrm/activity/keauhou/20181108-GDE_Symposium_Final.pdf).

GDEs can become dominated and overgrown by invasive terrestrial plants such as seashore paspalum (*Paspalum vaginatum*), mangrove species (*Rhizophora mangle*, *Bruguiera gymnorrhi* and *Conocarpus erectus*), and water hyacinth (*Eichornia crassipes*; Allen 1998). Even the Polynesian introduction, *hau*, (*Hibiscus tiliaceus*), can become weedy and require removal from anchialine pools and *loko iʻa* (Allen 1998). If left unmaintained, *Hau* and mangrove act as invasive species, grow rapidly and reduce open water and overgrow mudflats and shallow coastal waters (Allen 1998). *Kūpuna* (elders) of the Kekaha region in interviews by Maly and Maly (2003) identified invasive mangrove growing in fishponds and anchialine pools that elder generations used to collect *ʻōpae ʻula* for *ʻōpelu* fishing.

In the nearshore region, invasive macroalgal species can form bloom conditions where SGD becomes elevated in nutrients, and where herbivorous fish populations are low (Littler and Littler 2006, Dulai 2021). While the only instance recorded in the literature for Kona is *Acanthophora spicifera* in the Kaloko fishpond of Kaloko Honōkohau (Weijerman et al. 2008), the introduction of alien species and pollution of nearshore groundwater are a primary concern for GDEs in Kona, with problematic blooms occurring on the nearby islands of Maui and Oʻahu (Smith et al. 2005, Vermeij et al. 2009, Dailer 2012b, Amato et al. 2016, Dulai 2021). See A1 Table 2 for a summary of invasive species recorded in Kona GDEs.

A1.3. GDE historical context

Prior to Western contact in 1778, a from mountain to sea, *ahupuaʻa* , were held in trust by *aliʻi* (ruling class), who extended rights to use these resources to the *hoaʻāina* (tenants of the land) either themselves or through their *konohiki* (McGregor 1996, Maly and Maly 2003). The *konohiki* system was based on an intimate understanding of interconnected land and ocean resources , and the ecology and practices associated with these systems (Costa-Pierce 1987, Jokiel et al. 2011, Friedlander et al. 2013, Mackenzie 2015, Vaughan 2018).

The Hawaiian Kingdom, established in 1795 by Kamehameha I, was illegally overthrown by the United States of America in 1893. Under Hawaiian Kingdom law, private ownership and commodification of land began following the Land Commission of 1845, the Māhele (division of lands) of 1848, and the Kuleana act of 1850, which contributed to shifts in access and rights to land, including to GDEs, across Hawaiʻi (McGregor 1996, Osorio 2004, Friedlander et al. 2013, Mackenzie 2015, Vaughan and Caldwell 2015, Beamer and Tong 2016). In the case of *loko iʻa* and *loko wai kai*, the Māhele designated both as private property of the individual or corporate land owners (Mackenzie 2015). In the case of nearshore fisheries following the Māhele, *konohiki* fishing rights designated the land owner as the *konohiki* and gave the *konohiki* and *hoaʻāina* (tenants) rights to fisheries associated with their *ahupuaʻa* (Mackenzie 2015). Later,

after the illegal overthrow, the Organic Act of 1900 that established Hawai‘i as a territory of the United States: “specifically sought to terminate exclusive fishing rights and open the fisheries to all, and thus required all konohiki and hoa‘āina to register their rights to preserve them as ‘vested.” (Mackenzie 2015: p.7). Many fisheries were not registered leading to a loss of traditional fishing and management rights (Mackenzie 2015).

The impacts of colonization and associated economic and political changes that occurred post-Western contact led to decreased cultural practice, management, and decreased perpetuation of knowledge related to GDEs, as generational knowledge of language and practice, and Kānaka ‘Ōiwi populations themselves declined, primarily from introduced diseases (Osorio 2002, Jokiel et al. 2011, Friedlander et al. 2013, Mackenzie 2015, Vaughan and Caldwell 2015). However, *kūpuna* recall abundant and productive fisheries throughout the islands and point to declines in resource abundance. For example, Maly and Maly (2003: p. 19) interviewed *kūpuna* about Hawai‘i and concludes that “fisheries throughout the islands from Hawai‘i to Ni‘ihau and the Moku Manamana [Necker Island of Papahānaumokuākea] (Moku ‘Aha [the archipelago as a whole]) were rich and sustained all the families who fished.”

In recent decades there has been resurgence in advocacy for protection of GDEs and associated cultural practices, and a movement for biocultural restoration. In 1994 subsistence fishing communities throughout Hawai‘i advocated for the development of Community-Based Subsistence Fishing Areas (CBSFAs), and in 1994 the Hawai‘i Revised Statutes §188-22.6 was passed by the legislature, which gave the Department of Land and Natural Resources the authority to create CBFSAs “to protect and reaffirm fishing practices customarily and traditionally exercised for purposes of native Hawaiian subsistence, culture, and religion,” (Vaughan 2018). Today the vested rights associated with *konohiki* fisheries remain uncertain, and could play an important role in the future of Hawai‘i’s nearshore fisheries, especially as they relate to constitutional protections of Hawaiian traditional practices and legal provisions for CBFSAs (Mackenzie 2015).

