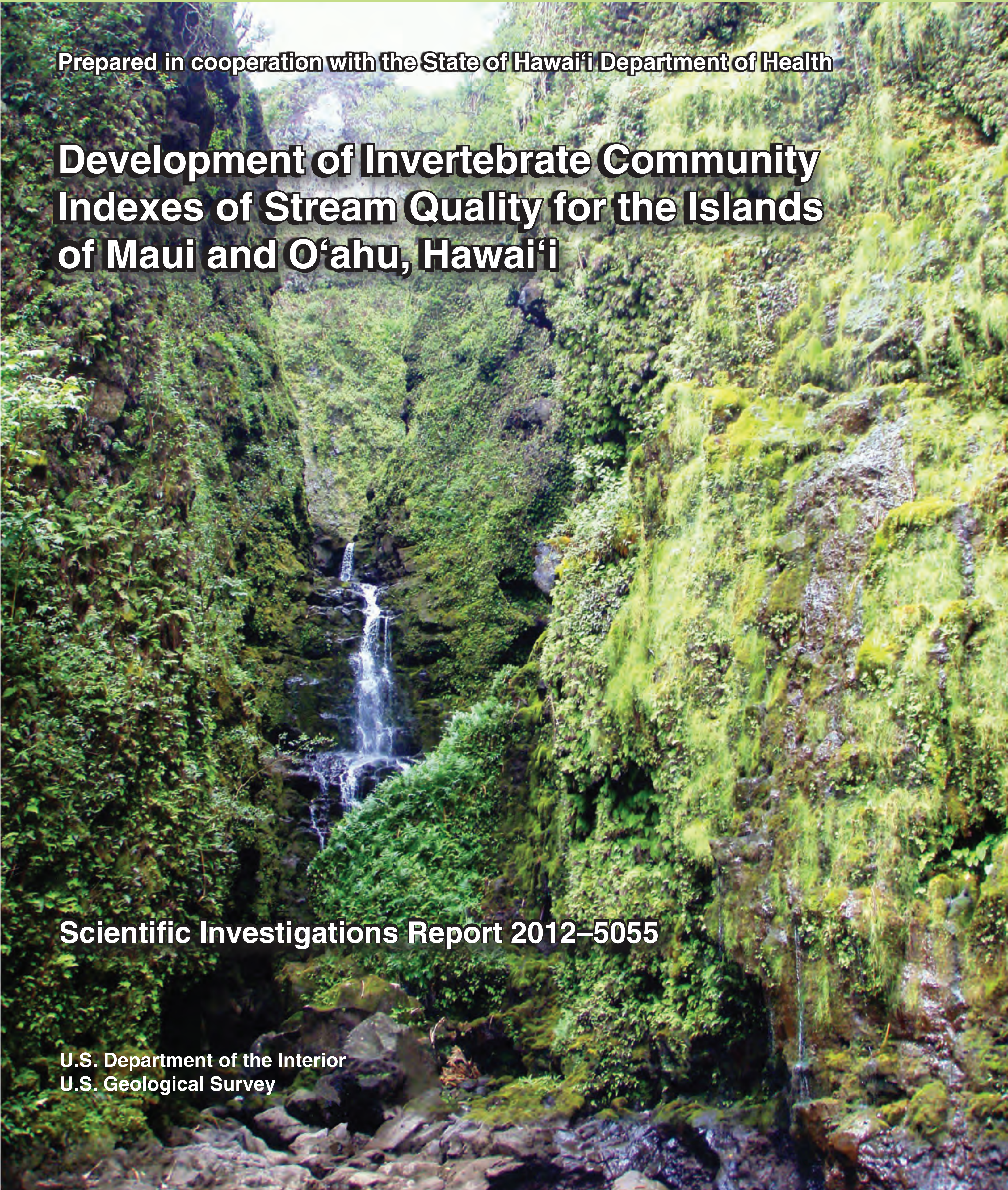
Prepared in cooperation with the State of Hawai‘i Department of Health

Development of Invertebrate Community Indexes of Stream Quality for the Islands of Maui and O‘ahu, Hawai‘i



Scientific Investigations Report 2012–5055

U.S. Department of the Interior
U.S. Geological Survey

COVER:
Waterfall at one of the valleys of East Wailua Iki Stream near Wailua, east Maui, Hawai‘i. (Photograph by Adam G. Johnson, U.S. Geological Survey)

Development of Invertebrate Community Indexes of Stream Quality for the Islands of Maui and O‘ahu, Hawai‘i

By Reuben H. Wolff

Prepared in cooperation with the State of Hawai‘i Department of Health

Scientific Investigations Report 2012–5055

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

This report and any updates to it are available online at:
http://pubs.usgs.gov/sir/2012/5055/

Suggested citation:
Wolff, R.H., 2012, Development of invertebrate community indexes of stream quality for the islands of Maui and O‘ahu, Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2012-5055, 191 p.

Contents

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to mean sea level.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Development of Invertebrate Community Indexes of Stream Quality for the Islands of Maui and O‘ahu, Hawai‘i

By Reuben H. Wolff

Abstract

In 2009–10 the U.S. Geological Survey (USGS) collected physical habitat information and benthic macroinvertebrates at 40 wadeable sites on 25 perennial streams on the Island of Maui, Hawai‘i, to evaluate the relations between the macroinvertebrate assemblages and environmental characteristics and to develop a multimetric invertebrate community index (ICI) that could be used as an indicator of stream quality. The macroinvertebrate community data were used to identify metrics that could best differentiate among sites according to disturbance gradients such as embeddedness, percent fines (silt and sand areal coverage), or percent agricultural land in the contributing basin area. Environmental assessments were conducted using land-use/land-cover data and reach-level physical habitat data.

The Maui data were first evaluated using the previously developed Preliminary–Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) to determine if existing metrics would successfully differentiate stream quality among the sites. Secondly, a number of candidate invertebrate metrics were screened and tested and the individual metrics that proved the best at discerning among the sites along one or more disturbance gradients were combined into a multimetric invertebrate community index (ICI) of stream quality. These metrics were: total invertebrate abundance, Class Insecta relative abundance, the ratio of Trichoptera abundance to nonnative Diptera abundance, native snail (hīhīwai) presence or absence, native mountain shrimp (‘ōpae) presence or absence, native torrent midge (*Telmatogeton* spp.) presence or absence, and native *Megalagrion* damselfly presence or absence. The Maui ICI classified 15 of the 40 sites (37.5 percent) as having ”good” quality communities, 17 of the sites (42.5 percent) as having “fair” quality communities, and 8 sites (20 percent) as having “poor” quality communities, a classification that may be used to initiate further investigation into the causes of the poor rating.

Additionally, quantitative macroinvertebrate samples collected from 31 randomly selected sites on O‘ahu in 2006–07 as part of the U.S. Environmental Protection Agency’s Wadeable Stream Assessment (WSA) were used to refine and develop an ICI of stream quality for O‘ahu. The set of metrics that were included in the revised index were: total invertebrate abundance, Class Insecta relative abundance, the ratio of Trichoptera abundance to nonnative Diptera abundance, turbellarian relative abundance, amphipod relative abundance, nonnative mollusk abundance, and nonnative crayfish (*Procambarus clarkii*) and/or red cherry shrimp (*Neocaridina denticulata sinensis*) presence or absence. The O‘ahu ICI classified 10 of the 31 sites (32.3 percent) as “good” quality communities, 16 of the sites (51.6 percent) as ”fair” quality communities, and 5 of the sites (16.1 percent) as ”poor” quality communities. A reanalysis of 18 of the O‘ahu macroinvertebrate sites used to develop the P–HBIBI resulted in the reclassification of 3 samples.

The beginning of a statewide ICI was developed on the basis of a combination of metrics from the Maui and O‘ahu ICI’s. This combined ICI is intended to help identify broad problem areas so that the Hawaii State Department of Health (HIDOH) can prioritize their efforts on a statewide scale. Once these problem areas are identified, the island-wide ICIs can be used to more accurately assess the quality of individual stream reaches so that the HIDOH can prioritize their efforts on the most impaired streams. By using the combined ICI, 70 percent of the Maui sites and 10 percent of the O‘ahu WSA sites were designated as “good” quality sites; 25 percent of the Maui sites and 45 percent of the O‘ahu WSA sites were designated as “fair” quality sites; and 5 percent of the Maui sites and 45 percent of the O‘ahu WSA sites were designated as “poor” quality sites.

Introduction

The Hawaiian Islands are the most isolated island chain in the world. Over the past few million years, the islands developed a unique biota that have adapted to fill the available niches on the tropical volcanic oceanic islands. Since the arrival of humans on the islands, the landscape has continually been modified to accommodate each succeeding generation and, more recently, a rapidly expanding and diverse population. The pressures exerted on the native ecosystems by human activities over the years have taken their toll, as Hawai‘i has been labeled the “extinction capital of the world” (Groombridge, 2008). Agricultural activity has expanded from subsistence farming of taro to feed local populations to large-scale sugarcane and pineapple operations with world-wide distributions. The harvesting of precious woods, and decades of foraging by free-ranging cattle, goats, and pigs have destroyed much of the native forests, decimated many watersheds, and polluted many of the streams and rivers (Judd, 1919; Cox, 1991). Many streams have been altered by channelization for flood control and bridges, diverted for off-stream water uses, affected by a proliferation of numerous introduced species, and contaminated with runoff from households, roadways, farmlands, military complexes, and industries (Brock, 1952; Timbol and Maciolek, 1978; Wilcox, 1996; Brasher, 2003; Brasher and Wolff, 2004). These problems are not unique to Hawai‘i, as governments around the world strive to accommodate an ever-growing populace.

Recognition of these problems has propelled efforts to protect and conserve the watershed ecosystems. Forests have been replanted, reserves have been created, ungulates have been removed, and watersheds are being protected (Hosmer, 1908; Gagne, 1988; Holt, 1988; Derrickson and others, 2002). Diverted water has in some cases been either restored or partly restored, and diversion structures have been modified to be more accommodating to the migratory native species (Commission on Water Resource Management, 2006; Commission on Water Resource Management, 2010; Board of Water Supply, 2010). Federal, State, and local agencies have endeavored to protect native species, prevent the introduction of potentially harmful species, and regulate harmful contaminants from entering the environment. These combined efforts have, over the years, restored some of the structure and function of the watershed ecosystems, though many native species have already been replaced or displaced by introduced species and habitat loss. It is within this complexity of shifting environmental paradigms and competing demands on limited resources that State and Federal agencies are mandated to protect and restore the water resources of Hawai‘i.

In 1972, the U.S. Congress enacted the Clean Water Act (CWA) to protect the Nation’s vital water resources. The CWA is administered by the U.S. Environmental Protection Agency (USEPA) and gives states the primary responsibility for implementing programs to protect and restore water quality, including monitoring and assessing the Nation’s waters and reporting on their quality. The Clean Water Act’s objective is to restore and maintain the chemical, physical, and biological integrity of the Nation’s surface waters (33 U.S.C. §1251).

Under section 305 of the CWA, each State is required to prepare and submit biennial reports to the USEPA with an analysis detailing their efforts to protect and restore the Nation’s surface waters. The reports provide an evaluation of whether these conservation efforts have achieved, or eventually will achieve, the desired goals, which include: the protection and propagation of a balanced population of shellfish, fish, and wildlife, and the safety of recreational activities in and on the water (305(b) Report). The USEPA, in turn, provides this information to the U.S. Congress and to the American public.

Section 303(d) of the CWA requires the State of Hawai‘i Department of Health (HIDOH) to generate the CWA §303(d) List of Water Quality-Limited Segments (WQLS) for surface waters that are exceeding or will likely exceed State Water Quality Standards (WQS) (303(d) List of Impaired Waters) (Henderson and Harrigan-Lum, 2002; Koch and others, 2004). Surface waters that have been determined to be water-quality limited must then be surveyed to ascertain the Total Maximum Daily Load (TMDL) for each identified constituent that exceeds the State WQS. The TMDL is the maximum daily load of the constituent, established for each WQLS, which can enter the stream without violating the State WQS.

The HIDOH is tasked with determining the health and biological integrity of the State’s freshwater streams by using consistent and repeatable methods. The HIDOH has been testing and refining the Hawai‘i Stream Bioassessment Protocol (HSBP) (Kido, 2002) for the past several years and is interested in expanding the protocol to include benthic invertebrates. The HSBP is currently based on physical habitat characteristics; the diversity, abundance, and age class distribution of native fish, mollusks, and crustaceans; and the diversity and abundance of introduced fish, mollusks, and crustaceans as indicators of biotic integrity (Kido, 2002). Bioassessment protocols, such as the HSBP, are designed to identify stream-quality problems associated with both point- and nonpoint-source pollution and document long-term regional changes in stream quality (Resh and Jackson 1993), and to do so in a cost-effective way (Lenat and Barbour, 1994; Resh and Jackson, 1993). Bioassessment protocols typically evaluate a variety of organisms to provide an integrated and robust assessment of stream quality (Lenat and Barbour, 1994). The HIDOH may eventually include aquatic-community-based biocriteria into the State water quality standards to assist in determining the condition of various waterbodies. Eventually, when enough data exist for the inclusion of biocriteria into the State water quality standard Chapter 11-54, HIDOH anticipates integrating biological integrity methods to ascertain the condition of various waterbodies, not only streams, by consideration of the health status of the biological communities and not on the basis of water chemistry alone. These improved methods will enable the State to make better decisions in the protection of aquatic resources.

Benthic invertebrates are by far the most commonly used group of organisms for biomonitoring because: (1) they are ubiquitous and, consequently, can be affected by environmental perturbation in a variety of aquatic systems and habitats; (2) the large number of species offers a wide spectrum of responses to environmental stressors; (3) their basic sedentary nature allows effective spatial analyses of pollutants or disturbance effects; and (4) some have relatively long life cycles, which allows elucidation of temporal changes caused by perturbation (Rosenberg and Resh, 1993).

Results from a study conducted by the U.S. Geological Survey (USGS) Pacific Islands Water Science Center (PIWSC) in cooperation with the HIDOH demonstrated that a combination of metrics based on native and nonnative benthic macroinvertebrates collected from streams on the islands of Oahu and Kauai in 1999, 2000, and 2003 could be used as indicators of stream quality in Hawai‘i (Wolff, 2005). The individual metrics that were most effective for discerning stream quality were combined to create the Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI). The individual metrics were: (1) the total invertebrate abundance (per square meter); (2) the abundance of nonnative mollusks (per square meter); (3) the abundance of amphipods (per square meter); (4) the relative abundance of the class Insecta (as a percentage of the total abundance); (5) the presence or absence of the nonnative crayfish *Procambarus clarkii*; (6) the presence or absence of the native mountain shrimp *Atyoida bisulcata*; and (7) the total number of taxa (taxonomic richness). The conclusions of this feasibility study, however, were based on a limited number of samples collected at only 19 sites on 14 streams on O‘ahu and at 9 sites on 7 streams on Kaua‘i. The study also concluded that differences in the macroinvertebrate assemblages among the islands should be examined further, and that a larger number of sites, especially sites representing “least disturbed” reference conditions on the other Hawaiian Islands, would be needed to develop an effective statewide invertebrate community index (ICI) of stream quality.

Subsequently, the USGS and the HIDOH, in a cooperative effort, collected information on macroinvertebrates, water quality, and habitat at 40 randomly selected sites on O‘ahu as part of the USEPA’s probability-based Wadeable Streams Assessment (WSA) in 2006–07 (Wolff and Koch, 2009). This sampling effort greatly increased the number of sites available to develop an Invertebrate Community Index (ICI) for O‘ahu.

In response to a need for additional information on the relationships between benthic macroinvertebrate assemblages and stream quality in Hawai‘i, the USGS, again in cooperation with the HIDOH, in 2009 and 2010 conducted the study described in this report. The objective of this study was to provide the HIDOH with new tools needed to assess the biological condition of streams in Hawai‘i. The new assessment tools are based on aspects of the aquatic macroinvertebrate assemblages and can be applied to both targeted and probabilistic monitoring designs employed by the HIDOH. The results generated by the present cooperative study will help the HIDOH in its effort to incorporate biological criteria into the State water quality standards by providing scientific information addressing the relations among benthic macroinvertebrate assemblages and stream quality parameters.

The current study does not directly address the issues surrounding the effects of surface-water withdrawal on the benthic macroinvertebrate communities or on the amphidromous species. The study was not intended to provide comprehensive biological surveys of the study areas. The sampling methods employed in this study, and described in this report, were not intended to assess the overall biodiversity of the instream and riparian habitats, but to provide a consistent, repeatable technique for collecting representative samples of the benthic macroinvertebrate assemblages, in a quantitative way, to allow for comparisons among streams. Although this study was not intended to directly assess or monitor the status of the native aquatic species, this report does provide valuable information on the distributions and abundances for some native species.

More specifically, this report describes the development of an effective island-specific invertebrate community index (ICI) of stream quality for the islands of Maui, using the new benthic macroinvertebrate data collected on Maui during this study, and O‘ahu, using macroinvertebrate data collected on O‘ahu during a previous study, and to refine the preliminary statewide index developed earlier by the USGS (Wolff, 2005).

Acknowledgments

Access to study sites was graciously provided by the following entities and individuals: East Maui Irrigation Co., Ltd. (Mark Vaught), West Maui Land Company (Dave Minami), Mākila Land Co., LLC (Rory Frampton and Peter Martin), West Maui Investors, LLC (Sharon Wright), Hui O Nā Wai ‘Ehā (John Duey), Maui District State Parks Superintendent (Phil Ohta), Waihe‘e Valley Plantation (Kim Gaines and Frank Rocha), Maui Land and Pineapple Co., Inc. (Marlon Domingo), Kā‘anapali Farm Services Inc. (Robbie Vorfeld), Maui County, Department of Water Supply (Joe Mendonca), State of Hawai‘i, Department of Land and Natural Resources, Division of Aquatic Resources (Dan Polhemus and Skippy Hau), David Niehaus, Harry Apolo, Gladys Kanoa, and Hans Michel. Additional field assistance was provided by Eric Luke (East Maui Watershed Partnership). Identification and enumeration of the benthic macroinvertebrate sampling was performed by EcoAnalysts, Inc. (Gary Lester and Shanda McGraw).

This study could not have been completed without the help of the following U.S. Geological Survey personnel who provided assistance with stream reconnaissance and in all aspects of data collection: Bobbie L. Arruda, Maoya Bassiouni, Stephen B. Gingerich, Adam G. Johnson, and Sarah N. Rosa.

Macroinvertebrates in Hawaiian Streams

The native stream fauna of Hawai‘i is relatively depauperate compared to that of continental streams. Widespread diverse orders of insects such as Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) are absent from the native biota (Howarth and Polhemus, 1991). Historically, the isolation of the Hawaiian archipelago prevented large-scale colonization because of the limited dispersal mechanisms of most aquatic invertebrates. Many native stream species were most likely derived from marine ancestors, although a few arrived by flight, including the ancestors of the native damselflies and dragonflies, or by various other mechanisms such as rafting, carried in the jet stream, or attached to migratory birds (Zimmerman, 1947). Native insects of the order Diptera are thought to have adapted from marine ancestors (Newman, 1977; Newman, 1988; Howarth and Mull, 1992). The isolation of the islands enabled the few successful colonizers to undergo natural selection and adaptive radiation, resulting in a high degree of endemism and specialization among the islands' biota (Carlquist, 1980).

The native species of Hawai‘i adapted to the unique environment of precontact Hawaiian streams and, in the absence of competitors and predators, evolved to be less aggressive than many of the introduced species (Carlquist, 1980). Today, altered and degraded streams contain a proliferation of introduced species that are better competitors and far more tolerant of these conditions than are native species. These introduced species arrived in Hawai‘i in a variety of ways and for various reasons. Some introductions were State sanctioned, such as the Tahitian prawn *Macrobrachium lar*, whereas others, such as the Asiatic clam, *Corbicula fluminea*, were not, although both were intentionally introduced for food purposes (Devick, 1991). A myriad of insect species were accidentally introduced aboard ships and planes and amongst imported aquatic plants (Eldredge, 1992). Aquatic fish parasites, such as the nematode *Camallanus cotti*, were accidentally introduced together with intentionally released Poeciliid fishes (Font and Tate, 1994; Vincent and Font, 2003a, 2003b).

There is some evidence that species with univoltine life cycles (reproducing once per year) in temperate streams may have the ability to switch to multivoltine life cycles (reproducing throughout the year) in Hawaiian tropical streams, which lack the marked seasonality of temperate streams. This has been documented for the introduced caddisfly (Trichoptera) *Cheumatopsyche analis* (previously *pettiti*) (Kondratieff and others, 1997; Wolff, 2000). Although the seasons in Hawai‘i are considerably less variable than those in temperate regions, even minor seasonal variations in discharge, water temperature, and sunlight can be important in the development of macroinvertebrate communities in Hawaiian streams (Wolff, 2000).