An interviewee from our current study describes the resurgence in GDE management in recent decades at Kīholo:

> *"Before us there was a private landowner, nothing was happening down here. And that was the time when [lineal descendent members of today’s community management groups were] here in the 1970’s, [their] family were the caretakers...It was a smaller community then, but during the decades when it was neglected from the 1980s on there was a disconnect, right. There was a time when no one was here being active stewards. So I think we’re trying to rebuild those connections again."*

Several legal battles in the past few decades have highlighted continued interest to maintain GDEs and associated cultural practices, and set the precedent for the current legal protections surrounding GDEs (Public Access Shoreline Hawaii, by Jerry Rothstien and Angel Pilago, v. Hawai‘i County Planning Commission and Nansay Hawaii, Inc. 1995 County of Maui v. Hawaii Wildlife Fund 2019, Ka Pa‘akai o Ka‘aina, Kona Hawaiian Civic Club, and Protect Kohanaiki Ohana v. Land use commission, State of Hawai‘i 2000). The entire island of Moloka‘i was designated as a groundwater management area (GMA) by CWRM in 1992 in response to concerns over water resources (Oki 2006). For instance, at least one contested case hearing ruling limited the pumping of the groundwater by Moloka‘i ranches to a suitable limit to sustain groundwater flow to GDEs used for gathering of of fish (mullet, *‘hole‘hole*, milkfish), and limu (*ogo*, *manauea*, *‘ele‘ele*, and *huluhuluwaena*; IN RE: the Contested Case Hearing on Water Use, Well Construction, and Pump Installation Permit Applications, Filed By Wai‘ola O Moloka‘i,

Inc. and Molokaʻi Ranch, Limited. 2004). During this hearing, the right to *malama ʻaina* (care for the land) was also testified as being sustained by “protecting the natural ecosystems from desecration and deprivation of its natural freshwater resources" (IN RE: the Contested Case Hearing on Water Use, Well Construction, and Pump Installation Permit Applications, Filed By Waiʻola O Molokaʻi, Inc. and Molokaʻi Ranch, Limited. 2004).

A petition to designate Kona’s Kaloko Honōkohau, a site with numerous *loko wai kai*, three *loko iʻa*, and large regions of *muliwai*, as a GMA was denied by CWRM in 2017 (Christian 2017). The criteria for designating a GMA under CWRM require a significant impact to GDEs and cultural practice be seen prior to designation, thus Kaloko Honōkohau could not be listed as a preventative measure. Finally, in 2012 a lawsuit on the neighboring island of Maui was brought by the community and the Sierra Club for violation of the clean water act by Lahaina wastewater treatment plant and the US supreme court ruled to maintain the Clean Water Act in the Maui case in 2019 (County of Maui v. Hawaii Wildlife Fund 2019).