The larger native stream animals in Hawai‘i (fishes, shrimp, and snails) are primarily amphidromous, having evolved from marine dwelling ancestors, and have retained a marine larval life-stage (McDowall, 1993; McDowall, 2003). Adults lay eggs in the streams, the eggs hatch, and the larvae drift to the ocean, where they spend months as plankton before returning to freshwater (Beckley, 1883; Ford and Kinzie, 1982; Kinzie, 1990; Yamamoto and Tagawa, 2000). Unlike the salmon of the Pacific Northwest, there is no current evidence that these animals return to their stream of birth, and it appears that there is enough mixing of the gene pool in the ocean currents to have prevented speciation among islands (Fitzsimmons and others, 1990). The longitudinal (upstream/downstream) distribution of these animals is largely controlled by their ability to migrate upstream unimpeded (Ford and Kinzie, 1982). Four of the five ‘o‘opu are true gobies and have fused pelvic fins. The fused pelvic fin forms a suction disk that enables these fishes to attach themselves to stream substrate and climb cascades and waterfalls (Benbow and others, 2002). Differences in clinging and climbing abilities have allowed the native fish species to migrate upstream and inhabit stream reaches according to their relative abilities to cling to the stream substrate. The mountain shrimp known as ‘ōpae or ‘ōpaekala‘ole has exceptional climbing ability and most often inhabits the upper stream reaches (Couret, 1976; Kinzie, 1990). The endemic freshwater snail, *Neritina granosa,* known as hīhīwai, generally inhabits lower and middle stream reaches, preferring cold, well-oxygenated waters (Ford, 1979; Kinzie, 1990). The endemic brackish-water snail, *Neritina vespertinus,* locally known as hapawai, and the endemic prawn, *Macrobrachium grandimanus,* locally known as ‘ōpae ‘oeha‘a, are restricted to the lower stream reaches and estuaries. Segregation along elevation and longitudinal gradients reduces the amount of competition among native species for resources.

Description of Study Areas

The study area included parts of the islands of Maui and O‘ahu. The Island of Maui, the second largest of the Hawaiian Islands, occupies an area of 727.3 mi^2 (Juvik and Juvik, 1998) between latitudes 20°30' and 21°05' North and between longitudes 156°45' and 155°55' West (fig. 1). The island is composed mainly of two shield volcanoes (Stearns and Macdonald, 1942): the older West Maui Volcano (West Maui Mountain), which rises to an altitude of 5,788 ft, and the younger East Maui Volcano (Haleakalā), which rises to an altitude of 10,023 ft. The interior parts of the West Maui Mountain are relatively rugged and steep in comparison to the gently sloping central saddle, or isthmus, that connects the East and West Maui Volcanoes. The central isthmus was formed by Haleakalā lava flows that banked up against and were deflected by the preexisting West Maui Mountain and were later buried by marine and terrestrial sedimentary deposits. The interior parts of West Maui Mountain and the northern flank of Haleakalā in East Maui are mainly forested conservation areas, the central isthmus is used primarily for agricultural purposes, and the coastal areas commonly are developed for residential or other urban uses. The Kahului and Wailuku areas of north-central Maui are the main population centers near the study area. Much of the water used to irrigate crops on Maui is diverted from streams, in both east and west Maui, along an extensive system of ditches (fig. 1; Wilcox, 1996).

The island of O‘ahu, the third largest of the Hawaiian Islands, occupies an area of 597.1 mi^2 (Juvik and Juvik, 1998) between latitudes 21°15' and 21°45' North and between longitudes 158°20' and 157°35' West (fig. 2). The landscape of O‘ahu ranges from a broad coastal plain, surrounding much of the island, to steep interior mountains. O‘ahu can be divided into two primary physiographic regions, windward and leeward, which relate to the exposure of these areas to the northeasterly trade winds and orographic rainfall. In general, the windward side has smaller drainage basins, higher rainfall, and perennial streams, whereas the leeward side has larger drainage basins, lower rainfall, and intermittent streamflow (Oki and Brasher, 2003). The leeward area can be further subdivided into the physiographic regions of leeward, central, and Wai‘anae (west) areas (Oki and Brasher, 2003).

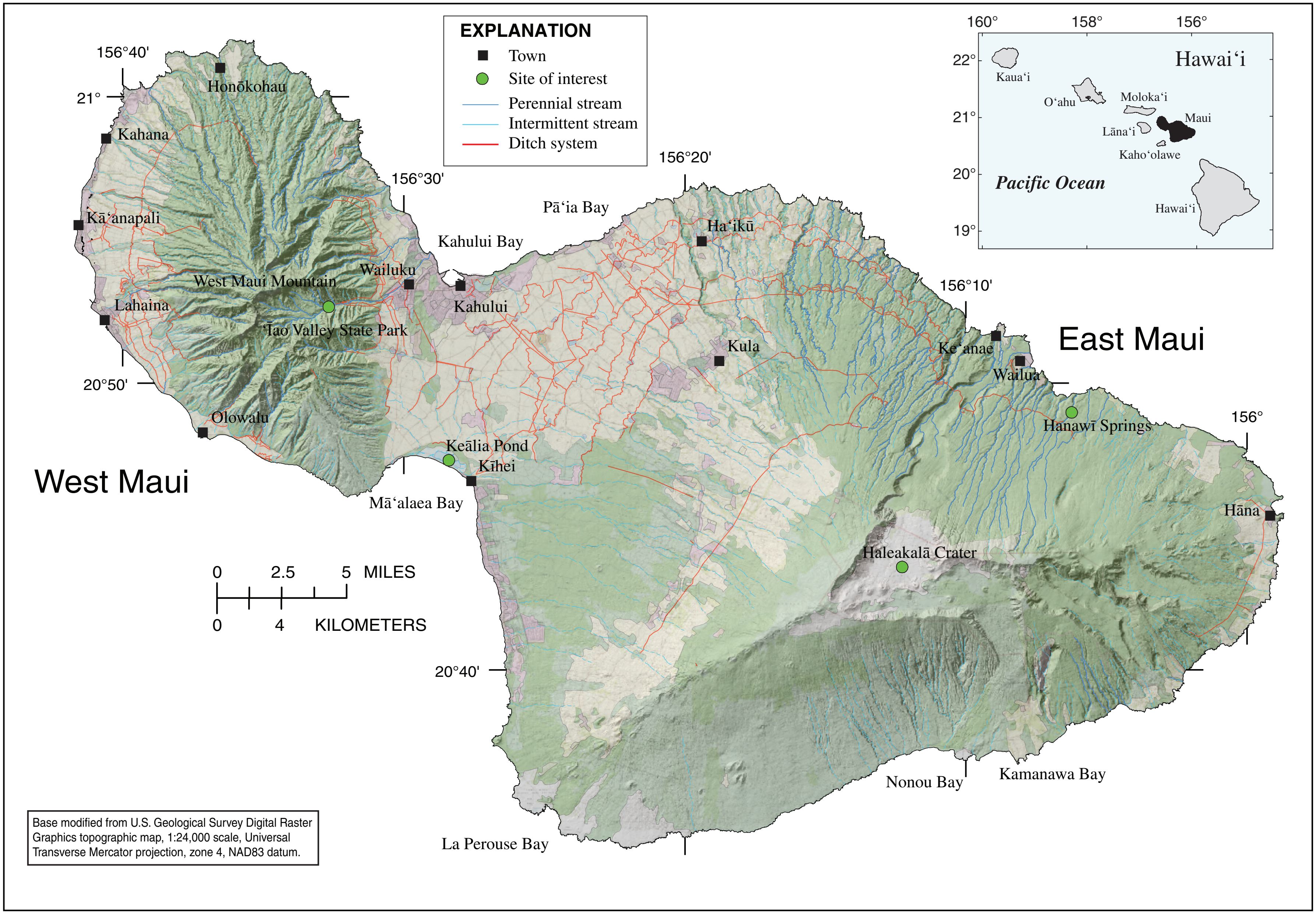


Figure 1. Map of Maui, Hawaiʻi.

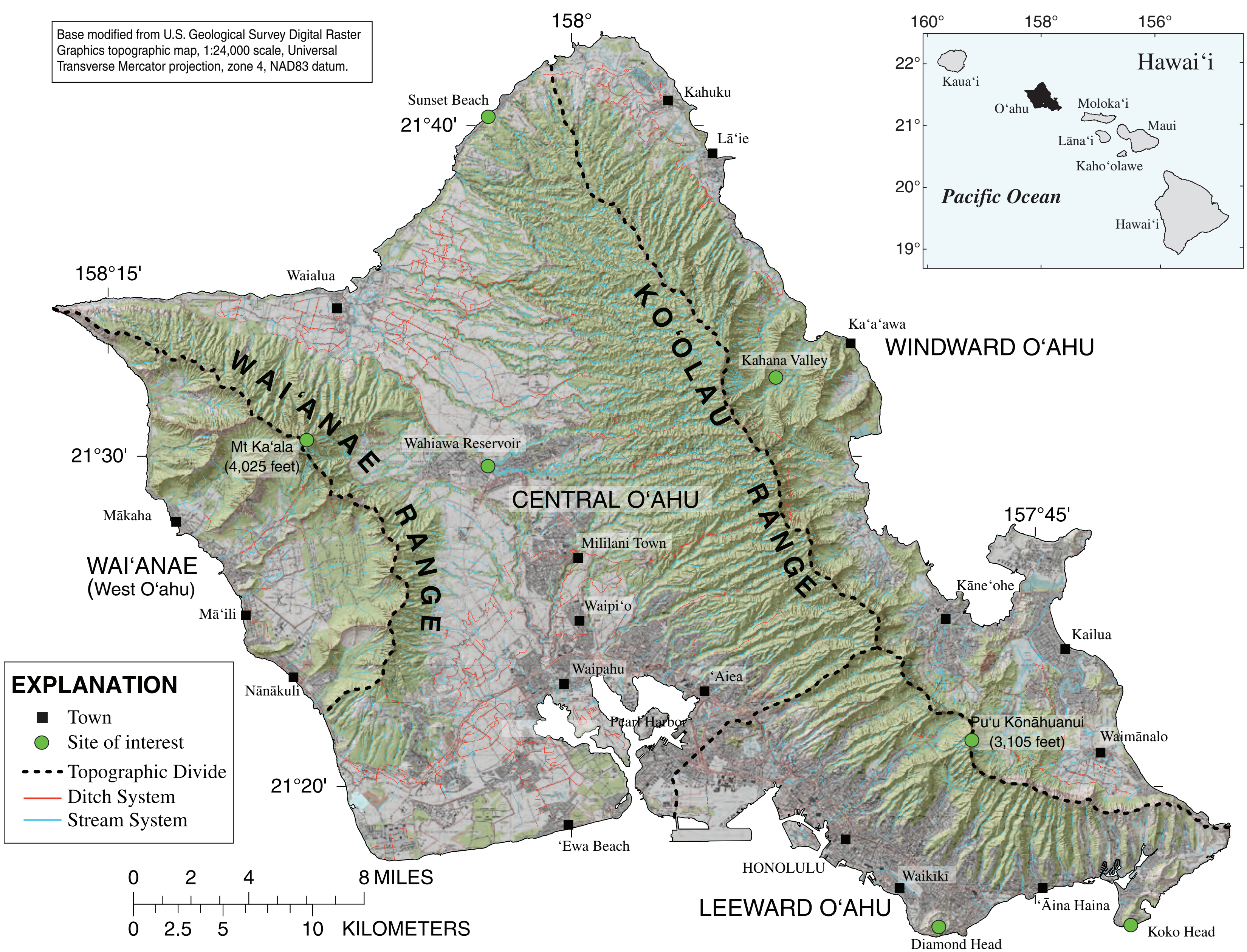


Figure 2. Map of O‘ahu, Hawai‘i.

East Maui

Sampling sites were located on the northern flank of Haleakalā, which forms the eastern part of the island of Maui (fig. 3; table 1). The study area lies between (and includes) the drainage basins of Kōlea Stream to the west and Hanawī Stream to the east. Land-surface altitudes range from sea level to about 10,000 ft at the summit of Haleakalā. The topography is gently sloping, except for the steep sides of gulches and valleys that have been eroded by the numerous streams. The largest valley is Keʻanae Valley, which extends from the coast to Haleakalā Crater, where the valley walls are nearly 1,000 ft high. Most of the study area is made up of forest reserves; at intermediate altitudes, rain forests densely cover the slopes to about 7,000 ft. Grasses and shrubs cover the upper slopes to the north wall of Haleakalā Crater. Two small villages (Keʻanae and Wailua) are at low altitudes along the coast at the mouth of Keʻanae Valley. Land use around the villages is mainly small-scale agriculture, including wetland taro cultivation. At higher altitudes, most of the land is forested State conservation land.

Streams flow generally from the high-altitude flank of Haleakalā in the south to the coast in the north. Twenty-one named streams reach the coast in the study area. The drainage areas of these streams range from 0.1 to 17.6 mi^2 and the median area is 2.6 mi^2 (Gingerich, 2005). Access to streams is made difficult by the steep, rugged terrain of the incised stream valleys and dense vegetation. Rainfall is highly orographic, and rainfall rates average between about 45 in/yr at the summit of Haleakalā to greater than 350 in/yr at about 2,500 ft altitude (Giambelluca and others, 1986), with all of the drainage areas having similar rainfall gradients.

Since the 1930s, the Territory and then the State of Hawaiʻi issued water permits to Alexander and Baldwin, Inc., Hawaiian Commercial and Sugar Co., and East Maui Irrigation Co., Ltd. (EMI), for the diversion of water from streams in northeast Maui. The collection system consists of 388 separate intakes, 24 mi of ditches, and 50 mi of tunnels, as well as numerous small dams, intakes, pipes, and flumes (Wilcox, 1996). With few exceptions, the diversions capture all of the base flow, which represents the groundwater contribution to total streamflow, and an unknown percentage of total streamflow at each stream crossing (Gingerich and Wolff, 2005).

West Maui

West Maui is deeply dissected by numerous streams that originate near the summit of West Maui Volcano. The eastern side of West Maui Mountain includes Nā Wai ʻEhā, composed of the Waiheʻe River, and Waiehu, ʻĪao, and Waikapū Streams, which drain the eastern part of the mountain (fig. 4). These streams have eroded deep valleys that in places are incised to depths of a few thousand feet. The drainage basins of Waiheʻe River, Waiehu Stream, and ʻĪao Stream, respectively, are 7.0, 4.7, and 11.4 mi^2. Waikapū Stream drains the West Maui Mountain only and this part of the drainage basin is about 6.9 mi^2. The western (Lahaina) side of West Maui Mountain encompasses about 96 mi^2. This area is characterized by steep and mountainous terrain in the interior and an area of sloping alluvial and colluvial plains extending westward and northward from the mountains. Streams in the Lahaina area flow from the wet interior of the West Maui Mountain, where the water has cut deep valleys. Many of these streams are diverted and the water is transported by tunnels and ditches for agricultural and domestic uses. The stream diversion structures are designed to capture all of the low flow, and therefore the streams are frequently dry in some sections downstream of the diversions.

Oʻahu

The island of Oʻahu is formed by the eroded remnants of the Waiʻanae and Koʻolau shield volcanoes. The western part of the island is formed by the Waiʻanae Range, with a peak altitude of 4,025 ft at Mount Kaʻala, the highest peak on Oʻahu. The eastern part of the island is formed by the Koʻolau Range, with a peak altitude of 3,105 ft at Puʻu Kōnāhuanui (fig. 2). The original domed surfaces of the volcanoes have been modified by weathering and erosion, producing a landscape of deep valleys and steep ridges (Oki and Brasher, 2003). The Schofield Plateau lies between the two mountain ranges, and a coastal plain surrounds much of the island. Drainage basins on Oʻahu are generally small compared to continental drainages, mainly because the distance between the headwaters and mouths of streams is short, and adjacent streams are closely spaced (fig. 5; table 2; Oki and Brasher, 2003). In most of the windward area, drainage basins generally are smaller, shorter, and wider than those in central Oʻahu, and drainage basins in the Honolulu area are intermediate in size and shape. Main courses of streams generally follow the consequent drainage pattern established on the original domed surfaces of the shield volcanoes. Numerous lower order tributaries commonly join the main courses. Streambed slopes are steep in the mountainous interior, where rainfall is high, and flatter near the coast. Steep terrain and steep stream gradients cause water to run off rapidly following precipitation. As a result, streamflow is characteristically flashy, with high flood peaks and negligible baseflow. Some streams flow perennially throughout their entire course. Other streams are naturally or artificially interrupted with dry reaches, but flow perennially over parts of their course (Polhemus and others, 1992). The remaining intermittent streams flow only during parts of the year throughout their entire course.

Stream Diversions and Instream Flow Studies

Although not directly investigated in this study, the withdrawal of surface water for off-stream uses can disrupt the biological communities upstream and downstream of the diversion structures (Kinzie and others, 2006). In previous USGS studies, the relations between flow and habitat availability for the native

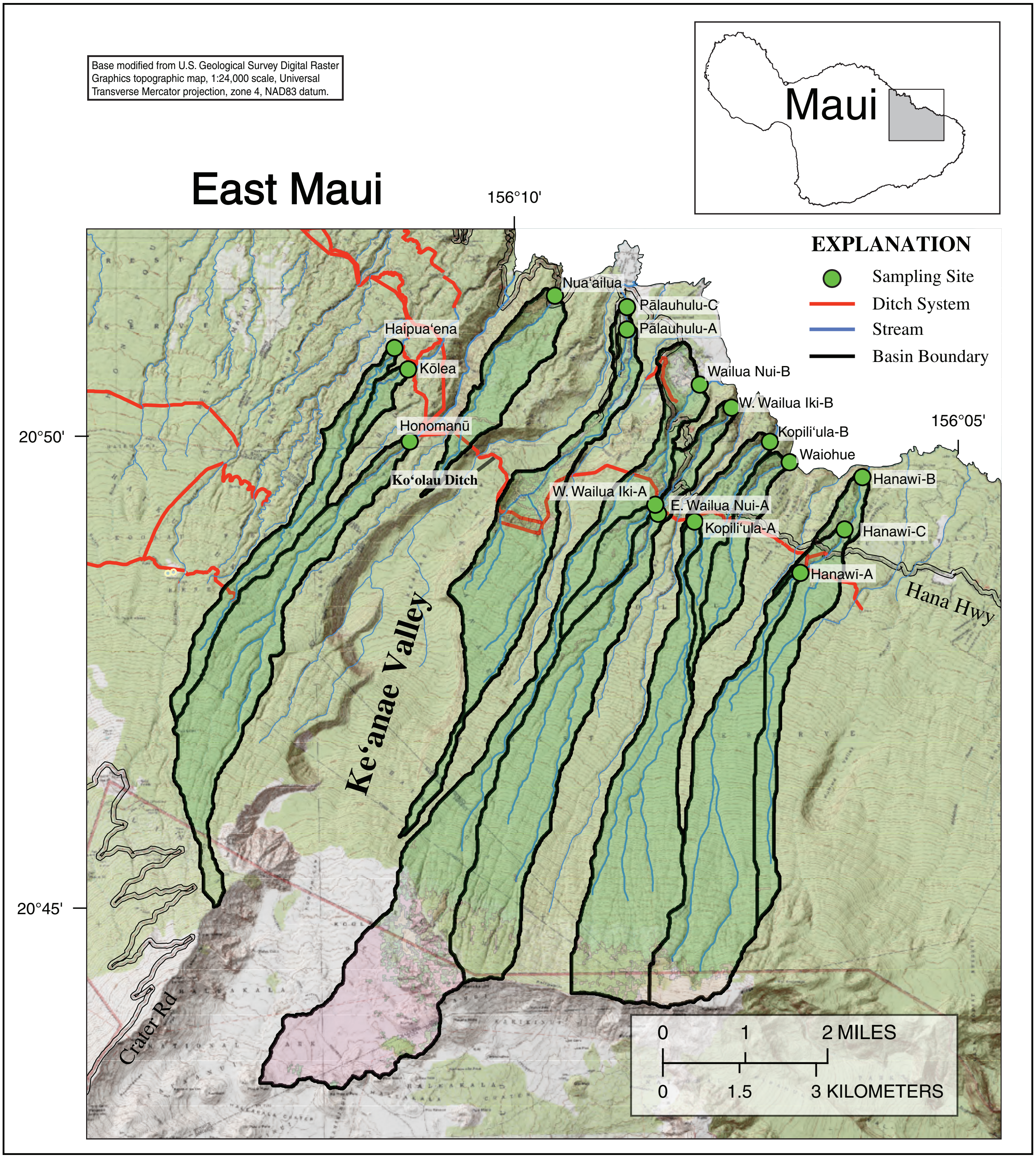


Figure 3. Locations of stream sampling sites on East Maui.

Table 1. Station information for sampling sites on Maui.