A1: Table 1, GDE species

Category	Species	Hawaiian name	Common name	Status	Loko wai kai	Muliwai	Loko i'a	GDE resources	Associated values
Bird	*Fulica alai*	ʻalae keʻokeʻo	hawaiian coot	endemic	x		x	nesting habitat; water	
Bird	*Himantopus mexicanus knudseni*	aeʻo	hawaiian stilt	Endemic; endangered	x		x	nesting habitat; water	
Bird	*Branta sandvicensis*	nēnē	goose	endemic	x		x	nesting habitat; water	
Bird	*Anas wyviliana*	Koloa maoli	hawaiian duck		x		x	nesting habitat; water	
Bird	*Pterodroma sandwichensis*	ʻuaʻu	hawaiian petrel		x		x	nesting habitat; water	
Bird	*Nycticorax nycticorax hoactli*	ʻaukuʻu	black crowned night heron		x	x	x	habitat	
Bird	*Anas clypeata*	koloa mōhā	northern shoveler	Indigenous; migratory	x		x	habitat	
Bird	*Ayatha affinis*		lesser caup	migratory	x		x	habitat	
Bird	*Arenaria interpres*	ʻakekeke	ruddy turnstone	migratory	x		x	habitat	
Plant	*Bacopa monnieri*	ʻaeʻae	bakopa	indigenous	x		x	water; nutrient source	
Plant; palm	*Pritchardia spp.*	loʻulu		Endemic and indigenous	x		x	water source	
Plant	*Cyperus laevigatus*				x		x	water source	
Plant; palm	*Cocos nucifera*	Niu	coconut palm	indigenous	x		x	water source	food; weaving; building
Plant; succulent	*Sesuvium portulacastrum*	ʻākulikuli		indigenous	x		x	water; nutrient source	food; medicine
Plant; succulent	*Lycium sandwichensse*	ʻōhelo kai			x		x	water source	
Plant; sedge	*Bolboschoenus maritimus*	kaluhā			x		x	water	
Plant; sedge	*Cyperus laevigatus*	makaloa			x		x	water; nutrients	weaving
Aquatic plant	*Ruppia maritima*		Widgeon grass	indigenous	x	x		water; nutrients	
Eel	*Gymnothorax pictus*	puhi kāpʻā	Moray eel	indigenous	x	x	x	habitat	
Shrimp	*Palaemon debilis*	ʻōpae huna	Feeble shrimp	indigenous	x	x	x	habitat	food; fishing
Shrimp	*Machrobrachium grandimanus*	ʻōpae ʻoehaʻa	Hawaiian prawn	endemic	x	x	x	habitat	
Shrimp	*Halocardinia rubra*	ʻōpaeʻula	Anchialine pool shrimp	endemic	x	x	x	salinity- specific reproductive needs; habitat	fishing; environmental indicator
Shrimp	*Procaris hawaiana*			endemic	x			habitat	
Shrimp	*Palaemonella burnsi*			endemic	x			habitat	
Shrimp	*Metabetaues lohena*			indigenous	x			habitat	fishing
Dragonfly	*Pantala flavescens*		globe skimmer	indigenous				habitat; reproduction	
Damselfly	*Megalagrion xanthomelas*		orangeback hawaiian damselfly	endemic	x			salinity- specific reproductive needs	
Crab	*Portunus sanguinolentus*		three spot swimming crab	endemic subspecies		x		nursery habitat	
Fish	*Kuhlia sandvicensis and Kuhlia xenura*	āholehole	flagtail	endemic	x	x	x	salinity-specific reproductive needs; nursery habitat	food; spirituality

A1: Table 1, GDE species

Category	Species	Hawaiian name	Common name	Status	Loko wai kai	Muliwai	Loko i'a	GDE resources	Associated values
Fish	*Chanos chanos*	ʻawa	milkfish	indigenous	x	x	x	nursery habitat	food; spirituality
Fish	*Eleotridae; Gobiidae; and Blennidae*	ʻoʻopu	general term for gobies		x		x	nursery habitat	food; stocked in loko wai
Fish	*Elotris sandwichensis*	ʻoʻopu akupa		endemic	x			habitat; nursery habitat	
Fish	*Awaous stamineous*	ʻoʻopu nākea	stream goby	endemic	x			habitat	
Fish	*Arothron hispidus*	ʻoʻopu hue	white spotted puffer	indigenous		x		nursery habitat	
Fish	*Abudefduf sordidus*	kūpīpī	blackspot sergeant	indigenous	x			habitat	
Fish	*Acanthurus trigostegus*	manini	convict tang	indigenous	x			habitat	food
Fish	*Acanthurus nigrofuscus*	māʻiʻiʻi	brown surgeonfish	indigenous		x		juvenile habitat	
Fish	*Mulloidichthys flavolineatus*	wekeʻā	square spot goatfish	indigenous	x	x		habitat; soft sediment feeding; juvenile habitat	food
Fish	*Albula virgata and Albula glossodonta*	ʻoiʻo	bonefish	Endemic (*A. virgata*) and indigenous (*A. glossodonta*)		x	x	hunting; shelter; juvenile habitat	food
Fish	*Mugil cephalus*	ʻamaʻama	mullet			x	x	anadroumous; salinity specific reproduction	food; spiritual practice
Fish	*Polydactylus sexfilis*	moi	six finger threadfin	indigenous		x	x	anadroumous; salinity specific reproduction; juvenile habitat	food
Fish	*Caranx ignobilis; C. melampygus; C. sexfasciatus*	ʻUlua; papio (juvenile)	jacks			x	x	opportunistic hunting; shelter; juvenile habitat	food
Fish	*Selar crumenophthalmus*	ʻakule	big eyed scad	indigenous		x	x	nursery habitat	food
Fish	*Myripristis berndti and Myripristis amaena*	ʻuʻu	mempachi; squirrelfish	indigenous		x		opportunistic hunting; shelter	food
Fish	*Mulloidichthys spp.*	weke	goatfish	indigenous		x	x	nursery habitat	food
Fish	*Elops hawaiensis*	awaʻawa	ladyfish	indigenous		x	x	nursery habitat	food
Fish	*Neomyxus leucisus*	uouoa	sharpnose mullet	indigenous		x		nursery habitat	food; spirituality
Fish	*Naso unicornis*	kala	bluespine unicornfish	indigenous		x		nursery habitat	food
Fish	*Atherinomorus insularum*	ʻiao	hawaiian silverside	endemic		x		nursery habitat	spirituality
Fish	*Scomberoides lysan*	lai	leatherback	indigenous		x		nursery habitat	food; drum making
Fish	*Sphyraena barracuda*	kākū	great barracuda	indigenous		x		nursery habitat	
Fish	*Encrasicholina purpurea*	nehu	hawaiian anchovy	endemic		x	x	nursery habitat	bait fish
Fish	*Hemiramphus depauperatus; H. acutus*	iheihe	polynesian halfbeak; acute halfbeak	indigenous		x		nursery habitat	
Macroalgae	*Gracilaria coronopifolia*	Limu manauea	ogo	indigenous		x	x	salinity specific growth needs; nutrients; shelter	food; medicine
Macroalgae	*Gracilaria parvispora*	Limu manauea loloa	ogo			x		salinity specific growth needs; nutrients; shelter	food; medicine

A1: Table 1, GDE species

Category	Species	Hawaiian name	Common name	Status	Loko wai kai	Muliwai	Loko i'a	GDE resources	Associated values
Macroalgae	*Ulva prolifera*	Limu ‘ele‘ele		indigenous		x	x	salinity specific growth needs; nutrients; shelter	food; medicine; groundwater indicator; cultured fish food
Macroalgae	*Ulva lactuca*	Limu pālahalaha	Sea lettuce	indigenous		x	x	salinity specific growth needs; nutrients; shelter	food; medicine; groundwater indicator
Macroalgae	*Erythrotrichia carnea*			indigenous			x	habitat	
Macroalgae	*Centroceras clavulatum*			indigenous			x	habitat	
Macroalgae	*Ceramium spp.*			indigenous			x	habitat	
Macroalgae	*Phycocalidia vietnamensis*	Limu pahe‘e	Slippery algae	indigenous		x		associated with SGD habitat	food
Maroalgae	*Grateloupia filicina*	Limu huluhuluwaena		indigenous			x	grow on the seaward side of loko i‘a	food; medicine
Macroalgae	*Hypnea spp.*			indigenous		x		brackish tolerant; nutrients	
Macroalgae	*Spirogyra spp.*			indigenous			x	habitat at spring fed inlets	cultured fish food
Macroalgae	*Vaucheria spp.*						x	habitat	cultured fish food
Macroalgae	*Cladophora spp.*			indigenous	x	x	x	brackish tolerant; nutrients	groundwater indicator; cultured fish food
Macroalgae	*Polysiphonia spp.*			indigenous			x	habitat	cultured fish food
Macroalgae	*Acrochaetium sp.*						x	habitat	cultured fish food
Cyanobacteria	*Lyngbya*			indigenous	x			habitat	
Cyanobacteria	*Schizothrix*			indigenous	x			habitat	
Cyanobacteria	*Scytonema*			indigenous	x			habitat	
Cyanobacteria	*Oscillatoria*			indigenous	x		x	habitat	cultured fish food
Cyanobacteria	*Merismopedia*						x	habitat	cultured fish food
Cyanobacteria	*Microcystis*						x	habitat	cultured fish food
Diatoms	*Navicula; Cymbella; Pleurosigma; Amphora; Melosira; Mastogloia; Coscinodiscus; Nitzchia; Surirella; and Hyalodiscus*						x	habitat; calm water; nutrients	cultured fish food

Appendix 1, Table 1: GDE species that were mentioned in our literature review or in interviews. This table is not an extensive list of GDE associated species or GDE species relevant to cultural practice in Kona; nor are the species-specific associated cultural practices extensive.

A1 Table 2 GDE invasive species

Category	Species	Common name	Status	Loko wai kai	Muliwai	Loko i'a	Impacts
Macroalgae	*Acanthophora spicifera*	Spiny seaweed	introduced	x	x	x	Overgrowth and displacement of native macroalgae; coral
Macroalgae	*Claophora spp.*		native	x	x	x	Bloom forming with excess nutrients and/or sunlight; reduced herbivory
Plant	*Batis maritima*	Pickleweed	introduced	x		x	Overgrowth of GDE systems; displacement of natives; sedimentation
Plant, grass	*Paspalum vaginatum*	Seashore paspalum grass	introduced	x		x	Overgrowth of GDE systems; displacement of natives; sedimentation
Plant, Tree	*Prosopis pallida*	Kiawe	introduced	x	x	x	Increased nitrogen delivery; leaf litter leads to sedimentation
Plant, tree	*Hibiscus tiliaceus*	Hau	polynesian introduction	x		x	Overgrowth of GDEs; shading of GDes
Fish	*Gambusia affinis and Poecilia reticulata*	Guppies	alien invasive	x			Predation of native shrimp; sedimentation of pools; displacement of native species
Fish	*Tilapia spp.*	Tilapia	alien invasive			x	Increased sedimentation; predation of native fish and insect larvae
Jellyfish	*Cassiopea spp.*	Upside down jelly fish	alien, invasive			x	Displacement of native species; stinging cells released into water; stinging of volunteers and caretakers
Appendix 1 Table 2: A list of some invasive species found in Kona's GDEs							