[NDAR Code, Hawai‘i Department of Land and Natural Resources, Division of Aquatic Resources’ numeric coding of all segments of Hawai‘i’s streams; Upstream length, linear miles of contributing streams and tributaries; mi^2, square miles; mi, miles; ft, feet; ASL, above sea level; coordinate information in the North American Datum 1983; –, not applicable; locations of sites in figs. 3-4]

Station ID	Stream name	Site	NDAR code	Basin area, in mi^2	Latitude	Longitude	Upstream length, in mi	Distance to mouth, in mi	Elevation ASL, in ft	Sample date
HI_MAUI_09-001	Kopili‘ula Stream	A[3]	64017003	3.86	20.816	-156.134	12.15	1.73	1,272	1-Jun-09
HI_MAUI_09-002	West Wailua Iki Stream	B	64015001	4.01	20.836	-156.127	9.49	0.10	36	2-Jun-09
HI_MAUI_09-003	Wailua Nui Stream	B[3]	64014001	6.34	20.840	-156.133	9.44	0.32	39	2-Jun-09
HI_MAUI_09-004	Hanawī Stream	A[3]	64022001	3.58	20.807	-156.114	9.03	1.72	1,364	3-Jun-09
HI_MAUI_09-005	West Wailua Iki Stream	A	64015001	3.64	20.817	-156.141	7.73	1.86	1,365	3-Jun-09
HI_MAUI_09-006	Haipua‘ena Stream	–	64007001	1.20	20.848	-156.190	5.20	2.67	1,533	4-Jun-09
HI_MAUI_09-007	Pālauhulu Stream	C	64011002	2.73	20.854	-156.146	9.86	0.54	140	4-Jun-09
HI_MAUI_09-008	East Wailua Nui Stream	A	64014002	0.51	20.819	-156.141	1.68	2.10	1,349	5-Jun-09
HI_MAUI_09-009	Pālauhulu Stream	A	64011002	2.65	20.850	-156.146	9.57	0.84	153	8-Jun-09
HI_MAUI_09-010	Honomanū Stream	–[3]	64009007	2.91	20.831	-156.187	9.18	2.76	1,769	9-Jun-09
HI_MAUI_09-011	Kōlea Stream	–	64008001	0.21	20.844	-156.187	0.84	2.19	1,640	9-Jun-09
HI_MAUI_09-012	Hanawī Stream	C[3]	64022001	5.06	20.814	-156.106	13.77	0.89	661	10-Jun-09
HI_MAUI_09-013	Waiohue Stream	–	64018001	0.75	20.826	-156.116	2.66	0.05	28	11-Jun-09
HI_MAUI_09-014	Kopili‘ula Stream	B[3]	64017001	4.65	20.830	-156.120	16.11	0.24	76	12-Jun-09
HI_MAUI_09-015	Hanawī Stream	B[3]	64022001	5.31	20.823	-156.102	14.50	0.16	130	15-Jun-09
HI_MAUI_09-016	Nua‘ailua Stream	–	64010001	1.10	20.856	-156.159	3.01	0.28	74	17-Jun-09
HI_MAUI_09-017	Waikapū Stream	C[4]	66010005	2.84	20.856	-156.526	8.34	5.86	849	29-Jun-09
HI_MAUI_09-018	Waikapū Stream	A[4]	66010013	1.80	20.856	-156.536	5.29	6.68	1,191	29-Jun-09
HI_MAUI_09-019	Kanahā Stream	–	61005003	1.57	20.893	-156.642	3.59	2.86	1,122	30-Jun-09
HI_MAUI_09-020	Honolua Stream	–	61010003	1.89	20.981	-156.618	4.94	3.19	846	30-Jun-09
HI_MAUI_09-021	Honokōwai Stream	–	61007007	1.02	20.929	-156.621	3.81	5.19	1,592	1-Jul-09
HI_MAUI_09-022	Olowalu Stream	B	61002001	3.41	20.832	-156.600	5.18	2.31	528	2-Jul-09
HI_MAUI_09-023	Waihe‘e River	B[1]	62007003	6.69	20.947	-156.512	15.64	0.20	36	21-Sep-09
HI_MAUI_09-024	Waihe‘e River	B[2,4]	62007003	6.68	20.946	-156.512	15.56	0.27	49	21-Sep-09
HI_MAUI_09-025	Waihe‘e River	C	62007006	6.42	20.943	-156.518	14.93	0.72	138	22-Sep-09
HI_MAUI_09-026	Waihe‘e River	A[4]	62007020	4.27	20.936	-156.547	8.99	2.93	600	23-Oct-09

Table 1. Station information for sampling sites on Maui.—Continued

[NDAR Code, Hawai‘i Department of Land and Natural Resources, Division of Aquatic Resources’ numeric coding of all segments of Hawai‘i’s streams; Upstream length, linear miles of contributing streams and tributaries; mi^2, square miles; mi, miles; ft, feet; ASL, above sea level; coordinate information in the North American Datum 1983; –, not applicable; locations of sites in figs. 3-4]

Station ID	Stream name	Site	NDAR code	Basin area, in mi^2	Latitude	Longitude	Upstream length, in mi	Distance to mouth, in mi	Elevation ASL, in ft	Sample date
HI_MAUI_09-027	North Waiehu Stream	C[4]	62008009	0.76	20.910	-156.530	2.64	3.07	826	23-Sep-09
HI_MAUI_09-028	North Waiehu Stream	A[4]	62008009	0.73	20.910	-156.531	2.53	3.18	879	23-Sep-09
HI_MAUI_09-029	South Waiehu Stream	C	62008008	1.09	20.907	-156.522	2.51	2.76	561	24-Sep-09
HI_MAUI_09-030	South Waiehu Stream	A	62008008	1.01	20.907	-156.527	2.13	3.14	676	24-Sep-09
HI_MAUI_09-031	‘Īao Stream	C[4]	62009020	6.09	20.882	-156.540	16.62	4.55	820	19-Oct-09
HI_MAUI_09-032	‘Īao Stream	A	62009030	4.17	20.879	-156.548	10.64	5.09	975	19-Oct-09
HI_MAUI_09-033	Kaua‘ula Stream	–	61004009	1.86	20.878	-156.622	2.75	3.79	1,582	20-Oct-09
HI_MAUI_09-034	Launiupoko Stream	–	61003005	1.05	20.854	-156.614	1.50	2.90	1,365	21-Oct-09
HI_MAUI_09-035	Ukumehame Stream	B	61001001	3.91	20.814	-156.586	11.82	1.21	246	21-Oct-09
HI_MAUI_09-036	Waiehu Stream	–[4]	62008007	2.79	20.915	-156.507	8.31	1.26	193	22-Oct-09
HI_MAUI_09-037	Makamaka‘ole Stream	A	62006001	0.70	20.958	-156.535	2.98	1.10	751	25-Jan-10
HI_MAUI_09-038	Makamaka‘ole Stream	B	62006001	1.09	20.963	-156.528	3.89	0.19	92	26-Jan-10
HI_MAUI_09-039	Ukumehame Stream	A	61001003	3.72	20.819	-156.584	10.92	1.66	397	27-Jan-10
HI_MAUI_09-040	Olowalu Stream	A	61002001	3.00	20.837	-156.596	4.70	2.78	640	28-Jan-10

[1] Open canopy.

[2] Closed canopy.

[3] Sites previously established in Gingerich and Wolff (2005).

[4] Sites previously established in Oki and others (2010).

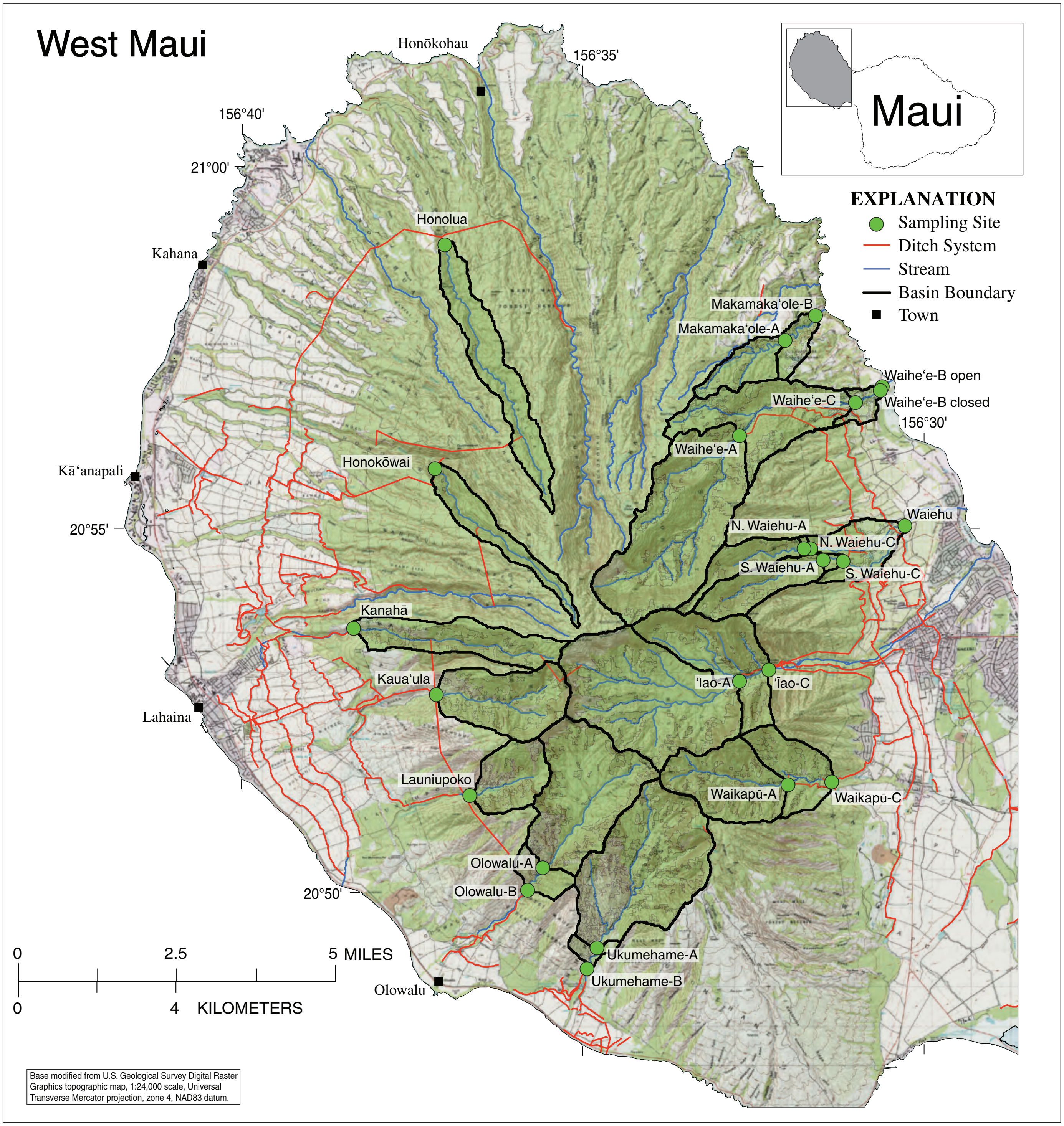


Figure 4. Locations of stream sampling sites on West Maui.

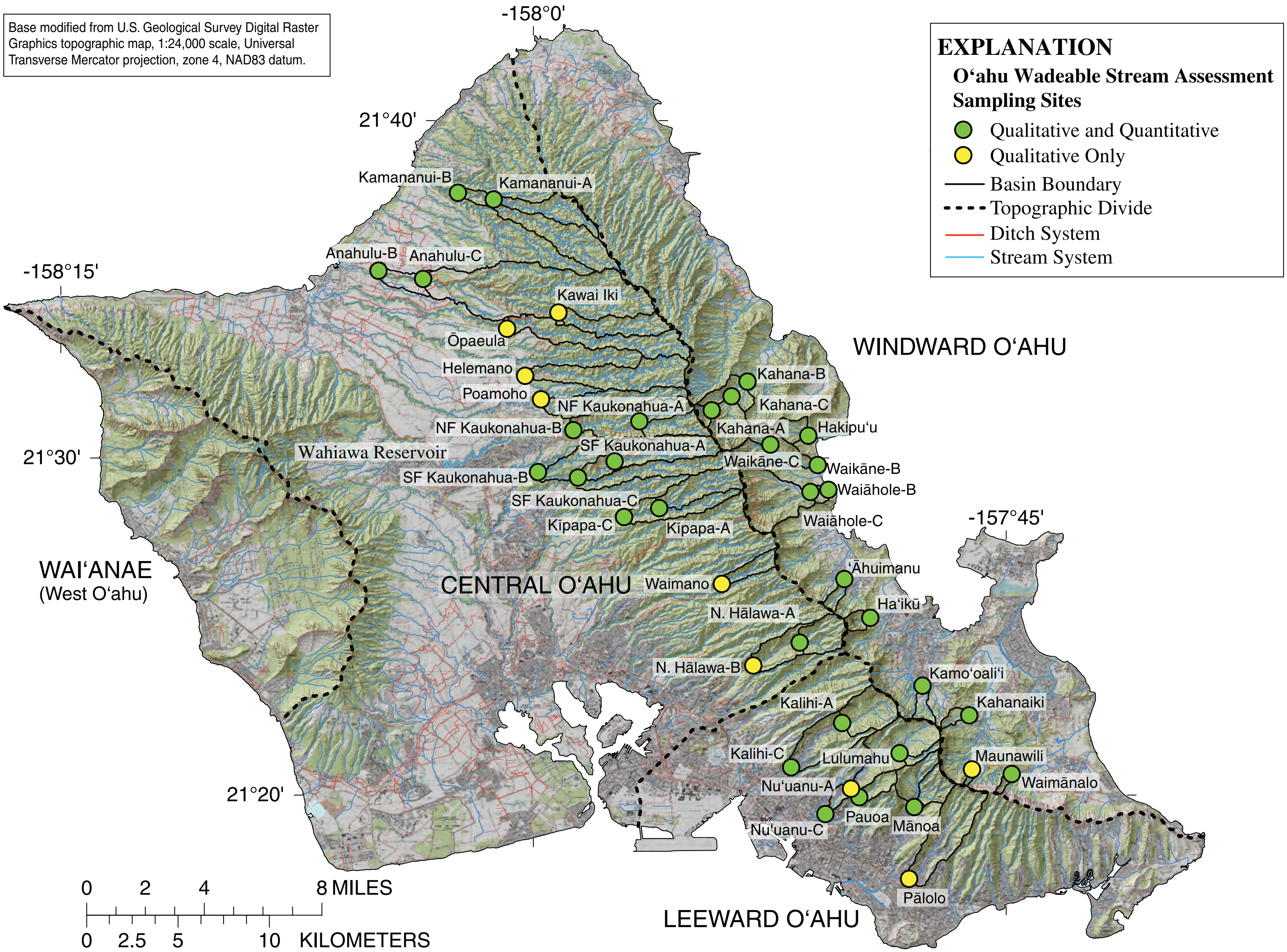


Figure 5. Locations of Wadeable Stream Assessment (WSA) stream sampling sites on the Island of O‘ahu.

Table 2. Station information for O'ahu Wadeable Stream Assessment (WSA) sampling sites.

[NDAR Code, Hawai'i Department of Land and Natural Resources, Division of Aquatic Resources' numeric coding of all segments of Hawai'i's streams; Upstream length, linear miles of contributing streams and tributaries; mi^2, square miles; mi, miles; ft, feet; ASL, above sea level; coordinate information in the North American Datum 1983; –, not applicable; SF, South Fork; NF, North Fork; locations of sites in fig. 5]

Station ID	Stream name	Site	NDAR code	Basin area, in mi^2	Latitude	Longi-tude	Upstream length, in mi	Distance to mouth, in mi	Elevation ASL, in ft
HIO05518-002	Nu'uanu Stream	C	33009800	4.35	21.321	-157.849	12.79	1.26	98
HIO05518-003	N. Hālawa Stream	A	34002006	1.61	21.406	-157.862	5.05	7.38	784
HIO05518-005	Poamoho Stream[1]	–	36006137	2.77	21.527	-157.997	14.39	14.42	1,089
HIO05518-010	SF Kaukonahua Stream	A	36006106	2.94	21.496	-157.959	15.52	23.56	984
HIO05518-011	Waiāhole Stream	B	32004001	3.82	21.482	-157.846	6.00	0.31	13
HIO05518-013	Kamananui Stream	B	36010020	5.72	21.630	-158.041	30.54	1.93	207
HIO05518-018	Kalihi Stream	C	33011003	4.77	21.345	-157.867	9.35	2.03	121
HIO05518-023	Kahana Stream	A	31018029	0.31	21.521	-157.907	1.45	5.26	705
HIO05518-025	Helemano Stream[1]	–	36007024	4.15	21.539	-158.006	21.81	10.51	988
HIO05518-026	Kīpapa Stream	A	34010071	2.24	21.473	-157.935	12.91	14.21	991
HIO05518-027	Waikāne Stream	B	32002003	2.52	21.494	-157.851	8.53	0.45	10
HIO05518-029	Kamananui Stream	A	36010021	1.9	21.626	-158.022	11.74	3.76	472
HIO05518-034	Nu'uanu Stream[1]	A	33009008	3.9	21.334	-157.835	11.32	2.74	308
HIO05518-035	Ha'ikū Stream	–	32008004	0.47	21.418	-157.824	0.77	2.62	230
HIO05518-037	Anahulu River	B	36008004	14.29	21.591	-158.083	62.35	1.52	36
HIO05518-038	SF Kaukonahua Stream	C	36006104	3.69	21.488	-157.978	18.64	18.65	912
HIO05518-039	Waikāne Stream	C	32002011	0.52	21.504	-157.876	1.84	2.56	262
HIO05518-151	Kahana Stream	C	31018028	2.14	21.528	-157.896	5.65	4.30	253
HIO05518-153	'Ōpae'ula Stream[1]	–	36007035	3.69	21.562	-158.015	19.80	9.07	955
HIO05518-155	Pālolo Stream[1]	–	33007003	3.73	21.289	-157.805	8.01	1.72	89
HIO05518-158	N. Hālawa Stream[1]	B	34002006	3.21	21.395	-157.886	7.59	4.84	394
HIO05518-159	Maunawili Stream[1]	–	32013038	0.11	21.343	-157.771	0.66	7.48	617
HIO05518-160	Kahana Stream	B	31018024	3.26	21.535	-157.888	8.85	2.86	79
HIO05518-162	Kalihi Stream	A	33011005	2.19	21.366	-157.839	3.87	4.60	515
HIO05518-163	'Āhuimanu Stream	–	32007015	0.4	21.438	-157.838	1.70	1.23	102
HIO05518-164	Kamo'oali'i Steam	–	32010033	0.54	21.384	-157.797	2.00	1.95	197
HIO05518-166	Kīpapa Stream	C	34010065	4	21.469	-157.954	21.90	11.45	748

Table 2. Station information for O‘ahu Wadeable Stream Assessment (WSA) sampling sites.—Continued

[NDAR Code, Hawai‘i Department of Land and Natural Resources, Division of Aquatic Resources’ numeric coding of all segments of Hawai‘i’s streams; Upstream length, linear miles of contributing streams and tributaries; mi^2, square miles; mi, miles; ft, feet; ASL, above sea level; coordinate information in the North American Datum 1983; –, not applicable; SF, South Fork; NF, North Fork; locations of sites in fig. 5]

Station ID	Stream name	Site	NDAR code	Basin area, in mi^2	Latitude	Longitude	Upstream length, in mi	Distance to mouth, in mi	Elevation ASL, in ft
HIO05518-168	Kawai Iki Stream[1]	–	36008011	2.19	21.570	-157.988	12.05	10.25	1,102
HIO05518-171	Mānoa Stream	–	33007008	2.43	21.325	-157.802	9.12	3.78	246
HIO05518-174	Waimano Stream[1]	–	34006022	0.91	21.436	-157.902	4.02	9.49	827
HIO05518-175	Kahana Iki Stream	–	32013018	0.36	21.370	-157.772	1.03	5.05	102
HIO05518-177	SF Kaukonahua Stream	B	36006096	5.35	21.491	-157.999	28.11	16.38	876
HIO05518-181	Anahulu River	C	36008006	13.35	21.587	-158.059	59.46	3.41	203
HIO05518-182	NF Kaukonahua Stream	B	36006076	4.46	21.512	-157.980	19.32	17.12	951
HIO05518-183	Waiāhole Stream	C	32004001	3.51	21.481	-157.855	5.26	1.06	52
HIO05518-186	NF Kaukonahua Stream	A	36006088	1.38	21.516	-157.945	5.98	22.26	1,194
HIO05518-187	Lulumahu Stream	–	33009014	0.35	21.351	-157.809	1.84	5.22	974
HIO05518-191	Waimānalo Stream	–	32015013	0.19	21.340	-157.750	0.09	3.45	279
HIO05518-194	Pauoa Stream	–	33009002	0.71	21.330	-157.831	1.05	2.96	476
HIO05518-203	Hakipu‘u Stream	–	32001001	0.78	21.508	-157.856	2.09	0.39	46

[1] No Targeted Riffle sample collected.

stream-dwelling fishes, shrimp, and mollusk were examined on O‘ahu and on East and West Maui (Gingerich and Wolff, 2005; Oki and others, 2006; Oki and others, 2010). These studies modeled the effects of returning different proportions of the total amount of water diverted back to the diverted streams, the downstream creation of available habitat, and the suitability of that habitat for potential use by migratory native species.