A1 Table 3 GDE salinity tolerance

Species	Organism	Hawaiian Name	Salinity Tolerance	Value
Gracilaria coronopifolia	Macroalgae	Limu manauea	Maximum growth at 27‰; minimum 35‰	Food; medicine; primary productivity
Ulva prolifera	Macroalgae	Limu ‘ele‘ele	Maximum growth at 10 ‰	Food; medicine; primary productivity
Mugil cephalus	Fish	‘Ama‘ama	Maximum survival eggs: 30-32‰; Larvae: 26-28‰; larvae higher growth at 22-23‰; Juveniles <15‰	Food; spiritual practice
Kuhlia xenura, Kuhlia sandvicensis	Fish	Āholehole, āhole	Similar to ‘ama‘ama	Food; spiritual practice
Caranx ignobilis	Fish, Jacks	‘Ulua, Papio	Wide, rely on GDE to prey on *M. cephalus* and *Kuhlia spp.*	Food
Megalagrion xanthomelas	Damselfly		Maximum 15‰	Endemic; endangered species
Appendix 1 Table 3: Salinity tolerance of some GDE associated species.				

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Appendix 2: Results

Quotes of storied histories of GDEs:

“For me, it’s a really sacred relationship with Keahuolū...And you know the *ahupua‘a*, it’s a relationship that you have with her and like with any relationship it’s only over time that you gain deeper and deeper understanding. But, you know, at first you just see the *ahupua‘a* and you’re trying to understand the *ahupua‘a*, but somewhere along the line the *ahupua‘a* is teaching you. You learn a lot more about yourself, you know, the things that are important, all of these things, reflecting and childhood, you know how special it is, and then coming here even as an adult is almost like their childhood, you’re so young yet, you know stomping all over the place, looking, and she begins to reveal herself when you’re ready. Yeah, when you’re ready, and it happens when it happens. And, every time, when it does, it kind of blows you away. It’s almost like getting deeper and deeper, it’s kind of an intimate relationship that you have." -*Kanaka ‘Ōiwi* resource manager

“...resources, that again is a really western term when we look at it... Science uses it a lot but when you look at it from a Hawaiian perspective that is our sources, our sources of who we are, so, because, you’re related because there’s a kinship connection to these sources. It’s like other things, that’s stewardship. That feels good like you’re a good steward, but really it’s a kinship. It kind of jerks you down even further when you’re doing that. So when other kinds of challenges are going on they said when it pertains to the sources, whether it’s mountains or oceans or whatever it is, we’re going to come up with a management plan. These sources are *kūpuna* [ancestors]! So, do you say you’re going to manage your *kūpuna*? No, you’re going to *mālama* your *kūpuna*, when you say *mālama* that’s a whole different feel. We need to *mālama* these sources." -Kanaka ‘Ōiwi resource manager

"This is the Ka‘ele Huluhulu area. So, yeah, I’m taking you to Ka‘ele huluhulu and then I’m taking you to what is the remnant of the Pai‘ea pond. I’m sure you’ve read about it… according to the story when Pele came through she asked for fish and they gave her and then she told them to put up the *lepa* (flags), and this whole area was spared, you can see where the lava stopped. Mahai‘ula behind my grandfather’s house, you can see where the lava stopped. The archaeologist, he did archaeological excavation of *‘iwi* (bones or burials) and while he was excavating the *‘iwi* out to be interred somewhere else he found the coconut tree mold from the lava. He was telling me as far down as in this area, there’s a lava flow piece that comes out. The coconut tree molds are all in that area, so the land did come this far out and he’s sure there was a whole village. Because according to the story it wiped out whole villages and plantations and farms and stone walls and houses, so this whole area must have been just loaded with people. I’m sure the pond went from here, according to the story, it went from here at Ka‘ele Huluhulu all the way to where the airport is today at Keahole." -Kanaka ‘Ōiwi lineal descendant

“To learn the history, and to know that it’s not just an anchialine pool. There is a history to it, and if the *kūpuna* said so that is what it is. And please don’t change the history, please don’t change the words of the kupuna because they were here before we were. And it’s fine to put in your ideas, but don’t change their ideas to fit yours.”-Kanaka ‘Ōiwi lineal descendant

“In 1993 or 1994 there was the second of two that I know of, that I have participated in, 24 hour prayer vigils that the Kānaka community here organized and in 1994, vigil we already had permission from Kamehameha Schools to go to Ahu a ‘Umi and we got permission from the *kumu* [teachers] for the prayer vigil to conduct the 24 prayer vigil up there because it was, in our thinking, was the *piko*, is the *piko* of the island, so the center of the island and, I am telling you

this story because, hiʻuwai, to ceremonially cleanse would be part of such a ceremony, but we were in the middle of the island so we bought salt from Kalaemanō and there is a known water cave up on the Ahu a ʻUmi plane, so we collected water from the water cave and mixed it with the salt of Kalaemanō to conduct the ceremony. So just talking about being at the top of the hydrologic cycle at the point of interception and mixing it with the salt at kalae mano, so that the salt is the *paʻa kai*, that fluid thing made firm."- Kanaka ʻŌiwi lineal descendent

"When we grew up down here, we weren't the only ones that visited down here. For us, we have identity down here and the identity is the three trails that come out down here. The three walking trails from the *mauka makai* [upland to lowland] trail, us and the people that use it, the people from Kalama, you know, we knew everybody from Kalama...It was an important part of our identity. Come from the Kohananui, the Noholani family, my grandmother was born down here at Honokōhau, you know?... My Uncle grew up to be a great hunter, a great horseman so he became a cowboy on Huihui ranch, and Huihui ranch had control of all this land up here." -Kanaka ʻŌiwi lineal descendant and resource manager

"...If you look at the work that Puakea Nogelmeir's folks are doing, they will have the stories of especially the waters of Kāne that speak of the use of the waters there at Kahuwai and using that basal spring to meet the water needs of the people during drought time, but then once identified, that resource is known even until today for people to go there for self care and well being." -Kanaka ʻŌiwi lineal descendant

"So Kīholo was like this place that, one it was a fishing village so it provided food for King Kamehameha and his men but there's just so much history in this area...his two advisors were the uncles that were twins, so Kamanawa was the uncle, the twin that managed this *ahupuaʻa*, we're in the *ahupuaʻa* of Puʻuwaʻawaʻa…So Puʻuanahulu and Puʻu waʻa waʻa there was a ranch up there and they would bring the cattle down to Kīholo, they would hold them on the south side, but the cowboys actually had cottages here at the fishpond, but they would bring the cattle down and a ship from Honolulu would come into the bay. They'd swim the cattle out to the ship and take it to Honolulu. There was a dairy in Honolulu and then the butcher to feed the city. So this place fed, through cattle, through the ranching era, the city of Honolulu." -Resource Manager, Hawaiʻi Island resident

"I like to think of the groundwater as almost the blood that keeps the pond alive, it's coming in through lava tubes and veins through the watershed, it enters the fishpond, and then I like to think of the tides as the heartbeat, because it's moving that fresh water around. So most time the fresh water is discharging out into the bay except for on a high high tide for about an hour the water flow switches and all comes in from the ocean and during that time it increases the residence time of the water in the pond, so you get a phytoplankton bloom, it turns bright green, and then it switches really fast and flushes out. All of that is connected with why this reef is so healthy, because it's increasing productivity, we have these phytoplankton blooms that are feeding the fish offshore and you see this change of like the phytoplankton, the trophic levels change as you move out of the fishpond." -Resource Manager, Hawaiʻi Island resident

"To bring back the health and abundance of Kīholo fishpond to feed the community once again. And feeding the community can be in the physical sense so we'd like to have traditional harvests, sustainable harvests from the fishpond again and we've started that in a very limited way for special occasions. When we have our *keiki* [children's] camps, we'll have one dinner where everyone will eat an *ʻaholehole* from the pond. We feel that's very significant, work in the pond, learn from the pond, and eat from the pond. It sustains and grows them, it makes that connection even more visceral." -Resource Manager, Hawaiʻi Island resident

“So Kīholo was this place that, one it was a fishing village so it provided food for King Kamehameha and his men but there’s just so much history in this area.” -Resource Manager, Hawai‘i Island resident

“So at Waikoloa they wanted to expand a huge development and basically wipe out a bunch of anchialine pools... The call went out to our Hui Loko network to all of our agencies that we need advocates at these meetings to say, one, you can’t just bulldoze anchialine pools, they’re valuable resources that should be protected. There was a whole complex of anchialine pools in that area. So a lot of people showed up to the meeting and they didn’t give the developer the permit to develop. When people show up and say no this isn’t okay, that you do have the power to stop those things from happening. But it takes people being active and being willing to drop everything and go to those meetings, or submit testimony.” -Resource Manager, Hawai‘i Island resident

Appendix 3: Acronyms and Glossary

Acronyms

CWRM: Commission on Water Resource Management

GDE(s): Groundwater dependent ecosystem(s)

GMA: Groundwater management area

SGD: Submarine groundwater discharge

ʻŌlelo Hawaiʻi, Hawaiian Language Terms

The following translations are from Pukui and Elbert (1986) via wehewehe.org, unless otherwise specified. Please note that while many ʻŌlelo Hawaiʻi terms have multiple meanings, we have only included the translations used in the context of this publication here.