Several studies in Hawai‘i have considered the effects of stream diversions on benthic macroinvertebrate assemblages and biomass downstream of diversions. A 3-year study from 1994 to1997 on the Wainiha River on Kaua‘i examined the effects of a hydroelectric diversion dam both upstream and downstream of the diversion structure and upstream and downstream of the return flow from the hydroelectric plant (Kinzie and others, 2006). Macroinvertebrate abundance and diversity were found to be greater at the site downstream of the return, while macroinvertebrate biomass, due to higher abundances of the native shrimp, was greater at the site upstream of the diversion structure. Abundance and biomass of macroinvertebrate drift were also greater upstream of the diversion, whereas the site downstream of the diversion was found to have the lowest abundance, biomass, and diversity. A 2-year study from 1994 to 1995 investigated the effect of a 40-percent reduction in stream discharge in ‘Īao Stream, Maui, on the native torrenticolous insects *Telmatogeton* and *Procanace* (Benbow and others, 2005). The standing stock biomass of *Telmatogeton* was found to have significantly decreased with the reduced flow (Benbow and others, 2003).

A 5-month study in 2000 in ‘Īao Stream on Maui examined macroinvertebrate populations collected from riffle habitats above and below the ‘Īao–Māniania diversion (McIntosh and others, 2002). This structure diverts 100 percent of the flow of the stream under dry-weather conditions. Study results indicated that the mean total macroinvertebrate abundance was 46 percent higher above the diversion than below it. The three numerically dominant taxa above the diversion were still proportionally the dominant taxa below the diversion, but the mean density of each was lower. Some species, including the native mountain shrimp, were present upstream but not downstream of the diversion. The mean total biomass was 60 percent lower downstream of the diversion (McIntosh and others, 2008). The biomass and densities of two introduced species of the insect order Trichoptera were determined to be greater upstream of the diversion (McIntosh and others, 2003). More recently, a 2-year study in 2007 to 2008 investigated the effects of stream diversions in all of the Nā Wai ‘Ehā streams on West Maui (‘Īao, Waiehu, and Waikapū Streams and Waihe‘e River) on benthic macroinvertebrates utilizing cascade and amphibious habitats (Shoda, 2009). This study found that endemic macroinvertebrate taxa made up 38.5 percent of the amphibious microhabitat (constantly wetted splash zones) fauna as compared to only 6.3 percent of the torrenticolous microhabitat (fast flowing water) fauna. Benthic macroinvertebrate densities and diversity were found to be 33 percent higher in cascades upstream of diversions than in cascades with diverted flows (Shoda and others, 2011).

The results of these studies indicate that a reduction of surface-water flow, whether caused by natural or anthropogenic factors, reduces the amount of suitable habitat and habitat quality for a number of species. The biological structure and function within a stream reach is altered by water removal, which affects species diversity, abundance, and biomass, which in turn affects the trophic relations and energetics of the larger stream communities.

Another factor related to stream diversions is the effect that reduced flow has on the amphidromous species. The native Hawaiian stream-dwelling fish (‘o‘opu), shrimp (‘ōpae), and mollusks (hīhīwai), having evolved from marine ancestors, are all amphidromous, retaining an obligate marine larval stage (McDowall, 1993; McDowall, 2003). Amphidromy is a type of diadromy that requires fauna to migrate between freshwater and saltwater at some point in their life cycle. With amphidromous species, females deposit their eggs in streams, where they are fertilized and eventually hatch. The newly born larvae are carried passively downstream to the ocean, where they drift as zooplankton for a species-specific period of time. At some point in the larval development, they cue on a freshwater plume and follow it back to a stream mouth where they undergo a metamorphosis into postlarvae. The postlarvae then make their way upstream, growing into recruits. Once they find suitable habitat or a barrier preventing their continued upstream migration, they settle down as juveniles, mature into adults, and live and breed for the remainder of their lives (Beckley, 1883; Ego, 1956; Tomihama, 1972; Ford and Kinzie, 1982; Kinzie, 1988; McDowall, 1988; Radtke and others, 1988; Tate and others, 1992; Radtke and others, 2001; McRae, 2007a).

The amphidromous life cycle requires unimpeded access to and from the ocean. Reduced streamflow due to diversions can have a number of effects on the amphidromous species by: (1) increasing the amount of time it takes for larvae to reach the ocean, thereby increasing the chance that the larvae may die from starvation (Lindstrom and Brown, 1996; Iguchi and Mizuno, 1999; Benbow and others, 2004; Iguchi, 2007; McRae, 2007b); (2) entraining into the ditch system large percentages of larvae that were headed downstream to the ocean, removing them from the gene pool (Benstead and others, 1999); (3) consequently decreasing the marine-phase pool of locally available postlarvae recruits; (4) reducing the size and frequency of the freshwater plumes that the marine-phase larvae cue on; and (5) creating long stretches of dry streambed that impede the upstream migration of recruits and possibly trap them in unsuitable habitats where they may perish.

Historical Land Use

The environmental landscape of the main Hawaiian Islands has undergone extreme changes since the arrival of the first human colonists. Much of the lush forested watersheds appear to be in a natural state, but for the majority of the

Hawaiian forests this is far from true. A knowledge of the past land use is needed in order to fully understand the diversity and abundance of the flora and fauna of today's watersheds. What Harding and others (1998) called "the ghost of land use past" has a direct influence on the ecological systems that we observe today.

The native biota of the Hawaiian Islands had developed over millions of years in isolation through the processes of colonization and adaptation (Jordan, 1905; Usinger, 1941; Loope and Mueller-Dombois, 1989; Howarth, 1990). Colonizing organisms arrived by long-distance dispersal mechanisms such as flying, swimming, rafting, or drifting in the sea or in the winds (Hubbell, 1968; Howarth, 1990). Because of the long distances that organisms had to travel, many continental groups are absent from the native biota whereas other groups are more represented, forming what is called a "disharmonic" biota. Of the relatively few groups of colonizing organisms that survived the long journey, those that were able to find suitable habitats and become established were unconstrained by predators and competitors found in continental settings. Many of these organisms radiated out into the various other available island habitats, thereby evolving into the many endemic forms that compose the native biota of the islands (Howarth, 1990). The terrestrial endemic fauna consisted mainly of arthropods (mostly insects), birds, and land snails. The only mammals represented were bats and the marine monk seal. The amphidromous species of stream fishes, shrimp, mollusks, and prawn were derived from marine ancestors that colonized brackish water and freshwater habitats. The endemic insect species were derived from both marine and terrestrial ancestors.

In the time since human colonization of the Hawaiian Islands, many native species have been substantially affected by habitat alteration and by the introduction of nonnative species (Kirch, 1982). Anthropogenic alteration of the Hawaiian landscape started with the ancient Hawaiians, who modified the environment to allow for their survival and expansion as a people. They brought with them their necessities to ensure their continued way of life, including their knowledge of fishing and farming. The Hawaiians introduced pigs, fowl, and dogs into the islands, as well as oceanic island agricultural staples such as taro. Inadvertent introductions of the Polynesian rat, lizards, snails, and various insects and weeds were possibly made during the cross-ocean voyages. The Hawaiians modified much of the arable lowland areas to farm taro and other products by diverting streams and clearing land by burning (Kirch, 1982).

After 1778, the Hawaiian landscape began to rapidly change. Contact with the western world brought with it vast and dramatic changes. Cattle, goats, horses, and sheep were introduced into the islands soon after contact was made. The cattle were protected by order of the King, and were allowed to breed and roam unfettered by fences (Jarves, 1843; Hall, 1904; Judd, 1919). The sandalwood era flourished from 1815 to 1826, with China purchasing as much of the wood as they could from the Hawaiian Kingdom (St. John, 1947). Many acres of sandalwood were harvested without efforts to preserve or replant the trees until they were all but gone from the islands by 1829 (Thrum, 1904; Kuykendall and Gregory, 1926; St. John, 1947). It wasn't until the 1830s that the free-ranging cattle were allowed to be hunted, and this pursuit chased the herds farther back into the valleys and into the higher elevation forests (Reynolds, 1850). By this time, cattle and goats were abundant on all the main islands. By 1851 it was recognized that the cattle were causing damage to the native forests (Lee, 1851). In 1874, Nordhoff (1874) commented about the disappearance of the native forests from higher elevations and mountain slopes that was most likely caused by the grazing cattle. The effect of the grazing and the barren land it left behind was believed to have caused a reduction in streamflow (Nordhoff, 1874; Judd, 1919). Deforestation of the watersheds by cattle and goats continued at a rapid pace on all the islands, creating vast areas of barren soil or fields of Hilo grass (*Paspalum conjugatum*) that inhibited the growth of the native flora (Lyon, 1922). Remnants of native forests were able to exist only in inaccessible areas such as ravines and other steeply sloping areas. This deforestation led to erosion, declines in streamflow, sedimentation, and poor water quality for agriculture and human consumption (Stubbs, 1901; Judd, 1919). The effect of these conditions on the native stream and nearshore marine biota is unknown. But the loss of habitat for the native species likely affected the biota in a substantial way.

The birth of the sugar plantation era put even more pressure on the native Hawaiian ecosystems. As large-scale agriculture expanded in Hawai‘i, greater demands were placed on the streams and rivers to supply water for irrigation. Elaborate ditches were constructed throughout the islands to deliver water to plantations established in the lower plains (Wilcox, 1996). Many Hawaiian streams were diverted for the commercial off-stream uses, reducing the amount of available habitats for the native stream fauna and impeding the upstream-downstream migration of the native amphidromous species.

A planting of gum trees by Captain Makee of Maui appears to be one of the first reforestation efforts (Nordhoff, 1874). Conservation efforts began in the late 1800s, after it was accepted by the sugarcane plantation owners that the deforestation had led to negative commercial effects. Watersheds on O‘ahu began to be replanted with a variety of mostly nonnative trees propagated in the government nursery (Bishop and others, 1884). Fences were slowly erected to protect the new trees, and feral cattle were removed. This work progressed slowly, while the deforestation continued around the islands. In 1893, the Hawaiian Legislature created the Bureau of Agriculture and Forestry to oversee the protection of Hawai‘i's watersheds. The newly appointed Commissioner of the Bureau set to work around the Islands with plantation owners and ranchers to erect fences, remove cattle, and reforest the denuded watersheds (Marsden, 1894). The first Territorial Forester was appointed in 1904 to continue the reforestation efforts (Hall, 1904). Under the Territorial Forester, forest reserves began to be established on all the main Hawaiian Islands, setting aside hundreds of thousands of acres of land to be protected by the Territorial Government (Hosmer, 1908). Most of this reforestation effort continued to use nonnative trees, but the importance of maintaining the native forests was also recognized (Judd, 1919). The protection and reforestation of the Hawaiian watershed has continued since those early days, with efforts such as the Civilian Conservation Corps in the 1930s and 1940s to reforest areas in Maui and Kaua‘i. In 1970, the Natural Areas Reserve System (NARS) was created to protect and preserve areas supporting natural terrestrial and aquatic ecosystems (Maciolek, 1975; Devick and others, 1992).

The cumulative effects that these legacy disturbances have had on the native biota may never be fully known. Edmondson and Wilson (1940) conjectured that the reason that the native stream snail *Neritina granosa* (hīhīwai) was uncommon on O‘ahu was because it might never have been established there. But it might also be possible that hīhīwai populations on O‘ahu were eradicated by the loss of suitable habitat due to increased sedimentation stemming from the extensive deforestation years earlier. A decrease in the abundances of nearshore fishes noted during the early 1900s was believed to have been entirely caused by overfishing, but the effects of the increased sediments on the nearshore environments may have had some effect on the nearshore fauna as well (Bell and Higgins, 1939). The effects on the native aquatic invertebrates may also never be fully known. Many of the very sensitive species may have been extirpated years before the early naturalists ever began to look for them. Some of these populations have survived in pockets of refuge, some have reestablished themselves around the islands, and some remain in only the most undisturbed habitats. The current land-use/land-cover maps that reveal the conditions of today's watersheds do not necessarily correlate with the distributions of many of the native species due to the legacy of changes that are no longer evident.

Recent History

The resident population of Hawai‘i has increased from about 154,000 in 1900 to more than 1.2 million in 2000 (State of Hawai‘i, 2009). Anthropogenic influences, both urban and agricultural, can adversely affect stream systems. Effects such as stream-channel revetment to allow for flood control or roadways; increases in sedimentation from construction and farming; contaminants from agricultural, urban, and industrial activities transported in storm-water runoff; and diversions to redirect stream water to farms and other off-stream uses can all affect stream water quality (Oki and Brasher, 2003).

Environmental contamination can directly affect aquatic invertebrate assemblages in a number of ways. The diverse taxa have varied ranges of tolerances for the myriad of contaminants that have been detected in sediments, tissues, and surface waters (Wiederholm, 1984; Rowe and others, 1997). Some invertebrates are sensitive to heavy metals such as arsenic; others are sensitive to pesticides like dieldrin. The levels of contamination, the specific taxa and the life stage of the taxa, and the duration of exposure to the contaminant all play roles in how the community will be affected. In many cases, multiple contaminants have been detected in sediments and fish tissue (Brasher and Wolff, 2004). Most toxicity testing involves only one or two compounds to determine the physiological and biochemical reactions of the test taxa. The effects of exposure to multiple contaminants simultaneously are still unknown.

Data-Collection and Analysis Methods

Watershed, riparian, instream-habitat, and benthic macroinvertebrate data were collected to determine the relations among components of the macroinvertebrate assemblages and the quality of the instream habitat and land use within the contributing basin area.

Selection of Sampling Sites

An attempt was made to select sampling sites that would represent a range of land-use and habitat characteristics on the Island of Maui. Thus the sampling sites were in urban (developed, residential, and commercial), agricultural, forested, and mixed-use watersheds; however, because of the extensive ditch systems and surface-water diversions on the island, none of the sampling sites can be considered to represent perennial streams draining the large agricultural or urban areas (figs. 3–4). The sites also were selected to represent the different climatic conditions around the island caused by the prevailing trade winds and mountain ranges. Windward areas tend to have greater mean annual rainfall and cloud cover, leeward areas tend to be sunnier and drier, and central areas have variable weather depending on the altitude of the terrain (Armstrong, 1983). Sites were required to have perennial flow and be wadeable. Because most of the perennial streams on Maui are diverted for agriculture, many stream reaches downstream of the diversion structures are at times dry. Therefore many of the sampling sites were located upstream from the diversion structures in predominantly forested, relatively pristine terrain. Some of these streams have perennial flow at the coast because of groundwater discharge to their channels in their lower reaches, or because diverted water is subsequently returned to the lower reaches. Sampling sites were located near the coast in streams where flow was perennial at the lower altitudes. For the purposes of this study, sites located at 100 ft altitudes or lower are characterized as "lower" altitude sites, sites at altitudes greater than 100 ft but less than 650 ft are characterized as "middle" altitude sites, and sites at or greater than 650 ft altitude are characterized as "high" altitude sites.

The 40 sampling sites on O‘ahu were selected and sampled during the O‘ahu Wadeable Stream Assessment study conducted previously by the USGS (fig. 5; Wolff and Koch, 2009). A probability-based survey design was used to select sampling sites in order to ensure an unbiased representation of aquatic-resource conditions across Oʻahu. The target population consisted of all perennial streams on the Island of Oʻahu, Hawaiʻi.

Determination of Habitat Characteristics

Habitat characterization data were collected using a modified set of methods derived from the USGS National Water-Quality Assessment (NAWQA) protocols and the USEPA Wadeable Stream Assessment (WSA) protocols, which are described in Meador and others (1993), Fitzpatrick and others (1998), and U.S. Enviromental Protection Agency (2004). A 300-ft study reach was delineated at each sampling site, and a number of physical habitat characteristics were determined (measured and (or) observed) within the reach. Data were recorded on field data sheets and were reviewed for accuracy prior to leaving the study reach.

At the beginning of each site visit, instantaneous specific conductance and water temperature were measured using a calibrated EcoSense® model EC300 meter. Land uses and practices adjacent to and upstream from each study reach were noted. The 300-ft reach was divided into ten 30-ft sections. Instream habitat characteristics were estimated within each section and averaged for the entire reach. These data included visual estimates of the percentage of open canopy, the percentage of instream substrate size categories (boulder, cobble, gravel, and so forth), the percentage of instream substrate embeddedness, and the percentage of habitat type (riffle, run, or pool). The average wetted width and thalweg depth were calculated from multiple measurements (2 to 6 width measurements per section; 3 to 8 depth measurements per section) within each 30-foot section of stream. The amount of vegetative cover and stream-bank erosion were visually estimated for both the right and left banks. Any type of channel alteration was recorded.

Geographic Information System (GIS)

Geographic coordinates were recorded at the upstream and downstream ends of each study reach using a hand-held global positioning system (GPS) unit. These coordinates enabled entering the data in a Geographic Information System (GIS) for subsequent analyses. GPS points were also recorded at each quantitative sampling location. Basin area polygons were delineated from the downstream GPS points using the USGS web-based StreamStats application at http://water.usgs.gov/osw/streamstats/hawaii.html. StreamStats was used to calculate the area of each drainage basin. GPS point elevations and stream lengths were calculated using a 10-meter Digital Elevation Model (DEM) (tables 1 and 2). Land-use statistics were derived from the USGS National Land Cover Dataset (NLCD) file (tables 3 and 4; Homer and others, 2004).

Collection of Invertebrate Samples

Two types of invertebrate samples, quantitative and qualitative, were collected at each site following standard National Water-Quality Assessment (NAWQA) protocols (Cuffney and others, 1993; Moulton and others, 2002). All sampling was conducted during dry-weather, low-flow conditions during periods when flow was likely less than the median flow at each site.

Qualitative Benthic Macroinvertebrate Sampling

Qualitative multihabitat (QMH) samples were collected from all available habitats within the study reach at each sampling site to provide a comprehensive species distribution list. QMH samples were collected using a D-frame kick net with a 1-ft wide opening and a 0.0197-in. (500-µm) mesh. Samples were collected using techniques appropriate for the various habitats being sampled (Cuffney and others, 1993; Moulton and others, 2002; Brasher and others, 2004). The D-frame kick net collections were supplemented by "visual collection," which included manually turning over large rocks, woody debris, and other substrates, and removing all invertebrates present. QMH samples were combined to produce a single composite sample. The samples were elutriated to remove sand and pebbles and collected on a 425-µm mesh sieve in the field to produce a single sample of approximately 0.75 L from each site. The samples were stored in a 70 percent ethanol solution until they were shipped to the analytical laboratory, EcoAnalysts Inc. in Moscow, Idaho, for identification.

Quantitative Benthic Macroinvertebrate Sampling

Quantitative richest targeted habitat (RTH) samples were collected from the faunistically richest community of benthic invertebrates, which for Hawaiian streams is located in fast-flowing riffles (Moulton and others, 2002; Brasher and others, 2004). Analyses of RTH samples provide relative abundances to allow comparisons among sites. Samples were collected from five riffles within each study reach using a modified Surber sampler (Slack sampler) with a 0.0167-in. (425-µm) mesh net and composited into a single sample (Cuffney and others, 1993). The five sampling sites were selected using the criteria that: (1) the substrate was natural and mostly coarse grained (large gravel to large cobbles); (2) the flow was in the main channel; and (3) the net could be properly positioned. If riffles were not present, RTH sampling sites were positioned in the fastest flowing water. All substrate within a 2.69-ft^2 (0.25-m^2) area in front of the net, delineated by an aluminum quadrat, was gently dislodged and thoroughly scrubbed to remove all organisms. Five RTH samples were collected within each sampling reach, cleaned of extraneous inorganic and plant material, and then combined to produce a single composite sample. The samples were stored in a 70 percent ethanol solution until they were shipped to the analytical laboratory, EcoAnalysts Inc., for identification and enumeration as discussed below. The water depth was measured at each riffle collection site, and current velocity was estimated at 0.6-depth by measuring the velocity at six-tenths the water depth (measured

Table 3. Land-use statistics for sampling sites on Maui.

[mi^2, square miles; N, North; S, South; E, East; W, West; locations of sites in figs. 3-4]

Station ID	Site name	Agriculture		Developed		Forested	
		Area, in mi^2	Percentage of basin area	Area, in mi^2	Percentage of basin area	Area, in mi^2	Percentage of basin area
HI_MAUI_09-001	Kopiliʻula-A	0	0	0	0	3.86	100
HI_MAUI_09-002	W. Wailua Iki-B	0	0	0.04	0.95	3.96	99.05
HI_MAUI_09-003	Wailua Nui-B	0	0	0.09	1.36	6.25	98.64
HI_MAUI_09-004	Hanawī-A	0	0	0	0.01	3.58	99.99
HI_MAUI_09-005	W. Wailua Iki-A	0	0	0	0	3.63	100
HI_MAUI_09-006	Haipuaʻena	0	0	0	0	1.2	100
HI_MAUI_09-007	Pālauhulu-C	0	0	0.09	3.28	2.63	96.72
HI_MAUI_09-008	E. Wailua Nui-A	0	0	0	0	0.51	100
HI_MAUI_09-009	Pālauhulu-A	0	0	0.08	2.88	2.57	97.12
HI_MAUI_09-010	Honomanū	0	0	0	0	2.91	100
HI_MAUI_09-011	Kōlea	0	0	0	0	0.21	100
HI_MAUI_09-012	Hanawī-C	0	0	0.05	0.95	5.01	99.05
HI_MAUI_09-013	Waiohue	0	0	0.02	2.48	0.73	97.52
HI_MAUI_09-014	Kopiliʻula-B	0	0	0.03	0.73	4.61	99.27
HI_MAUI_09-015	Hanawī-B	0	0	0.05	0.94	5.25	99.06
HI_MAUI_09-016	Nuaʻailua	0	0	0.02	2.18	1.08	97.82
HI_MAUI_09-017	Waikapū-C	0	0	0.02	0.74	2.82	99.26
HI_MAUI_09-018	Waikapū-A	0	0	0	0	1.8	100
HI_MAUI_09-019	Kanahā	0	0	0	0	1.57	100
HI_MAUI_09-020	Honolua	0	0	0	0	1.89	100
HI_MAUI_09-021	Honokōwai	0	0	0	0	1.02	100
HI_MAUI_09-022	Olowalu-B	0	0	0	0	3.41	100
HI_MAUI_09-023	Waiheʻe-B open	0.06	0.94	0.25	3.81	6.37	95.24
HI_MAUI_09-024	Waiheʻe-B closed	0.06	0.95	0.25	3.81	6.36	95.24
HI_MAUI_09-025	Waiheʻe-C	0.01	0.13	0.13	1.97	6.28	97.9
HI_MAUI_09-026	Waiheʻe-A	0	0	0.03	0.73	4.23	99.27
HI_MAUI_09-027	N. Waiehu-C	0	0	0	0	0.76	100
HI_MAUI_09-028	N. Waiehu-A	0	0	0	0	0.73	100
HI_MAUI_09-029	S. Waiehu-C	0	0	0	0	1.08	100
HI_MAUI_09-030	S. Waiehu-A	0	0	0	0	1.01	100
HI_MAUI_09-031	ʻĪao-C	0	0	0.01	0.24	6.07	99.76
HI_MAUI_09-032	ʻĪao-A	0	0	0	0	4.16	100
HI_MAUI_09-033	Kauaʻula	0	0	0	0	1.86	100
HI_MAUI_09-034	Launiupoko	0	0	0	0	1.05	100
HI_MAUI_09-035	Ukumehame-B	0	0	0.02	0.44	3.89	99.56
HI_MAUI_09-036	Waiehu	0.29	10.28	0.14	4.97	2.36	84.66
HI_MAUI_09-037	Makamakaʻole-A	0	0	0	0.65	0.69	99.35
HI_MAUI_09-038	Makamakaʻole-B	0	0	0.09	8	1	92
HI_MAUI_09-039	Ukumehame-A	0	0	0.02	0.47	3.7	99.53
HI_MAUI_09-040	Olowalu-A	0	0	0	0	3	100

Table 4. Land-use statistics for Oʻahu Wadeable Stream Assessment (WSA) sampling sites.

[mi^2, square miles; SF, South Fork; NF, North Fork; locations of sites in fig. 5]

Station ID	Site name	Agriculture		Developed		Forested	
		Area, in mi^2	Percentage of basin area	Area, in mi^2	Percentage of basin area	Area, in mi^2	Percentage of basin area
HIO05518-002	Nuʻuanu-C	0	0	0.78	17.87	3.57	82.13
HIO05518-003	N. Hālawa-A	0	0	0.06	3.94	1.55	96.06
HIO05518-005	Poamoho[1]	0.07	2.56	0.02	0.7	2.68	96.74
HIO05518-010	SF Kaukonahua-A	0	0	0	0	2.94	100
HIO05518-011	Waiāhole-B	0.29	7.61	0.18	4.66	3.35	87.72
HIO05518-013	Kamananui-B	0	0	0	0	5.73	100
HIO05518-018	Kalihi-C	0	0	0.88	18.42	3.9	81.58
HIO05518-023	Kahana-A	0	0	0	0	0.31	100
HIO05518-025	Helemano[1]	0.1	2.39	0	0	4.05	97.61
HIO05518-026	Kīpapa-A	0	0	0	0	2.24	100
HIO05518-027	Waikāne-B	0.05	2.08	0	0.01	2.47	97.91
HIO05518-029	Kamananui-A	0	0	0	0	1.9	100
HIO05518-034	Nuʻuanu-A[1]	0	0	0.43	11.13	3.46	88.87
HIO05518-035	Haʻikū	0.01	2.38	0.03	6.49	0.43	91.13
HIO05518-037	Anahulu-B	1.75	12.25	0.04	0.28	12.5	87.47
HIO05518-038	SF Kaukonahua-C	0.01	0.14	0	0	3.68	99.86
HIO05518-039	Waikāne-C	0	0	0	0	0.52	100
HIO05518-151	Kahana-C	0	0	0	0	2.15	100
HIO05518-153	ʻŌpaeʻula[1]	0.08	2.18	0	0.09	3.61	97.73
HIO05518-155	Pālolo[1]	0.19	5.13	1.04	27.97	2.49	66.9
HIO05518-158	N. Hālawa-B[1]	0	0	0.14	4.43	3.07	95.57
HIO05518-159	Maunawili[1]	0	0	0	0	0.11	100
HIO05518-160	Kahana-B	0	0	0.01	0.21	3.26	99.79
HIO05518-162	Kalihi-A	0	0	0.05	2.4	2.14	97.6
HIO05518-163	ʻĀhuimanu	0	0	0.09	22.49	0.31	77.51
HIO05518-164	Kamoʻoaliʻi	0	0	0.33	60.45	0.21	39.55
HIO05518-166	Kīpapa-C	0	0	0	0	4	100
HIO05518-168	Kawai Iki[1]	0	0	0	0	2.19	100
HIO05518-171	Mānoa	0.06	2.43	0.15	6.32	2.22	91.24
HIO05518-174	Waimano[1]	0	0	0	0	0.91	100
HIO05518-175	Kahana Iki	0	0	0.03	8.76	0.33	91.24
HIO05518-177	SF Kaukonahua-B	0.04	0.77	0	0.05	5.31	99.17
HIO05518-181	Anahulu-C	1.15	8.6	0.04	0.3	12.17	91.11
HIO05518-182	NF Kaukonahua-B	0	0	0	0	4.46	100
HIO05518-183	Waiāhole-C	0.19	5.43	0.1	2.86	3.22	91.71
HIO05518-186	NF Kaukonahua-A	0	0	0	0	1.38	100
HIO05518-187	Lulumahu	0	0	0	0	0.35	100
HIO05518-191	Waimānalo	0	0	0	0	0.19	100
HIO05518-194	Pauoa	0	0	0.03	4.66	0.68	95.34
HIO05518-203	Hakipuʻu	0.04	5.03	0	0.35	0.74	94.62

[1] No Targeted Riffle sample collected.

down from the water surface) using an acoustic-Doppler velocity (ADV) meter and taking that as the mean velocity. GPS coordinates were recorded at each sampling location.

Handling of Native Species

In accordance with conditions specified in the Hawaiʻi State Division of Aquatic Resources (DAR), Special Activity Permit, specimens of the native mollusk, *Neritina granosa* (hīhīwai), and the native shrimp, *Atyoida bisulcata* (ʻōpae kalaʻole), that were collected in the QMH and RTH samples were individually counted, measured, photographed, and released unharmed back into the stream from which they were captured. These data were incorporated into the sample data received back from the analytical laboratory. Whenever possible, naiads (immature aquatic stage) of the native *Megalagrion* damselflies were handled in a similar manner.

Laboratory Methods

The sorting, identification, and enumeration of all the macroinvertebrate samples were conducted by the contract laboratory, EcoAnalysts Inc. Expert laboratory personnel picked through the samples, sorting out the macroinvertebrates from the bits and pieces of plant and inorganic material using standard procedures as discussed in Barbour and others (1999). Both sample types, QMH and RTH, were processed in the same manner. Each sample was spread evenly in a sorting tray of known dimensions, marked with grid lines. The sorting was conducted incrementally by randomly selecting, removing, and sorting individual grids of material until a fixed count of 500 organisms was obtained from each sample. The number of grids of material that were picked through from each sample was compared to the total number of grids of the whole sample to determine the percentage of each sample that was needed to reach the 500-organism threshold. This percentage is called the subsample factor. The subsample factor was then used to estimate the total number of organisms in each whole sample. For example, if 6 out of 12 total grids (50 percent) of a sample produced 500 organisms, the subsample factor would be $12 \div 6$, or 2, and the whole sample would be estimated to contain 500×2, or 1,000 organisms. The sorted organisms were identified to the lowest practical taxonomic level, usually to the genus or species level. Damaged organisms were more difficult to identify and were usually determined at the family or class level. Aquatic worms were identified at the class Oligochaeta level.

Data received from the analytical laboratory included the unique station and sample identifiers, along with the associated taxonomic identifications, counts, and subsample factors for each sample. The total abundance for each taxon in each sample was calculated by multiplying the sample count by the subsample factor. The total abundances for the RTH samples were then standardized to a 1-m^2 (10.76-ft^2) area. These areal values were then analyzed using the preliminary Hawaiian benthic macroinvertebrate multimetric index developed by Wolff (2005).

Quality Control

Laboratory Methods

Laboratory quality-control procedures included a second sort of the material of each sample by a second laboratory taxonomist until a 90 percent or better sorting efficacy was attained. Further quality-control measures were conducted on 10 percent of the samples to verify the taxonomic identifications by the original taxonomist. A second taxonomist independently examined and identified the sorted organisms until a 90 percent or better similarity was attained between the two taxonomists.

Re-sort of Samples

In order to evaluate the variability in the subsampling process of the contract laboratory, EcoAnalysts Inc. were requested to re-sort the remaining unsorted material of four quantitative samples, following the same procedures describe-above. These samples all had large subsample factors, indicating that only small fractions of the original samples were sorted to achieve the 500-organism count.

Replicate Sampling

As part of the quality control, a replicate RTH composite sample was collected at eight sampling sites concurrently with the primary RTH sample. These samples were collected and processed following the same procedures as described in the section “Quantitative Benthic Macroinvertebrate Sampling.” The study sites where replicates were collected were required to have sufficient stretches of riffle habitat so that two sets of five undisturbed samples could be collected. Whenever possible, paired samples were collected from discrete riffles, as near to each other as was practicable, and composited into separate containers and processed as described earlier. The macroinvertebrate compositions of the paired composite samples were compared to each other to evaluate the within-site variability.

Repeat Sampling

The Waiheʻe-A study site was selected as a repeat sampling site because the site was easily accessible and contained a large quantity of riffle habitat that met the sampling requirements. A total of three RTH composite samples were collected at this site over the duration of the study. The large number of optimal riffles made it possible to avoid sampling the same riffles within the study reach during the subsequent repeat sampling. These samples were collected and processed following the same procedures as described in the section “Quantitative Benthic Macroinvertebrate Sampling.” The macroinvertebrate compositions of these samples were compared among each other as a measure of temporal variability.

Additional Biological Surveys

In addition to the collection of the benthic macroinvertebrate samples, brief snorkel surveys were conducted to observe the conspicuous fish fauna and other organisms that may not have been collected in the benthic samples. Fish, mollusks, and large crustaceans such as prawns or crayfish may themselves be indicators of stream quality and can play a part in structuring macroinvertebrate communities. Furthermore, surveys of adult native *Megalagrion* damselflies were conducted during each site visit. The native damselfly genus *Megalagrion* is unique to the Hawaiian Islands, and the presence or absence of these delicate odonates may also be indicative of local stream conditions. Visual observations of macroinvertebrates supplemented the information provided by the benthic samples for presence/absence metrics.

Snorkel Surveys

Brief snorkel surveys were conducted at each site to observe the fish communities and other stream fauna. These surveys were conducted after the benthic macroinvertebrate sampling was completed and were restricted due to time limitations. The conspicuous fauna were not counted; however, rough estimates of abundances were determined. This method may fail to spot some of the more cryptic species such as the dojo loach, *Misgurnus anguillicaudatus*, and the Chinese catfish, *Clarius fuscus,* which have a propensity to hide (Yamamoto and Tagawa, 2000). In conducting these surveys, a snorkeler entered the stream below the downstream end of the reach and slowly moved upstream and identified the observed fish, snail, insect, and crustacean species.

Damselflies

The Hawaiian Islands are home to a diversity of odonates. This includes the endemic Hawaiian damselfly genus *Megalagrion* McLachlan, 1883 (Arthropoda: Insecta: Odonata: Zygoptera: Coenagrionidae). This genus, known locally as pinao ‘ula, includes 23 species and 3 subspecies (Polhemus, 1993; Polhemus and Asquith, 1996). Some species of *Megalagrion* have an obligate aquatic larval stage that requires them to inhabit freshwater as immature naiads. Some species, as adults, rely on other aquatic organisms as their primary food sources, requiring them to forage in and around the stream corridors. Introduced species, predation, competition, and habitat loss have caused declines and extirpations of local populations of native damselflies (Williams, 1936; Zimmerman, 1948; Polhemus, 1993; Polhemus and Asquith, 1996; Liebherr and Polhemus, 1997; DiSalvo and others, 2003). Due to their sensitivity to environmental alterations and their susceptibility to introduced fishes and amphibians, some species of native Hawaiian damselflies and dragonflies are considered to be indicator species, so that their presence is thought to be indicative of relatively undisturbed stream ecosystems (Liebherr and Polhemus, 1997; DiSalvo and others, 2003; Englund and others, 2007; Polhemus, 2008). In some instances, however, *Megalagrion* have been found existing in degraded habitats (Evenhuis and Cowie, 1994; this study)

The decline in populations of some *Megalagrion* species have been so severe that in 1996, the U.S. Fish and Wildlife Service included six species as candidates for listing as endangered or threatened (U.S. Fish and Wildlife Service, 1996). In 2009, the USFWS proposed endangered status for two of the candidates, *M. nesiotes*, the flying earwig Hawaiian damselfly, endemic to the Islands of Hawai‘i and Maui, and *M. pacificum*, the Pacific Hawaiian damselfly, historically endemic to all the main Hawaiian Islands, and in 2010, the USFSW published the final rule that determined endangered species status for *M. nesiotes* and *M. pacificum*, under the Endangered Species Act (ESA) of 1973 (U.S. Fish and Wildlife Service, 2009, 2010).

During each site visit, conspicuous adult damselflies were observed and occasionally captured, photographed, identified, and released unharmed. The location of each sighting was recorded. Identifications were determined on the basis of descriptions in Polhemus and Asquith (1996), and questionable identifications were confirmed, using photographs, by Dr. Polhemus (D.A. Polhemus, Coastal Conservation Program Manager, U. S. Fish and Wildlife Service, oral commun., 2010). One of the challenges in using adult *Megalagrion* damselflies in bioassessments is that they are very sensitive to changes in the weather and are rarely, if ever, seen on cold, rainy, or blustery days, being more active during warm sunny days (Polhemus and Asquith, 1996). The absence of adult native damselflies at some of the study sites may have been a consequence of suboptimal weather conditions during the sampling periods, as it was not practical to sample only during optimal weather conditions.

Evaluation of Re-sort, Replicate, and Repeat Samples

Multivariate statistical analyses were used to evaluate the results of the replicate, re-sort, and repeat samples collected on Maui. Nonmetric multidimensional scaling (nMDS) was used to examine the relations among the samples using abundance and proportional data (Clarke, 1993). Hierarchical agglomerative clustering was performed on both datasets using Bray-Curtis similarity scores to examine similarities among the samples. The results of these analyses are presented in appendix A.

In general, the analyses of the re-sorted samples demonstrated relatively high degrees of similarity with the original sorting results. Percent similarities were greater using the proportional data and ranged from 80 to 90 percent, whereas similarities using the abundance data ranged from 75 to 85 percent. The analyses of the paired replicate samples also demonstrated relatively high degrees of similarity, ranging from 75 to 85 percent using the proportional data and from 70 to 90 percent using the abundance data. The analyses of the repeat samples from the Waiheʻe-A site showed a higher similarity between the first and third samples, 85 percent, than with the second sample at 70 percent similarity.

Benthic Macroinvertebrate Community Structure in Maui and Oʻahu Streams

The various assemblages of benthic macroinvertebrates collected from the Maui study sampling sites are composed of a mixture of native and nonnative species representing 8 phyla, 14 classes, 37 families, and 48 genera. Descriptions, distributions, and abundances of some of the more common taxa collected during this study are discussed in this section. Photographic images of some of the more commonly collected macroinvertebrates are provided in appendix D. The abundance data were derived from the quantitative samples only, whereas observational or presence/absence data were derived from the quantitative, qualitative, and visual observations data sets. Maps showing the distributions of the various taxa are provided in appendixes A and B.

Native Macroinvertebrates

Atyoida bisulcata Randall, 1840; (Arthropoda; Crustacea; Decapoda; Atyidae); *A. bisulcata*, known locally as ʻōpaekalaʻole or ʻōpae, and commonly called mountain shrimp, is an endemic, freshwater, amphidromous shrimp found throughout the Hawaiian Islands (figs. D1–D3). As an amphidromous species, *A. bisulcata* larvae wash out into the ocean, where they spend time metamorphosing, returning to freshwater as post-larvae, and migrating upstream as juveniles (Kinzie, 1990). Adults of this species of crustacean are more commonly found at higher elevations in the more "pristine" streams; however, juveniles and recruits have been observed and collected from the lower reaches of streams, most often in the channel margins, during their upstream migration. If downstream conditions are impaired to the point at which post-larvae or juveniles are unable to survive, adult *A. bisulcata* may not be present at the less-impaired upstream sites.

The distribution and abundances of *A. bisulcata* identified in quantitative samples from Maui are shown in figures B1–B2. *A. bisulcata* were identified in 34 samples from 26 sites. Densities of *A. bisulcata* at sites where they were collected ranged from 0.8/m^2 (4 sites) to 497.2/m^2 at Makamakaʻole-B (33 percent of the Makamakaʻole-B sample). The high abundance at Makamakaʻole-B was due to a recruitment event, when post-larvae were returning to freshwater. The highest density of adults, 80/m^2 (1.0 percent of the Hanawī-A sample), was recorded at the Hanawī-A site. Site observations of *A. bisulcata* are shown in figures B3–B4. *A. bisulcata* were observed at all of the sampling sites in East Maui and at 15 of the 24 sites (62.5 percent) in West Maui. In West Maui, *A. bisulcata* were observed at 5 of the 13 (38.5 percent) upper altitude sampling sites, 7 of the 8 (87.5 percent) middle sites, and at all 3 of the lower elevation sites. Some of the water diversions on the Lahaina side of West Maui create barriers to the upstream migration of *A. bisulcata*. The downstream distance to the stream mouth from the sampling locations near the diversions averaged 2.1 miles for the 7 upper East Maui sites and 3.6 miles for the 5 Lahaina side West Maui sites that were devoid of *A. bisulcata*. The Lahaina side of West Maui is also much drier than Northeast Maui, therefore affording the amphidromous species less opportunity to migrate upstream to the perennial reaches of the streams.

The size class distribution of the *A. bisulcata* collected at the Maui sampling sites showed that 86.1 percent of those collected at lower elevation sites were new recruits (12 cm) and 13.9 percent were juveniles. No adults were collected at the lower elevation sites. At the middle elevation sites, 20.4 percent were adults, 38.9 percent were juveniles, and 40.8 percent were recruits; and at the upper elevation sites 57.1 percent were adults, 42.4 percent were juveniles, and 0.5 percent were recruits.

The distribution and abundances of adult and juvenile *A. bisulcata* identified in quantitative samples from the Oʻahu WSA sites are shown in figure C1. Densities of ʻōpae, in the 5 quantitative samples in which they were present, were lower than those in streams on Maui, and ranged from 2.4/m^2 at Anahulu-B to 9.0/m^2 at Kahana-A, with a mean density of 6.3/m^2, whereas in the Maui samples they ranged from 0.8/m^2 to 80/m^2 with a mean of 18.4/m^2 (not including the 497.2/m^2 collected at Makamakaʻole-B during a recruitment event). *A. bisulcata* were observed at 12 of the 40 Oʻahu WSA sampling sites (30 percent), with 7 of those sites on the windward side, 4 in central Oʻahu, and 1 site on the leeward side (fig. C2). Size class distribution data for the *A. bisulcata* identified in the Oʻahu WSA samples were not documented.

Neritina granosa Sowerby, 1825; (Mollusca; Gastropoda; Archaeogastropoda; Neritidae); *N. granosa*, known locally as hīhīwai or wī, is an endemic, freshwater, amphidromous, limpet-like mollusk found throughout the Hawaiian Islands (fig. D4; Yamamoto and Tagawa, 2000). Ford (1979) concluded that adult *N. granosa* were most abundant on clean boulders, cobbles, and gravel in shallow riffles but are also adapted to living in torrential flows. *N. granosa* are most active at night, spending daylight hours under rocks and in crevices and coming out in the evening to forage and mate (Brasher, 1997). *N. granosa* have not been commonly found in streams on Oʻahu for a number of years (Edmondson, 1933, Maciolek, 1972; Ford, 1979). In 1938, an attempt was made to translocate *N. granosa* gathered from Kauaʻi streams and planted into streams on Oʻahu, including Waiheʻe, Kōloa, Waianu, Punaluʻu, Waiāhole, and Nuʻuanu Streams (Hawaii Board of Commissioners, 1939). Edmondson and Wilson (1940) conjectured that *N. granosa* might not have ever been established on Oʻahu. It might also be possible that *N. granosa* populations on Oʻahu were affected by the loss of suitable habitat due to increased sedimentation stemming from the extensive deforestation and cattle wallows on Oʻahu during the 1800s and early 1900s.