Āholehole: *Kuhlia sandvicensis* and *Kuhlia xenura*, flagtail[2]

ʻAhupuaʻa: land division from mountain peak to reef crest, often associated with watersheds

ʻAhi: yellowfin tuna, *Thunnus albacares*

ʻĀina: land

Aku: skipjack tuna, *Katsuwonus pelamis*

Akua: god or gods and/or goddesses

Aloha: love, affection, compassion

Aloalo: most prawns[1]

Aliʻi: ruling class, royalty

ʻAmaʻama: *Mugil cephalus*, grey mullet[3]

Awaʻaua: *Elops hawaiensis*, Hawaiian ladyfish[2]

Ana wai: water cave

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[1] Titcomb et al. 1978
[2] Keala 2007

Awa: *Chanos chanos*, milkfish[3]

Awa‘aua: *Elops hawaiensis*, Hawaiian ladyfish[4]

Hāpuna: source water, spring, or pool

Hoa‘āina: tenant, caretaker

Holoholo: to journey

Ho‘omana: creating, spirituality[5]

Huna: hidden, sacred

‘Ike: Knowledge from diverse sources[6]

Iwi: literally bones, cherished remains

Kāheka: tide pool with groundwater influence

Kānaka ‘Ōiwi/Kanaka ‘Ōiwi: native Hawaiian (plural/singular)

Kāne: leading of the four major Hawaiian gods, the masculine

Kanaloa: A major god

Kapu: Taboo, prohibition; special privilege or exemption from ordinary taboo; sacredness; prohibited, forbidden; sacred, holy, consecrated; no trespassing, keep out

Keiki: child, children

Kuleana: Honored responsibility, privilege

Kupuna/Kūpuna: elder or elders, ancestors

Kilo: observation, study, examine

Ki‘o wai: pool of water

Ko‘a: on shore and in ocean fishing shrines and station markers where fish were fed and cultivated[7]

Konohiki: resource stewards under direction of the ali‘i (chiefs), to invite ability (kono-ability, hiki-invite)[8]

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[3] Jokiel et al. 2011
[4] Keala 2007
[5] Gould et. al 2019
[6] Pascua *et al.* 2017
[7] Maly and Maly 2003
[8] Andrade 2008

Konohiki management system: Under this system, *konohiki* were stewards of fisheries and *ahupua‘a* resources under the direction of the *ali‘i* (ruling class)

Kulāiwi: burial sites

Kuleana: privileged responsibility

Kumu wai: source or spring water

Kupuna/Kūpuna: elder (singular)/elders, ancestors (plural)

Kū‘ula: fishing altar associated with the man turned god of the same name[9]

Lā‘au lapa‘au: Hawaiian herbal and/or Indigenous medicine

Limu: macroalgae and some algae-like organisms (mosses, invertebrates)

Limu ‘ele‘ele: *Ulva prolifera*, a fine green hair-like seaweed[8]

Limu manauea: *Gracilaria coronopifolia*[9]

Limu pālahalaha: *Ulva lactuca*, sea lettuce[8]

Loko i‘a: Indigenous Hawaiian aquaculture systems[10], literally “fish pond”

Loko i‘a kuapā: walled aquaculture systems

Loko wai: freshwater pond or pool

Loko wai kai: anchialine pools where fresh and salt water mix[11]

Luawai: well

Makai: towards the ocean

Mālama: to care for

Mauka: inland, towards the mountains

Mana: Spirituality, spiritual strength

Mele: song

Momona: fat, fertile, juicy

Mo‘o: water spirits

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[9] Abbott 1984
[10] Maly and Maly 2003
[11] A term used by John Ka‘ele Makule Sr., a lineal descendant of the Kekaha Wai ‘Ole region, in nūpepa publications between 1928-1930, as translated by Maly (1998).

Mo‘olelo: story, tale, myth, legend

Muliwai: estuarine

Nūpepa: Hawaiian language newspaper

Ogo: Not a Hawaiian language term, but the japanese term that is used locally to refer to *Gracilaria parvispora*, for which no current Hawaiian language term is widespread[12]

‘Ō‘io: Bone fish, *Albula virgata* and *Albula glossodonta*[13]

Ola mau: physical and mental well being

Oli: chant

One hānau: birth sites

‘Ōpae: shrimp

‘‘ōpae ‘ula: *Halocardinia rubra*, Hawaiian anchialine pool shrimp

‘Ōpae huna: *Palaemon debilis,* anchialine pool shrimp

‘Opelu: *Decapturus spp.*, four species of this inshore and pelagic schooling fish species exist in Hawaiian waters. A historically important food species, caught and maintained with palu (chum) that in some cases contained ‘‘ōpae ‘ula (*Halocardinia rubra*). Used as bait for pelagic fishing of Ahi (tuna), ono, mahimahi, rainbow runners, and marlin.[14]

Pāpio: Young *Caranx ignobilis* and *Caranx melampygus*[13]

Pele: volcano goddess

Pilina kānaka: Social systems and networks[15]

Pono: righteous, correct, moral

Mākāhā: Sluice gates of a loko i‘a.