The distribution and abundances of *N. granosa* identified in quantitative samples from Maui are shown in figures B5–B6. *N. granosa* were identified in 11 samples from 9 sites. Densities of *N. granosa,* at sites where they were collected, ranged from 0.8/m^2 at Wailua Nui-B (0.06 percent of the sample) and Hanawī-B (0.01 percent of the sample) to 194/m^2 (11.6 percent of the sample) at Waiohue. Observations of *N. granosa* were made at 9 of the 40 (23 percent) Maui sampling sites—at 8 of the 16 (50 percent) East Maui sites and at 1 of the 24 (4 percent) West Maui sites. *N. granosa* were present at 6 of the 8 (75 percent) lower sites, 3 of the 11 (27 percent) middle sites, and were not present at any of the 21 higher elevation sites.

N. granosa were not collected or observed during the Oʻahu WSA sampling, although it was observed during previous USGS studies in Nuʻuanu Stream (Wolff, 2005) and in Punaluʻu Stream (Oki and others, 2006). Earlier observations of *N. granosa* on Oʻahu include Kubota (1972) in Kahana Stream; Ford (1979) in Kaluanui Stream; Archer (1984) in Kōloa Stream; and Timbol (1984a) in Kaluanui Stream.

Telmatogeton spp. (Arthropoda; Insecta; Diptera; Chironomidae); the Hawaiian *Telmatogeton* is a genus of flying insects that have aquatic larvae and pupae (figs. D5–D8). The larvae of this genus of Chironomidae (nonbiting midges) were first recorded from freshwater in Hawaiʻi by Terry in 1910 (Terry, 1913 [*Charadromyia*]). This genus of chironomid is found in coastal rocky shoreline habitats around the world, but in the Hawaiian Islands it has adapted from its marine ancestors to freshwater habitats (Wirth, 1947; Newman, 1975; Newman, 1988). Hawaiian *Telmatogeton* are known as torrent midges, because the larvae are found in fast flowing streams clinging onto smooth rocks and in splash zones of cascades and waterfalls (figs. D9–D10; Terry, 1913; Wirth, 1947; Benbow and others, 1997). They were also observed colonizing fast flowing ditches and flumes (Wirth, 1947). The larvae spin silken cases attached to flat, hard surfaces and feed on diatoms and green algae. There are five described freshwater *Telmatogeton* species endemic to Hawaiʻi: *T. abnormis* (Terry, 1913) recorded from Kauaʻi, Oʻahu, and Maui; *T. fluviatilis* Wirth, 1947, recorded from Oʻahu, Maui, and the Island of Hawaiʻi; *T. hirtus* Wirth, 1947, endemic to Kauaʻi; *T. torrenticola* (Terry, 1913) recorded from Kauaʻi, Oʻahu, Molokai, Maui, and Hawaiʻi Island; and *T williamsi* Wirth, 1947 endemic to Oʻahu.

The distribution and abundances of *Telmatogeton* identified in quantitative samples from Maui are shown in figures B7–B8. *Telmatogeton* larvae were identified in 20 samples from 17 sites. Densities at sites where *Telmatogeton* larvae were collected ranged from 1.3/m^2 (0.19 percent of the sample) at North Waiehu-C, below the diversion, to 307.2/m^2 (1.3 percent of the sample) at Kōlea. The highest relative abundance was at the Honomanū site (29.6/m^2; 9.2 percent of the sample). *Telmatogeton* abundance and relative abundance were determined to be significantly inversely correlated with specific conductance (Spearman's rho = — 0.43, p = 0.0014; and Spearman's rho = – 0.45, p = 0.0007 respectively). Benbow and others (2003) determined that *T. torrenticola* on Maui were more abundant in cascades and splash zones than in riffles. The quantitative methods used in the current study as well as in past USGS studies in Hawaiʻi focused on riffle communities and therefore may underrepresent the overall reach-wide abundances of *Telmatogeton*. Larval *Telmatogeton* were observed at 19 of the 40 (47.5 percent) study sites on Maui, including 8 of the 16 (50 percent) sites in East Maui and 11 of the 24 (45.8 percent) sites in West Maui. Larval *Telmatogeton* were more often observed at upper elevation sites, 17 of 20 sites, than at middle, 1 of 11 sites, or lower elevation sites, 1 of 9 sites.

Telmatogeton larvae were not observed in any samples collected from Oʻahu streams during the WSA or NAWQA studies (55 sites). Historically, four *Telmatogeton* species have been reported from streams, ditches, and flumes on Oʻahu. Illingworth (1931) reported that *T. fluviatilis* [syn. *Charadromyia torrenticola* (Terry, 1913)] were abundant in the Waiāhole Ditch in Waipiʻo in 1929. Wirth (1947) described the Oʻahu *T. fluviatilis* from specimens collected from streams and ditches in 1946 from Kīpapa, Waiāhole, Mānoa, Lulumahu, and Punaluʻu. Wirth (1947) described *T. williamsi* from hundreds of specimens collected in 1946 on Oʻahu from a rock-lined ditch that supplied irrigation water to the Waiʻanae Plantation, and *T. abnormis* from Kaluanui Stream upstream of Sacred Falls. Kawate (1969) reported *T. hirtus* (possibly *T. williamsi* because *T. hirtus* is endemic to Kauaʻi; Wirth, 1947; Nishida, 1992) as common in Punaluʻu Stream at 770 ft. More recently, during insect surveys at Kaluanui Stream in 1993-94, Polhemus (1995) observed *T. fluviatilis*, *T. abnormis*, and *T. williamsi* at 2,200–2,500 ft and *T. williamsi* at 350 ft. Englund (2000) reported *T. williamsi* as common in Kaipapaʻu Stream on Oʻahu from waterfalls at 600-800 ft, noting that this species was otherwise extremely rare.

Megalagrion spp. McLachlan, 1883; (Arthropoda; Insecta; Odonata; Coenagrionidae); this Hawaiian endemic genus of damselflies, known locally as pinao ʻula, is represented by 23 species and 3 subspecies (figs. D11–D14; Polhemus, 1993; Polhemus and Asquith, 1996). The field guide by Polhemus and Asquith (1996) "Hawaiian Damselflies: A Field Identification Guide" provides a comprehensive reference replete with descriptions, ecology, local distributions, and ranges of these unique damselflies. Like many other aquatic insects, adult *Megalagrion* are terrestrial but their naiads are mostly aquatic. Some species breed in flowing streams, some breed in side pools or spray zones, and still others breed in damp vegetation or in the damp axils of vines (Polhemus and Asquith, 1996). Due to the expertise required, the naiads were not identified to the species level.

The distribution of adult *Megalagrion* observed at Maui study sites is shown in figures B9–B10. As mentioned earlier, adult *Megalagrion* are usually active only from mid-morning to mid-afternoon during calm, sunny days, so their absence from sites may have been due to suboptimal weather conditions. The species observed on Maui include *M. blackburni* McLachlan, Blackburn's Hawaiian damselfly; *M. nigrohamatum nigrohamatum* (Blackburn, 1884), the Blackhook Hawaiian damselfly; *M. hawaiiense* (McLachlan), the Hawaiian Upland damselfly; *M. calliphya* (McLachlan), the Beautiful Hawaiian damselfly; and a possible sighting of *M. pacificum* (McLachlan) the Pacific Hawaiian damselfly, which is currently listed as an endangered species by the U.S. Fish and Wildlife Service.

The distribution and abundance of *Megalagrion* naiads collected in the quantitative samples on Maui are shown in figures B11–B12. *Megalagrion* naiads were identified in 17 samples from 15 sites. The densities of naiads, at sites where naiads were collected, ranged from 1.5/m^2 (0.2 percent of the sample) at the Waiheʻe-B, open canopy site to 54.2/m^2 (4.5 percent of the sample) at the North Waiehu-A site above the diversion. The three samples from North Waiehu, including two above the diversion and one below the diversion, had the highest densities—54.2/m^2 (4.5 percent), 42.7/m^2 (3 percent), and 30.7/m^2 (4.7 percent), respectively. The boulders and cobbles at this site had a thick mat of moss cover, which provides a suitable habitat for the *Megalagrion* naiads, and adult *M. blackburni* were commonly observed flying about during the sampling.

Adult *Megalagrion* were observed at 15 sites at which naiads were identified in either the quantitative (5 sites), qualitative (2 sites) or both (8 sites) sample types on Maui. *Megalagrion* naiads were collected in either the quantitative or qualitative samples at five sites at which adults were not observed, and adults were observed at nine sites at which naiads were not identified in either the quantitative or qualitative samples.

Megalagrion naiads were not detected in the benthic samples collected during the Oʻahu WSA study. The distribution of adult *Megalagrion* observed at Oʻahu WSA sampling sites is shown in figure C3. The species observed on Oʻahu included *Megalagrion nigrohamatum nigrolineatum* (Perkins), the Blackline Hawaiian damselfly. Native damselflies were observed at 6 of the 40 sampling sites, with 2 species observed at 1 of the sites.

Heteromeyenia baileyi (Bowerbank, 1863); (Porifera; Demospongiae; Haplosclerida; Spongillidae); *H. baileyi* is an indigenous freshwater sponge also found in North America (fig. D15). Svihla (1941) described the Hawaiian *H. baileyi* he observed in Haipuaʻena Stream on Maui in 1935 as large masses, vivid green, encrusting rocks and wood. He also identified samples collected on Oʻahu in 1936. Yamamoto and Tagawa (2000) describe *H. baileyi* as being bright green to olive brown in encrusting or branching forms, common on Oʻahu in Waikele Stream and Wahiawā Reservoir. This species was observed but not collected in the samples. Observations on Maui were made at West Wailua Iki-A and East Wailua Nui-A. Observations on Oʻahu were made at sites A, B, and C in South Fork Kaukonahua Stream, Ōpaeʻula, Kīpapa-C, and Kawai Iki.

Nonnative Macroinvertebrates

Nonnative macroinvertebrates were the most abundant component of the benthic stream samples collected on Maui. These included a number of insect, mollusk, and crustacean species. These species arrived in Hawaiʻi in a variety of ways and at different time periods. The spread of some of these species around the State has been rapid, while others have been restricted in the expansion of their ranges. The history, distribution, and abundance of some of the more common species are discussed in this section.

Insects

Insects were a major component of the benthic macroinvertebrate samples collected on Maui. Many of these insects are terrestrial as adults and return to the water to lay their eggs. The immature insects have aquatic larvae, pupae, or naiads that occupy a wide range of aquatic habitats. The relative abundance of immature insects in the Maui quantitative samples ranged from 29.9 percent to 99.3 percent with a mean of 86.3 percent.

Trichoptera

Four species of trichopterans have been recorded in Hawaiʻi, all of which are not native, including *Oxyethira maya*, *Cheumatopsyche analis*, *Hydroptila potosina* (formerly *H. arctia*), and *Hydroptila icona* (figs. D16–D23; Flint and others, 2003). It is commonly believed that they were accidently introduced along with imported aquarium plants. Trichopterans are an order of insects commonly known as caddisflies and have a world-wide distribution. Like other aquatic insects, the adults are terrestrial and, in most cases, the larvae and pupae are aquatic. Trichoptera are commonly used in benthic macroinvertebrate metrics such as the popular EPT metric, which is based on the ratio of the insect orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies). None of the EPT taxa are native to Hawaiʻi. A species of Ephemeroptera, *Caenis nigropunctata*, was accidentally introduced into Hawaiʻi in the 1940s, most likely as a stowaway in an airplane (Van Zwaluwenburg, 1945; Zimmerman, 1951). This species is uncommon on Oʻahu, although specimens are collected from time to time (Smith, 2000; Brasher and others, 2004). *C. nigropunctata* has not been reported from Maui. It was identified in the Oʻahu WSA qualitative samples from Anahulu-B, Kahana Iki, and Kalihi-A. Two other species of Ephemeroptera were intentionally released on Kauaʻi in 1961 as food for the introduced trout, but these species failed to become established (Needham and Usinger, 1961; Davis and Krauss, 1962; Smith, 2000). A single specimen of a fourth species, *Potamanthus formosus*, was collected at Hickam Air Force Base in 1954, but it did not become established (Bae and McCafferty, 1991). No species of Plecoptera have been reported from Hawaiʻi.

Oxyethira maya Denning, 1947; (Arthropoda; Insecta; Trichoptera: Hydroptilidae). This was the first trichopteran recorded in Honolulu, Hawai‘i, in 1940 (Zimmerman, 1943). The species in the family Hydroptilidae are commonly called micro-caddisflies because they are smaller than species in the other trichopteran families. The larvae of *O. maya* are small and live in clear, flat, silk cases that are attached to rocks. *O. maya* have spread throughout the islands, recorded in Hilo in 1957 (Adachi, 1958), Kōke‘e, Kaua‘i in 1959 (Beardsley, 1960), and Honokahua Stream, West Maui in 1970 (Beardsley, 1971). An analysis of stomach contents found *O. maya*, *C. analis*, and *H. potosina* being consumed by the native stream fish *Awaous guamensis* (‘o‘opu nākea) (Kido, 1997) and the introduced fish *Oncorhynchus mykiss* (rainbow trout) (Kido and others, 1999a).

O. maya were the least common trichopteran on Maui, identified in only four quantitative samples from three sites including Kopili‘ula-B (4.3/m^2; 0.2 percent), Wailua Nui-B (2.7/m^2; 0.2 percent), and Honolua (5.5/m^2 and 2.19/m^2; 0.6 percent and 0.2 percent). *O. maya* larvae and/or pupae were more common in the qualitative samples, observed at 21 of the 40 Maui sites, and more common in East Maui, 13 of the 16 sites, than West Maui, 8 of the 24 sites.

O. maya were identified in 12 of the 31 quantitative samples from the O‘ahu WSA study, with densities ranging from 0.8/m^2 (0.4 percent) at Lulumahu to 45.5/m^2 (1.5 percent) at the Kīpapa-C site. *O. maya* were observed in qualitative samples from 16 of the 40 O‘ahu WSA study sites, being more common in central O‘ahu, 13 of the 18 sites, than leeward O‘ahu, 1 of 8 sites, or windward O‘ahu, 2 of 14 sites.

Cheumatopsyche analis (Banks, 1908), [*pettiti* as junior synonym]; (Arthropoda; Insecta; Trichoptera: Hydropsychidae); *C. analis*, commonly known as little sister sedges, are much larger than *Oxyethira* and *Hydroptila*. *C. analis* larvae live in cases composed of pebbles, sand, and (or) small pieces of wood held together by a silk web. These cases are attached to the undersides of cobbles or sometimes in depressions or pores of the lava rocks. The cases are sealed with the pupae inside before they emerge as adults. The first record of adult *C. analis* in Hawai‘i was from light traps used by the Hawai‘i Department of Public Health on O‘ahu in 1965 (Beardsley, 1966, Beardsley, 1967a). The spread of *C. analis* was rapid around the islands as adults were caught in light traps in Punalu‘u, Kahana, and Waipahu on O‘ahu in 1966 (Beardsley, 1967b), on Molokai in 1969 (Joyce, 1970), in a black light trap in Hilo, Hawai‘i in 1971 (Shiroma, 1972), on Maui by 1971 (Denning and Blickle, 1971) and in Kōke‘e and Haena, Kaua‘i in 1972 (Kawamura, 1974),

The first larvae were collected in Ōpae‘ula Stream on O‘ahu by John Maciolek in 1966 (Beardsley, 1967c; Denning and Beardsley, 1967). By 1968, the larvae were becoming more abundant as Kawate (1969) reported dozens to hundreds in Poamoho and Punalu‘u Streams. Shima (1970) reported that *C. analis* was very abundant in Kamo‘oali‘i Stream on O‘ahu; commenting that “Caddisfly larvae clung to virtually every rock in the stream…,” Ibara and Conant (1972) reported the presence of larvae in Waiohonu Stream on Maui, and by 1975 Kinzie and Ford (1977) reported that the larvae were ubiquitous in sections of ‘Ohe‘o Gulch (Pīpīwai Stream) and present in Palikea Stream on Maui. Timbol (1977) reported that *C. analis* were abundant at every sampling site on the Wainiha and Hanalei Rivers on Kaua‘i, at almost every sampling site in the North Fork Wailua River, Kaua‘i, and in Wailoa Stream, on the Island of Hawai‘i. In a 1977 survey of the Wailuku River on the Island of Hawai‘i, the USFWS (1978) reported finding that nearly 78 percent of the stream fauna was nonnative, with nonnative insects accounting for 94 percent of the exotics, and that *C. analis* accounted for the majority of the nonnative insect abundance. Abundant at every station, *C. analis* were reported to account for more than 90 percent of the sample from the most downstream station. *C. analis* were also reported to be a major component in downstream drift samples (Barnes and Shiozawa, 1985). Many studies since then have reported that *C. analis* has become widely distributed and extremely abundant in streams throughout the State (for example: Archer and others, 1980; Ford, 1982; Brasher, 1991; Polhemus, 1992; Englund and others, 2000a; Wolff, 2005; Kinzie and others, 2006). Not only, as Maciolek (1976) noted, has *C. analis* spread throughout the islands in the span of about 10 years, *C. analis* has also become the numerically dominant species in many streams in Hawai‘i.

C. analis has also become a major component of the diet for some stream fish. Kido and others (1993) determined that the larvae were frequently consumed by *Awaous guamensis* (‘o‘opu nākea), and Kido (1996) found larvae in the stomach contents of *Sicyopterus stimpsoni* (‘o‘opu nōpili) from the Wainiha River on Kaua‘i. Heacock and others (1994) found the larvae in the stomachs of smallmouth bass (*Micropterus dolomieu*) from Wailua and Hule‘ia Rivers on Kaua‘i. Kido and others (1999a) determined that *C. analis* larvae were the most frequently consumed prey of rainbow trout (*Oncorhynchus mykiss*) from Wai‘alae Stream on Kaua‘i.

The distribution and abundance of larval *C. analis* collected in the quantitative samples on Maui are shown in figures B13–B14. *C. analis* larvae and (or) pupae were collected in every quantitative sample. The densities of *C. analis* ranged from 27.2/m^2 (16.4 percent) at Nua‘ailua Stream to 4,514.7/m^2 (48.2 percent) at the Pālauhulu-A site. The relative abundance of larval *C. analis* ranged from 6 percent at Wailua Nui-B to 88.5 percent at the South Waiehu-A site. *C. analis* was the dominant species at 18 of the 40 sites on Maui and was the second-dominant species at another 15 sites. McIntosh and others (2003) determined the mean densities of *C. analis* in ‘Īao Stream to be 799/m^2 upstream of the Māniania Ditch as compared to densities of 395.6/m^2 and 1,804.2/m^2 determined at ‘Īao-C, located near the McIntosh and others (2003) sampling site, and 1,930.4/m^2 at ‘Īao-A, located upstream within the ‘Īao Valley State Park.

The relative abundance of *C. analis* was determined to be significantly correlated to the specific conductance of the stream water at the sampling site (Spearman’s rho = 0.55, p<0.0001). *C. analis* abundance was determined to be significantly correlated with the mean Froude number (Spearman's rho = 0.51; $p<0.0001$) calculated for each site using the depth and velocity measurements collected at each of the five quantitative sampling sites. Additionally, *C. analis* abundance was found to be significantly correlated with the mean percentage of stream reach composed of fast riffles (Spearman's rho = 0.61; $p>0.0001$). This indicates that the abundance of *C. analis* was generally greater at sites with more turbulent flow. Froude numbers computed from velocity and depth measurements collected at the quantitative sampling sites ranged from 0.01 in areas with standing water to 1.52 in sections with rapidly flowing water.

The distribution and abundance of *C. analis* larvae and/or pupae collected in the Oʻahu WSA quantitative sampling are shown in figure C4. *C. analis* was the dominant species in 21 of the 31 quantitative samples and was second-dominant in 5 of the samples. The densities ranged from 12/m^2 at the Kalihi-C site to 3,317.4/m^2 (90 percent) at the Waikāne-B site. *C. analis* was not identified in the quantitative sample at ʻĀhuimanu Stream and was not identified in 4 of the 40 qualitative samples, including Poamoho, Ōpaeʻula, Pālolo, and ʻĀhuimanu Streams.

Hydroptila spp. (Arthropoda; Insecta; Trichoptera: Hydroptilidae); there are currently two species of *Hydroptila* recorded from Hawaiʻi, including *H. potosina* Bueno-Soria, 1984 (replacing the previously assigned name *H. arctia*), and *H. icona* Mosely, 1937, a recently recognized species that has probably been in Hawaiʻi for some time (Flint and Englund, 2003). Anatomically, the differences between these species require specialized training to detect; however, Flint and Englund (2003) point out that the cases that the two species spin are relatively easy to distinguish. The case spun by *H. potosina* is more granular, with sand grains attached to the surface, whereas the case spun by *H. icona* lacks the sand grains (fig. D11). The first record of *Hydroptila* in Hawaiʻi was in 1968 from adults in light traps in the Honolulu area (Joyce, 1969). Denning and Blickle (1971) reported *H. arctia* collected by J. W. Beardsley in 1969 in a light trap near Mānoa Stream. The first larvae were collected in Ōpaeʻula Stream in 1970 (Beardsley, 1971). *H. arctia* (*H. potosina*) were found in the stomach contents of the native gobies, *Awaous guamensis* (ʻoʻopu nākea) and *Sicyopterus stimpsoni* (ʻoʻopu nōpili) (Kido and others, 1993; Kido, 1996).

For the purposes of this study, *Hydroptila* were identified to the genus level, pooling the abundances of *H. potosina* and *H. icona*. The distribution and abundance of larval *Hydroptila* on Maui are shown in figures B15–B16. *Hydroptila* larvae and (or) pupae were identified in 47 of the 54 quantitative samples at 34 sites on Maui. Larvae were present at all 16 of the East Maui sites, and at 18 of the 24 West Maui sites. The larval densities ranged from 2.9/m^2 (0.2 percent) at the North Waiehu-A site, above the diversion, to 2,858.5/m^2 (20.4 percent) at the Hanawī-A site. The highest percentage of *Hydroptila*, 45.7 percent, was collected at the Wailua Nui-B site in East Maui. *Hydroptila* were observed at 38 of the 40 sites, and were absent only at Ukumehame-B and Launiupoko. Hydroptila were the dominant taxa at four sites and the second-dominant taxa at five sites.

The distribution and abundance of *Hydroptila* on Oʻahu are shown in figure C5. *Hydroptila* were not present in 7 of the 31 quantitative samples from the Oʻahu WSA study, including at 4 of the 6 leeward sites. Larval densities ranged from 0.8/m^2 (0.2 percent) at the Kalihi-C site to 1,752/m^2 (36.3 percent) at the Kahana-A site. The highest percentage, 38.9 percent, was collected at the Kamananui-A site. *Hydroptila* was the dominant taxa at two sites and the second-dominant taxa at two sites. *Hydroptila* were observed at 33 of the 40 WSA sampling sites, absent from the Helemano, Poamoho, Pauoa, South Fork Kaukonahua-B, Kalihi-A, ʻĀhuimanu, and Maunawili sites.

Chironomidae

Chironomidae is a family of insects commonly known as nonbiting midges. Many species have a superficial resemblance to mosquitoes but they do not bite or sting. A number of native species of chironomids are found in Hawaiʻi; however, they were not commonly collected in the samples from Maui or Oʻahu. The aquatic larvae and pupae of the various chironomids are difficult to distinguish without an expert knowledge of the family (figs. D24–D26).

Cricotopus bicinctus (Meigen, 1818); (Arthropoda; Insecta; Diptera; Chironomidae); the first record of this nonnative chironomid was from adults captured in light traps at Waipiʻo on Oʻahu in 1955 (Hardy, 1956). By 1960, Hardy (1960) stated that *C. bicinctus* was common at low elevations on Oʻahu and probably present on the other islands. In 1977–78, Yee and Ewart (1986) collected numerous *C. bicinctus* at sites ranging in altitude from 80 to 3,520 ft in the Wailuku River on Hawaiʻi Island. Polhemus (1992) recorded *C. bicinctus* at elevations of 2,899 and 4,956 ft in Hanawī, Maui. Numerous studies have since shown that *C. bicinctus* has spread throughout the State and has become one of the most abundant stream macroinvertebrates (Englund and others, 2000a; Brasher and others, 2004; Wolff, 2005; Kinzie and others, 2006; Wolff and Koch, 2009). *C. bicinctus* larvae were found in the stomach contents of the native gobies, *Sicyopterus stimpsoni* (ʻoʻopu nōpili) and *Awaous guamensis* (ʻoʻopu nākea) (Kido, 1996, Kido, 1997); the native Hawaiian flagtail, āholehole (*Kuhlia* sp.) (Englund and others, 2000b); and introduced fish including rainbow trout (*Oncorhynchus mykiss*) (Kido and others, 1999a).

The distribution and abundance of *C. bicinctus* on Maui are shown in figures B17–B18. Larvae were present in all but one (Ukumehame-A) of the quantitative samples. The larval densities ranged from 3.2/m^2 (1.9 percent) at Nuaʻailua to 8,470.4/m^2 (36.6 percent) at Kōlea Stream. The highest percentage of *C. bicinctus*, 50.1 percent, was recorded from the Waiheʻe-B open canopy site. *C. bicinctus* was the dominant taxa at 9 of the 40 sites and second-dominant at another 12 sites. *C. bicinctus* were observed at every Maui sampling site.

The distribution and abundance of *C. bicinctus* on Oʻahu are shown in figure C6. Larvae were present in all but 1

(South Fork Kaukonahua-B) of the 31 quantitative samples. The larval densities ranged from 2.4/m^2 (0.6 percent) at Anahulu-B to 1,322.7/m^2 (9.9 percent) at Waiāhole-B. The highest percentage of *C. bicinctus*, 49.1 percent, was recorded from the Mānoa site. *C. bicinctus* was the dominant taxa at two sites and second-dominant at seven sites. *C. bicinctus* was observed at 35 of the 40 WSA sites and was not observed at Poamoho, Maunawili, Waimano, Helemano, and South Fork Kaukonahua-B.

***Eukiefferiella* sp.** Thienemann; [*Eukiefferiella claripennis* gr.]; (Arthropoda; Insecta; Diptera; Chironomidae); the earliest record of this nonnative chironomid is from 1977–78 in the Wailuku River on Hawai‘i Island (Yee and Ewart, 1986). Way and Burky (1991) identified *Eukiefferiella* in qualitative samples collected in 1989 from Honoli‘i Stream on Hawai‘i Island. Wolff and others (2002) recorded this genus from specimens collected from Kaluanui, Punalu‘u, Waiāhole, Waihe‘e, and Waikakalaua Streams on O‘ahu during the NAWQA program in 1999. Wolff (2005) reported *E. claripennis* gr. collected from 6 streams on Kaua‘i in 2002.

The distribution and abundance of *Eukiefferiella* larvae on Maui are shown in figures B19–B20. *Eukiefferiella* was identified in every quantitative sample from every sampling site. Larval densities ranged from 4/m^2 (2.4 percent) at Nua‘ailua Stream to 9,699.3/m^2 (41.9 percent) at Kōlea Stream. The highest percentage of *Eukiefferiella*, 46.6 percent, was recorded from the Kaua‘ula Stream site. *Eukiefferiella* was the dominant taxa at 5 sites and second-dominant at 4 sites.

The distribution and abundance of *Eukiefferiella* on O‘ahu are shown in figure C7. *Eukiefferiella* was identified in 17 of the 31 quantitative samples. Larval densities ranged from 4/m^2 (0.4 percent) at Lulumahu Stream to 878.9/m^2 (18.8 percent) at Kamo‘oali‘i Stream. The highest percentage of *Eukiefferiella*, 23.9 percent, was recorded from North Fork Kaukonahua-A . *Eukiefferiella* was the second-dominant taxa at 1 site. *Eukiefferiella* was observed at 22 of the 40 WSA sampling sites.

Empididae

Hemerodromia stellaris Melander, 1947; (Arthropoda; Insecta; Diptera; Empididae); commonly known as dance flies or aquatic dance flies, the family Empididae is represented by two endemic species and three nonnative species in Hawai‘i. None of these species except for the nonnative *H. stellaris* are found in freshwater streams (figs. D27–D28). Timbol (1984a; 1984b) identified the few Empididae collected in Kaluanui and Kaneohe Streams in 1979 as *Hemerodromia* sp. Hardy (1985) remarked that *H. stellaris* larvae had been seen in Mānoa and Kāne‘ohe Streams on O‘ahu in the past 6 to 8 years and that adults were collected from Makiki Stream in 1982. Beardsley (1993) noted that the larvae were known since about 1975. Adult and larval *H. stellaris* were recorded from streams on Kaua‘i including Hanakapi‘ai, Anahola, and Makaleha (Asquith and Messing, 1992). *Hemerodromia* larvae were infrequently found in the stomach contents of *Awaous guamensis* (‘o‘opu nākea) and *Sicyopterus stimpsoni* (‘o‘opu nōpili) from the Wainiha River on Kaua‘i. (Kido and others, 1993; Kido, 1996).

H. stellaris were not found in any sample collected on Maui during this study. There are no records of this species ever being collected or observed on Maui, Moloka‘i, or the Island of Hawai‘i. Unlike the nonnative insect species discussed earlier, the dispersal of *H. stellaris* has somehow been constrained. The distribution and abundance of immature *H. stellaris* on O‘ahu are shown in figure C8. *H. stellaris* was identified in 25 of the 31 quantitative samples. Larval densities ranged from 0.8/m^2 at Lulumahu (0.4 percent) and Pauoa (0.2 percent) Streams to 503.5/m^2 (10.8 percent) at Kamo‘oali‘i Stream. The highest percentage of *H. stellaris*, 33.8 percent, was recorded from North Hālawa-A, where it was the dominant taxa. *H. stellaris* was observed at 32 of the 40 WSA sampling sites.

Decapods

Three species of nonnative decapod crustaceans were collected or observed during this study. This includes one atyid shrimp, one palaemonid prawn, and one cambarid crayfish.

Macrobrachium lar (Fabricius, 1798); (Arthropoda; Crustacea; Decapoda; Palaemonidae); *M. lar,* known commonly as the Tahitian prawn, is a nonnative, freshwater, amphidromous prawn that is widely distributed across the Indo-Pacific, from East Africa to the Marquesas (fig. D29; Kubota, 1972). These large freshwater prawns are highly valued as a delectable food source. *M. lar* was purposely introduced into Hawai‘i in 1956 by the Hawai‘i Division of Fish and Game as a potential prey for introduced game fish and for recreational fishing (Brock, 1960; Yoshida, 1961; Kubota, 1972). The original stock came from Guam and was released into Pelekunu Stream on Moloka‘i in 1956 and in Nu‘uanu Stream on O‘ahu in 1957. A later introduction in 1961 originated from Tahiti and the Marquesas and was released into Punalu‘u Stream on O‘ahu. In 1965, *M. lar* were reported from the Island of Hawai‘i, and by the end of 1968 had been reported in streams on O‘ahu, Kaua‘i, Maui, and Moloka‘i (Shima, 1968; Shima, 1969). The marine larval stage of this amphidromous species had enabled it to spread to every island and potentially to every stream that reaches the ocean. It is well adapted to the Hawaiian stream environment, and in the absence of predatory fish, has had notable success and is common throughout the State. It is believed that *M. lar* can negatively impact populations of the native stream shrimp, *Atyoida bisulcata* and native prawn *Macrobrachium grandimanus* (fig. D30) and possibly the native gobies (Kubota, 1972).

M. lar were not well represented in the quantitative samples because it is more commonly found in slower, deeper water than in riffles. Its large size makes it conspicuous and easy to observe. The distribution of *M. lar* observations on Maui is shown in figures B3–B4. *M. lar* were observed at 19 of the 40 Maui study sites, 7 of 16 East Maui sites and 12 of

24 West Maui sites. *M. lar* were not observed at East Maui sites located upstream of the Koʻolau Ditch diversions. The distribution of *M. lar* on Oʻahu is shown in figure C2. It was observed at 20 of the 40 WSA study sites. It was noticeably absent from sites in central Oʻahu, where largemouth and (or) smallmouth bass are present.

Procambarus clarkii (Girard, 1852); (Arthropoda; Crustacea; Decapoda; Cambaridae); commonly known as the Louisiana swamp crayfish, or crawdad, *P. clarkii* was purposely introduced as a food and feed source in 1923 and 1927 on Oʻahu (a taro field in ʻĀhuimanu) and Kauaʻi, with subsequent introductions to other locations on Kauaʻi and Hawaiʻi Islands stemming from the ʻĀhuimanu stock (fig. D31; Hawaii Board of Commissioners, 1939; Brock, 1952; Brock, 1960). Penn (1954) noted that a shipment of *P. clarkii* was imported in 1934 as feed for a frog farm on Oʻahu and that some moved to nearby taro fields during flooding. By 1940, farmers discovered that the feeding and burrowing behavior of *P. clarkii* made it a pest in the taro fields and a control program was initiated including the use of para-dichloro benzene, which killed all animal life (Fullaway, 1941; Devaney and others, 1982).

P. clarkii is established on all the main Hawaiian Islands (Brock, 1960; Yamamoto and Tagawa, 2000). *P. clarkii* were commonly found in the stomach contents of smallmouth bass in Nuʻuanu Stream in 2001 (USGS, unpublished data). *P. clarkii* is also considered a pest species because its burrowing behavior can destabilize stream and ditch banks, leading to increased erosion and sedimentation. Furthermore, *P. clarkii* has also been associated with predation on the naiads of the native *Megalagrion* damselflies (Johnson, 2001).

P. clarkii were not collected in the quantitative or qualitative samples on Maui. *P. clarkii* were observed during a snorkel survey at only one Maui site, Waikapū-C, in West Maui. *P. clarkii* were collected in three of the quantitative samples and in five of the qualitative samples collected on Oʻahu. Additionally, *P. clarkii* was visually observed at three Oʻahu sites where they were not collected in the benthic samples. Overall, *P. clarkii* were present at nine of the Oʻahu WSA sites. The distribution of the observations is shown in figure C2. *P. clarkii* were present at 5 of the 8 leeward sites and at 4 of the 14 windward sites and were not observed at any of the central Oʻahu WSA sites.

Neocaridina denticulata sinensis (Kemp, 1918); (Arthropoda; Crustacea; Decapoda; Atyidae); commonly known as the red cherry shrimp, or the Taiwan blue shrimp, *N. d. sinensis* is one of seven subspecies of *N. denticulata* (de Haan, 1844) and is native to parts of Asia (fig. D32; Hung and others, 1993). It is commonly cultured as food for aquarium fish. Unlike the native atyid shrimp, *N. d. sinensis* is not amphidromous and therefore cannot spread to other streams by means of marine recruitment. It was most likely accidently introduced by a release or escape from a home aquarium or commercial breeder (Englund and Cai, 1999). The first record of *N. d. sinensis* in Hawaiʻi was from Waiolani Stream on Oʻahu in 1991, where it was identified as *Caridina weberi* (Devick, 1991; Yamamoto, 1992; Yamamoto, 1993). By 1996 *N. d. sinensis* was recorded from Nuʻuanu, Mānoa, Kamoʻoaliʻi, and Maunawili Streams (Yamamoto, 1993; Yamamoto, 1996). It has continued to be spread around streams on Oʻahu and has been recorded in Lāwai Stream on Kauaʻi in 2005 (Kido, 2007). *N. d. sinensis* were commonly found in the stomach contents of smallmouth bass in Nuʻuanu Stream in 2001 (USGS, unpublished data). *N. d. sinensis* is believed to be a possible threat to the native stream shrimp *Atyoida bisulcata* and the native prawn *Macrobrachium grandimanus* (Kido, 2007; Englund and Cai, 1999).

N. d. sinensis were not observed or collected on Maui. *N. d. sinensis* were identified in 6 of the 31 quantitative Oʻahu WSA samples, with densities ranging from 5.6/m^2 (1.4 percent) at the Pauoa site to 75.2/m^2 (15.9 percent) at the Kahana Iki site. The highest percentage of a sample, 26.1 percent, was collected at the Lulumahu site. The distribution of *N. d. sinensis* observations on Oʻahu is shown in figure C2. *N. d. sinensis* were observed at 10 of the 40 Oʻahu WSA study sites.

Cryptogenic Macroinvertebrates

A cryptogenic species is defined as one whose taxonomic documentation lacks indisputable proof that it is either native or introduced (Carlton, 1982; Carlton, 1996; Cowie, 2001). This is not to be confused with cryptic species, which are defined, in this report, as species that commonly hide from view as part of their avoidance behavior. For most cryptogenic species there is simply a lack of historical data to confirm the species' place of origin. In Hawaiʻi, introduced species are considered as those that arrived with or after the arrival of the first Hawaiians. For many species in Hawaiʻi, especially small, easily overlooked organisms, the taxonomic descriptions occurred after extensive overseas travel and trade were well established with Europe, Asia, and the Americas.

Mollusks

Cowie (1998) lists 22 species of introduced freshwater mollusk species in Hawaiʻi, 11 of which he called cryptogenic, including 7 species of Thiaridae, 2 species of Hydrobiidae, 1 species of Physidae, and 1 species of Ancylidae. Burky and others (2000) identified two additional small (shell length <8 mm), cryptogenic mollusk species of Sphaeriidae clams found in Hawaiian taro fields on Maui. The taxonomic status of many of these species has been revised from native to nonnative or cryptogenic as the systematic work has progressed (Lea, 1856; Pease, 1870; Ancey, 1899; Sykes, 1900; Cowie, 1997; Walther, 2008).

Ferrissia sharpi (Sykes, 1900); (Mollusca; Gastropoda, Basommatophora; Ancylidae); first described by Sykes (1900) as "An insignificant little form with no striking characters," *Ferrissia* is a near-cosmopolitan limpet-like genus found in freshwater systems around the world (Walther, 2008). *F. sharpi* are small (shell length <5 mm), delicate, and often overlooked during stream surveys (fig. D33; Cowie, 1997;

Walther, 2008). A recent genetic and morphological analysis found that the Hawaiian endemic *F. sharpi* was not different from the near-cosmopolitan *F. fragilis* (Tryon, 1863), concluding that Sykes' original description of a new species was in fact the nonnative invader *F. fragilis* (Walther, 2008). *Ferrissia* has been collected during stream surveys from Oʻahu (Brasher and others, 2004), Maui (Kinzie and Ford, 1977), Kauaʻi (Ford, 1982), and the Island of Hawaiʻi (Yee and Ewart, 1986). *Ferrissia* has been reported in the stomach contents of *Lentipes concolor* (ʻoʻopu ʻalamoʻo) from Honoliʻi Stream (Way and Burky, 1991).

The distribution and abundance of *Ferrissia* on Maui are shown in figures B21–B22. *Ferrissia* were observed at 34 of the 40 Maui sites and identified in 40 of the 54 quantitative samples. Densities, from samples in which they were identified, ranged from 1.5/m^2 (0.2 percent), at the Waiheʻe-B open canopy site, to 131.7m^2 (0.6 percent) at Kōlea Stream. The highest percentage of *Ferrissia*, 4.3 percent, was recorded from the Honolua Stream sampling site.

The distribution and abundance of *Ferrissia* on Oʻahu are shown in figure C9. *Ferrissia* were not identified in 12 of the 31 quantitative samples from the Oʻahu WSA study. Densities ranged from 1.4/m^2 (0.2 percent) at the Waimānalo site to 317.5/m^2 (5.6 percent) at the Anahulu-B site. The highest percentage, 11.9 percent, was collected at the Hakipuʻu site. *Ferrissia* was the second-dominant taxa at four sites. *Ferrissia* were observed at 28 of the 40 WSA sites

Native Fish

The native stream-fish community in Hawaiʻi is composed of five amphidromous species commonly referred to as ʻoʻopu (table 5). This includes one Eleotridae and four Gobiidae, although all are commonly referred to as gobies. The amphidromous life history, requiring a period of development in the ocean, of these fish sets them apart from the true freshwater fish (Brock, 1960). The Gobiidae have fused pelvic fins that form a suction disk that enables these fishes to attach themselves to stream substrate and climb cascades and waterfalls (Ford and Kinzie, 1982; Schoenfuss and Blob, 2003; Blob and others, 2006). There are also a number of estuarine-related fish that can inhabit the lower reaches of the freshwater systems. Although fish were not collected as part of this study, brief snorkel surveys were conducted at each site to identify the conspicuous macrofauna. The observation of a fish species confirms its presence at a site; however, the lack of an observation does not necessarily confirm the absence of the species from a site. Snorkel surveys may fail to spot some of the more cryptic species which have a propensity to hide (Yamamoto and Tagawa, 2000). The distribution of native fish observed during the study on Maui is shown in figures B23–B24 (table 6). No native fish were observed at sites upstream of the Koʻolau Ditch diversions in East Maui. The distribution of native fish observed on Oʻahu during the WSA is shown in figure C10 (table 7).

Eleotris sandwicensis Vaillant & Sauvage, 1875; (Osteichthyes; Perciformes; Eleotridae); locally known as ʻoʻopu ʻakupa and commonly called the Sandwich Island sleeper, *E. sandwicensis* is an endemic, amphidromous stream fish that is not a true goby and lacks the fused pelvic fin and, therefore, is restricted to the lowest stream reaches, stream mouths, and estuaries. *E. sandwicensis* is a predatory fish that feeds on other fish species, native and nonnative, as well as snails and the clam *Corbicula fluminea* (fig. D34) (Yamamoto and Tagawa, 2000). *E. sandwicensis* were observed in the lower reaches of 5 streams in East Maui, including West Wailua Iki, Wailua Nui, Waiohue, Kopiliʻula, and Hanawī Streams. *E. sandwicensis* were not observed in West Maui during this study; however, a single individual was previously observed in the Waiheʻe River, at 210 ft altitude (Oki and others, 2010). *E. sandwicensis* were observed at only one site, Waiāhole-B, during the Oʻahu WSA study.