Māpuna: spring water

Moi; *polydactylus sexfilis*, king’s fish[13]

Muliwai: estuarine water, can occur as a result of SGD outflow in nearshore systems

Wahi pana: legendary place

Wai: water

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[12] Abbott 1984
[13] Jokiel et al. 2011
[14] Maly and Maly 2003
[15] Pascua 2017

Wai kai: mixing fresh and salt water

Wai ʻōpae: waters containing *ʻōpae* (shrimp)

Wai puna: spring water

Wana: sea urchin

Weke: goat fish, *Mulloidichthys spp.*

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Appendix 4: Interview Questions

There are two sets of research questions, the first is for agencies and resource managers, while the second is for community members.

4.1 Interview questions for agencies and resource managers

Overview/introduction:

1. Can you describe this place (these places) and your connection to this place (these places)?
    a) What role does your agency play in managing or influencing groundwater, spring, or freshwater influenced systems?
    b) What are the goals and objectives of your agency in managing these systems?
    c) What kind of influence do you think your agency ‘s management has on these systems?
2. What other key agencies, community groups, or people play a role in this place?
3. What do you think matters for the health of this place?
4. Are there living resources found here that are important for the community? Algae, fish, invertebrates (vana, limpets, ‘ōpae)?
5. Do you think springs and other freshwater matter for this place? If so, how?
    a) Do you know any names for the waters found in this area? If so, are there those that you would like to share?
    b) Are there particular fish, algae/limu, or inverts that need fresh or brackish water during their life cycle here?
6. Have you heard the term “groundwater dependent ecosystem” or GDE? If so, does it resonate with you?

General uses and values

7. What makes these systems important for your agency and the community? How do people use, value, and care for this place?
    a) Do these systems support livelihoods? If so, how?
    b) Do these systems support social connections in the community? If so, how?
    c) Do these systems support cultural practice and values? If so, how?
8. How do you think people‘s connection and use of groundwater dependent systems (fresh water influenced systems) has changed throughout time (your lifetime and before)?
    a) Do you know of any historical uses of these systems? Do those uses continue today?
    b) In what other ways do you think use and care for this place has changed?
    c) What role do you feel that land and water management decisions have had on these systems in the past and currently?
9. Have you noticed any changes in the amount, quality, or location of freshwater?
    a) Do you know of any historical changes in the amount, quality, or location of freshwater?
10. Have you noticed any changes in the algal or animal life in these systems?
    a) Do you know of any particular species to be indicators of water quality or other changes in the system?
11. Do you see any threats to the health of this place and peoples’ connection to it? If so, what?
    a) What role do you see the quality and quantity of water playing in this? If so, what do you think has caused this change?

    b) What, if anything, would you like to see changed to improve management/care of this place?
12. What vision does your agency have for the future of this place? What would you like to see?

Conclusion

13. Is there anything else you would like to share?
    a) Is there anyone you can refer me to who may be willing to share knowledge of these or similar places?

4.2 Interview questions for community members (anyone not associated with an agency or acting as a resource manager)

Overview/introduction:

1. Can you describe this place (these places) and your connection to this place (these places)?
2. What key agencies, community groups, or people play a role in this place?
3. What do you think matters for the health of this place?
4. Are there living resources found here that are important to you or your community? Limu, fish, other animals (vana, limpets, ʻōpae)?
5. Do you think springs and other freshwater matter for this place? If so, how?
    a) Do you know any names for the waters found in this area? If so, are there those that you would like to share?
    b) Are there particular fish, algae/limu, or other animals that need fresh or brackish water during their life cycle here?

6. Have you heard the term “groundwater dependent ecosystem” or GDE? If so, does it resonate with you?

General uses and values

7. What makes these systems important for you, your family and the community? How do people use, value, and care for this place?
    a) Do these systems support your, your family, or the community’s livelihoods? If so, how?
    b) Do these systems support social connections in the community? If so, how?
    c) Do these systems support cultural practice and values? If so, how?

8. How do you think peopleʻs connection and use of these fresh water influenced systems (fresh water influenced systems) has changed throughout time (your lifetime and before)?
    a) Do you know of any historical uses of these systems? Do those uses continue today?
    b) In what other ways do you think use and care for this place has changed?
    c) What role do you feel that land and water management decisions have had on these systems in the past and currently?

9. Have you noticed any changes in the amount, quality, or location of freshwater?
    a) Do you know of any historical changes in the amount, quality, or location of freshwater?

10. Have you noticed any changes in the algal or animal life in these systems?

a) Do you know of any particular species to be indicators of water quality or other changes in the system?

11. Do you see any threats to the health of this place and peoples' connection to it? If so, what?
    a) What role do you see the quality and quantity of water playing in this? If so, what do you think has caused this change?
    b) What, if anything, would you like to see changed to improve management/care of this place?

12. What vision do you or your community have for the future of this place? What would you like to see?

Conclusion

13. Is there anything else you would like to share?
    a) Is there anyone you can refer me to who may be willing to share knowledge of these or similar places?