Awaous guamensis Valenciennes, 1837; (Osteichthyes; Perciformes; Gobiidae); locally known as ʻoʻopu nākea and commonly called the Pacific river goby, *A. guamensis* is the largest of the native fish species, is a moderate climber, and is commonly found in lower and middle stream reaches. Thought to be indigenous to Hawaiʻi and Guam, current research examining mitochondrial DNA and morphology has determined the Hawaiian population to be a distinct species, endemic to Hawaiʻi, recommending a reversion to the earlier nomenclature of *A. stamineus* (Eydoux and Souleyet, 1850) (Lindstrom and others, in press). Stomach content analysis shows that *A. guamensis* feeds primarily on algae but also consumes aquatic insects and has shown an opportunistic shift from native species to nonnatives (Kido and others, 1993). *A. guamensis* were observed at 20 of the 40 Maui study sites, including 7 of the 16 East Maui sites and 13 of the 24 West Maui sites. *A. guamensis* were observed at 16 of the 40 Oʻahu WSA study sites, including 8 of the 18 central sites, 2 of the 8 leeward sites and 6 of the 14 windward sites. Adult *A. guamensis* were observed at the Kīpapa-A site coexisting with smallmouth bass.

Sicyopterus stimpsoni (Gill, 1860); (Osteichthyes; Perciformes; Gobiidae); known locally as ʻoʻopu nōpili and commonly called the rock-climbing goby, *S. stimpsoni* is an endemic amphidromous fish that often inhabits middle stream reaches. *S. stimpsoni* were observed at 18 of the 40 Maui study sites including 8 in East Maui and 10 in West Maui. Adult *S. stimpsoni* were found in abundance at 8 lower sites. *S. stimpsoni* was only observed at three lower elevation windward Oʻahu sites.

Lentipes concolor (Gill, 1860); (Osteichthyes; Perciformes; Gobiidae); known locally as ʻoʻopu ʻalamoʻo or ʻoʻopu hiʻukole and commonly called the Hiukole goby, *L. concolor* is an endemic, amphidromous goby that is the best climber and typically found in middle and upper stream reaches. Even though *L. concolor* is the best climber of the fishes, none were observed at sites upstream of the Koʻolau Ditch diversions in East Maui. *L. concolor* were observed at 11 of the 40 Maui study sites including 3 of the East Maui

Table 5. List of native and nonnative fish observed on Maui and (or) Oʻahu.

[Code, species code used in tables 6 and 7]

Family	Scientific name	Common name	Code	Status
Centrarchidae	*Micropterus dolomieui*	Smallmouth bass	DOL	Nonnative
	Micropterus salmoides	Largemouth bass	SAL	Nonnative
Cichlidae	*Cichlasoma nigrofasciatum*	Convict cichlid	CIC	Nonnative
	Hemichromis fasciatus	Banded jewel cichlid	HEM	Nonnative
	Oreochromis mossambicus	Mozambique tilapia	ORE	Nonnative
Clariidae	*Clarias fuscus*	Chinese catfish	CLA	Nonnative
Cobitidae	*Misgurnus anguillicaudatus*	Dojo loach	MIS	Nonnative
Cyprinidae	*Cyprinus carpio*	Koi carp	CYP	Nonnative
Ictaluridae	*Ictalurus punctatus*	Channel catfish	ICT	Nonnative
Loricariidae	*Ancistrus* sp.	Bristlenose catfish	ANC	Nonnative
Poeciliidae	*Gambusia affinis*	Western mosquitofish	GAM	Nonnative
	Poecilia reticulata	Guppy	RET	Nonnative
	Poecilia sphenops	Molly hybrids	SPH	Nonnative
	Xiphophorus helleri	Green swordtail	XIP	Nonnative
Eleotridae	*Eleotris sandwicensis*	ʻOʻopu ʻakupa	ELE	Native
Gobiidae	*Awaous guamensis*	ʻOʻopu nākea	AWA	Native
	Lentipes concolor	ʻOʻopu alamoʻo	LEN	Native
	Sicyopterus stimpsoni	ʻOʻopu nōpili	SIC	Native
	Stenogobius hawaiiensis	ʻOʻopu naniha	STE	Native
Kuhliidae	*Kuhlia xenura*	Āholehole	KUH	Native
Mugilidae	*Mugil cephalus*	Striped mullet	MUG	Native

Table 6. Fish species observed at Maui sampling sites.

[RET, *Poecilia reticulata*; XIP, *Xiphophorus helleri*; AWA, *Awaous guamensis*; ELE, *Eleotris sandwicensis*; KUH, *Kuhlia xenura* ; LEN, *Lentipes concolor*; SIC, *Sicyopterus stimpsoni;* fish richness, total number of fish]

Site name	Nonnative		Native					Fish richness		
	RET	XIP	AWA	ELE	KUH	LEN	SIC	Nonnative	Native	Total
E. Wailua Nui-A	–	–	–	–	–	–	–	0	0	0
Haipuaʻena-A	–	–	–	–	–	–	–	0	0	0
Hanawī-B	–	–	X	X	–	X	X	0	4	4
Hanawī-C	–	–	–	–	–	X	–	0	1	1
Hanawī-A	–		–	–	–	–	–	0	0	0
Honokōwai	–	–	–	–	–	–	–	0	0	0
Honolua	–	–	–	–	–	–	–	0	0	0
Honomanū	–	–	–	–	–	–	–	0	0	0
ʻĪao-A	–	–	–	–	–	X	–	0	1	1
ʻĪao-C	X	–	–	–	–	–	–	1	0	1
Kanahā	–	–	X	–	–	–	X	0	2	2
Kauaʻula	–	–	–	–	–	–	–	0	0	0
Kōlea	–	–	–	–	–	–	–	0	0	0
Kopiliʻula-B	–	–	X	X	X	–	X	0	4	4
Kopiliʻula-A	–	–	–	–	–	–	–	0	0	0
Launiupoko	–	–	–	–	–	–	–	0	0	0
Makamakaʻole-B	–	–	X	–	–	–	X	0	2	2
Makamakaʻole-A	–	–	–	–	–	X	–	0	1	1
N. Waiehu-A	–	–	X	–	–	X	X	0	3	3
N. Waiehu-C	–	–	X	–	–	X	X	0	3	3
Nuaʻailua	–	–	–	–	–	–	X	0	1	1
Olowalu-B	–	–	X	–	–	X	–	0	2	2
Olowalu-A	–	–	–	–	–	–	–	0	0	0
Pālauhulu-C	–	–	X	–	–	–	X	0	2	2
Pālauhulu-A	–	–	X	–	–	X	X	0	3	3
S. Waiehu-C	X	–	X	–	–	X	X	1	3	4
S. Waiehu-A	–	–	X	–	–	X	X	0	3	3
Ukumehame-B	X	–	X	–	–	–	–	1	1	2
Ukumehame-A	–	–	–	–	–	–	–	0	0	0
Waiehu-C	–	–	X	–	–	–	X	0	2	2
Waiheʻe-B closed	X	X	X	–	X	–	X	2	3	5
Waiheʻe-B open	X	X	X	–	X	–	X	2	3	5
Waiheʻe-A	–	–	X	–	–	X	–	0	2	2
Waiheʻe-C	X	X	X	–	–	–	X	2	2	4
Waikapū-C	–		–	–	–	–	–	0	0	0
Waikapū-A	–	–	–	–	–	–	–	0	0	0
Wailua Nui-B	–	–	X	X	–	–	X	0	3	3
Waiohue	–	–	X	X	X	–	X	0	4	4
W. Wailua Iki-B	–	–	X	X	X	–	X	0	4	4
W. Wailua Iki-A	–	–	–	–	–	–	–	0	0	0

Table 7. Fish species observed at Oʻahu Wadeable Stream Assessment (WSA) sampling sites.

[ANC, *Ancistrus* sp.; CIC, *Cichlasoma nigrofasciatum*; CLA, *Clarias fuscus*; CYP, *Cyprinus carpio*; GAM, *Gambusia affinis*; HEM, *Hemichromis fasciatus*; ICT, *Ictalurus punctatus*; DOL, *Micropterus dolomieui*; SAL, *Micropterus salmoides*; MIS, *Misgurnus anguillicaudatus*; ORE, *Oreochromis mossambicus*; RET, *Poecilia reticulata*; SPH, *Poecilia sphenops*; XIP, *Xiphophorus helleri*; AWA, *Awaous guamensis*; ELE, *Eleotris sandwicensis*; KUH, *Kuhlia xenura*; MUG, *Mugil cephalus*; SIC, *Sicyopterus stimpsoni*; STE, *Stenogobius hawaiiensis*; fish richness, total number of fish]

Site name	Nonnative														Native						Fish richness		
	ANC	CIC	CLA	CYP	GAM	HEM	ICT	DOL	SAL	MIS	ORE	RET	SPH	XIP	AWA	ELE	KUH	MUG	SIC	STE	Non-native	Native	Total
ʻĀhuimanu	X	–	–	–	–	–	–	–	–	–	–	X	X	–	X	–	–	–	–	–	3	1	4
Anahulu-B	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	–	–	1	0	1
Anahulu-C	–	–	–	–	X	–	–	–	–	–	–	X	X	–	X	–	–	–	–	–	3	1	4
Haʻikū	–	–	–	–	–	–	–	–	–	–	–	–	X	X	–	–	–	–	–	–	2	0	2
Hakipuʻu	–	–	–	–	–	–	–	–	–	–	–	X	–	X	–	–	–	–	–	X	2	1	3
Kahana-B	–	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	X	–	1	1	2
Kahana-C	–	–	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	0	1	1
Kahana-A	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0
Kahana Iki	–	–	–	–	–	X	–	–	–	–	–	–	–	X	–	–	–	–	–	–	2	0	2
Kalihi-C	X	–	–	–	X	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	2	1	3
Kalihi-A	X	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	0	2
Kamananui-C	–	–	–	–	–	–	–	–	–	–	–	–	–	X	X	–	–	–	–	–	1	1	2
Kamananui-A	–	–	–	–	–	–	–	–	–	–	–	–	–	X	X	–	–	–	–	–	1	1	2
Kamoʻoaliʻi	–	X	–	–	X	X	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	0	3
Kīpapa-C	X	–	X	–	–	–	–	X	–	X	–	X	–	–	X	–	–	–	–	–	5	1	6
Kīpapa-A	X	–	–	–	–	–	–	X	–	X	–	–	–	–	X	–	–	–	–	–	3	1	4
Lulumahu	–	–	–	–	–	–	X	–	–	–	–	–	–	X	–	–	–	–	–	–	2	0	2
Mānoa	X	–	–	–	–	–	–	–	–	–	–	–	–	X	X	–	–	–	–	–	2	1	3
NF Kaukonahua-B	–	–	–	–	–	X	–	X	–	–	–	–	–	–	–	–	–	–	–	–	2	0	2
NF Kaukonahua-A	–	–	–	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	1	0	1
N. Hālawa-A	–	–	–	–	X	–	–	–	–	–	–	–	X	–	X	–	–	–	–	–	2	1	3
Nuʻuanu-C	X	–	–	X	–	–	–	X	–	–	X	–	–	–	–	–	–	–	–	–	4	0	4
Pauoa	X	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	–	–	–	2	0	2
SF Kaukonahua-B	–	–	–	–	–	X	X	X	X	–	–	–	–	–	–	–	–	–	–	–	4	0	4
SF Kaukonahua-C	–	–	–	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	1	0	1
SF Kaukonahua-A	–	–	–	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	1	0	1
Waiāhole-B	–	–	–	–	–	–	–	–	–	–	–	–	X	X	X	X	X	X	X	X	2	6	8
Waiāhole-C	–	–	–	–	–	–	–	–	–	–	–	–	–	X	X	–	X	X	X	–	1	4	5
Waikāne-B	–	–	–	–	–	–	–	–	–	–	–	–	X	X	X	–	X	–	–	X	2	3	5
Waikāne-C	–	–	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	0	1	1
Waimānalo	–	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	–	1	0	1

sites and 8 of the West Maui sites. *L. concolor* were not observed at any of the Oʻahu WSA study sites.

Stenogobius hawaiiensis Watson, 1991; (Osteichthyes; Perciformes; Gobiidae); locally known as ʻoʻopu naniha and commonly called the tear-drop goby, *S. hawaiiensis* is an endemic, amphidromous goby typically found in lower stream reaches. *S. hawaiiensis* was not observed at any of the sites on Maui and was observed at only three lower elevation sites during the Oʻahu WSA study.

Kuhlia xenura (Jordan and Gilbert, 1882); (Osteichthyes; Perciformes; Kuhliidae); known locally as āholehole and commonly called flagtails or mountain bass, *K. xenura* is an endemic nearshore marine fish with juveniles inhabiting lower stream reaches and estuaries. Stomach contents analysis of juvenile fish from freshwater determined that *K. xenura* is omnivorous, with algae and plant matter composing over half the contents and insects (terrestrial) and crustaceans composing the bulk of the remaining contents (Tester and Trefz, 1954). *K. xenura* were observed at five lower elevation sites on Maui and at three lower elevation sites on Oʻahu.

Nonnative Fish

Approximately 40 species of nonnative fish have become established in streams and reservoirs in Hawaiʻi (Brock, 1960; Kanayama, 1967; Maciolek, 1984; Devick, 1991; Yamamoto and Tagawa, 2000; Brasher and others, 2006). These fish were introduced at various times, some purposefully, for food, pest control, or as recreational game fish, and some accidently, from home aquaria or ponds, or as escapees from aquaculture facilities. Brasher and others (2006) found that sites on Oʻahu, Kauaʻi, and the Island of Hawaiʻi with higher percentages of developed land in the watershed had higher percentages of nonnative fish species as well as higher abundances of nonnative fish. Historically, a number of fish that were introduced into streams or reservoirs on Maui failed to become established. These game fish included rainbow trout (Waiheʻe, ʻĪao, Honokāhau [1922]; Keʻanae [1925]; Kauaʻula [1926]; Ukumehame, Kahakuloa, Makamakaʻole [1928]; Waikapū [1929]; and ʻĪao [1930]); largemouth bass (Lahaina Reservoir [1949]; Honopou Pond, Huelo Pond, Hawaiian Commercial and Sugar Company (HC&S) reservoirs, Wailuku Sugar reservoirs, Hōpoe reservoir, and Waikamoi reservoir [1950]); and bluegill sunfish (Wailuku Sugar reservoir, Launiupoko reservoir and Honokāhau Stream [1952]) (Brock, 1952).

The distribution of nonnative fish observed on Maui is shown in figures B25–B26 (table 6). No nonnative fish were observed at the East Maui study sites. Two species of nonnative Poeciliidae fish were observed in West Maui. The distribution of nonnative fish observed during the Oʻahu WSA study is shown in figure C11. Fourteen species of nonnative fish from 8 different families were observed on Oʻahu (table 7).

Poeciliidae

At least 10 species of Poeciliidae, commonly known as topminnows, have been introduced into Hawaiian streams, ditches, ponds, and reservoirs, and many of these species have become established (Maciolek, 1984). The first introductions occurred in 1905, when the western mosquitofish, *Gambusia affinis* Baird & Girard, 1853, the killifish, *Fundulus grandis* Baird and Girard, 1853, and the sailfin molly, *Poecilia latipinna* LeSueur, 1821 [*Mollienesia latipinna*], were brought to Hawaiʻi from Seabrook, Texas, for the purpose of controlling mosquito populations (Seale, 1905; Van Dine, 1907). These fish were bred in ponds in Moanalua, Oʻahu and released into streams, taro fields, rice fields, ponds, ditches, and reservoirs around the State (Hawaiian Gazette, 9/19/1905; Van Dine, 1907). *G. affinis* and *P. latipinna* became established statewide in Hawaiʻi while *F. grandis* failed to become established (Brock, 1960). In the 1920s, three more species, including guppies, *Poecilia reticulata* Peters, 1859, green swordtails, *Xiphophorus helleri* Heckel, 1848, and the southern platyfish, *Xiphophorus maculatus* (Günther, 1866) [*Platypoecilus maculatus*] were introduced as ornamental aquarium fish (Mainland, 1939; Brock, 1952). By the 1960s, three more species had been introduced and became established, including the liberty molly, *Poecilia sphenops* Valenciennes, 1846 [*Mollienesia sphenops*] the Cuban molly, *Limia vittata* (Guichenot, 1853), and the shortfin molly, *Poecilia mexicana* Steindachner, 1863 (Brock, 1952; Devick, 1991).

The widespread distribution of Poeciliidae in Hawaiʻi was a response to the widespread dispersal of mosquitoes around the State. Mosquitoes are not native to the Hawaiian Islands. The earliest accounts place the first mosquito introduction about 1826–27, when the night-biting mosquito, *Culex quinquefasciatus*, a vector for avian malaria, was brought ashore in Lahaina, Maui, in water barrels from the trading ship Wellington (Osten-Sacken, 1884; Brigham, 1911; Bryan, 1915; Joyce, 1961). The two species of day mosquitoes, *Aedes aegypti*, a vector of yellow fever, and the Asian tiger mosquito, *Aedes albopictus,* a vector of dengue fever, arrived soon after. All three of these mosquito species bred and spread rapidly around the islands and were considered a pest and a nuisance (Jarves, 1843; Perkins, 1913; Fullaway, 1913; Bryan, 1915). In response to fears of yellow fever and dengue fever epidemics, the territorial government initiated an intensive eradication program that continued for decades. The control of mosquitoes using larvivorous (larvae eating) fish was first published as early as 1891 (S.A.M., 1891; Russel, 1891; Howard, 1900). Hawaiʻi residents were encouraged to put goldfish into ponds and troughs to help control the breeding of mosquitoes (Van Dine, 1903; Van Dine, 1904). The Territory of Hawaiʻi was the first locale where larvivorous fish were imported from the continental United States for use as a mosquito control agent to prevent outbreaks of dengue fever, yellow fever, and malaria (Krumholz, 1948). Alternatively, chemicals such as kerosene and coal oil, and later, arsenic compounds, pyrethrum, DDT, and malathion were used; these chemicals, however, tended to indiscriminately kill everything in the water (Howard, 1901; Illingworth, 1930; U.S. Army, 1945; Nakagawa and Hirst, 1959). The successful use of larvivorous topminnows for mosquito control required the release of these fishes into every accessible mosquito breeding area. Starting in 1905, topminnows were released into standing and flowing waters around the Territory (Hawaiian Gazette, 9/19/1905; Van Dine, 1907). In 1958, a combination of *Tilapia mossambica* and topminnows were released into a standing pond in Diamond Head crater to combat a mosquito outbreak (Nakagawa and Hirst, 1959). The tilapia consumed the algal growth at the surface, thereby enabling the topminnows to more efficiently devour the mosquito larvae. This technique worked so effectively that the Hawai‘i State Department of Health used helicopters to deliver this combination of tilapia and poeciliids to previously inaccessible areas around the state (Nakagawa, 1964, Iizuka, 1979). Iizuka (1979) determined that the most effective larvivorous fish in Hawai‘i were the western mosquitofish, *Gambusia affinis*, guppies, *Poecilia reticulata*, the Cuban limia, *Limia vittata,* and young *Tilapia mossambica* because of a higher survival rate during the collection, transportation, and helicopter aerial dispersal. Other species tested included green swordtails, *Xiphophorus helleri*, moon fish, *X. maculatus*, mollies, *Poecilia sphenops* and *Poecilia latipinna*, and mature *Tilapia*, but these fish had a much higher mortality rate during the translocations.

There are a limited number of studies that have determined the impact of the introduced poeciliids on the native Hawaiian stream biota. Bryan (1915) noted that the topminnows did not appear to discriminate between the targeted mosquito larvae and the eggs and juveniles of other species. Edmondson (1929) observed that young *Atyoida bisulcata*, the native ‘ōpae or mountain shrimp, 6–12 mm in length, were devoured by topminnows in an aquarium. Williams (1936) noted that topminnows adversely affected the native stream invertebrates but could also become prey to large *Anax* dragonfly naiads as well. He explained the coexistence of native aquatic insects such as *Megalagrion xanthomelas* and topminnows as due to the protection afforded by dense algal growth; moreover, fishless reservoirs, he observed, contained a greater abundance of invertebrates than those with topminnows. Zimmerman (1948) noted a decline in the lowland populations of native damselflies since the introduction of topminnows. Englund (1999) also observed a correlation between the presence of poeciliids and the absence of the native *Megalagrion* damselflies, concluding that the damselfly naiads were preyed upon to the point of exclusion.

Poecilia reticulata Peters, 1859; (Osteichthyes; Cyprinodontiformes; Poeciliidae); commonly called guppies, rainbow fish, or millions fish, *P. reticulata* (previously named *Lebistes reticulatus*) were first introduced in 1920–22 on O‘ahu as an ornamental aquarium fish and for mosquito control (Mainland, 1939; Brock, 1952; Brock, 1960; Devick, 1991; Yamamoto and Tagawa, 2000). *P. reticulata* were observed at six sites on four streams in West Maui. *P. reticulata* were the only nonnative fish observed at three of the sites. *P. reticulata* were observed at seven sites on O‘ahu.

Xiphophorus helleri Heckel, 1848; (Osteichthyes; Cyprinodontiformes; Poeciliidae); commonly known as green swordtails, *X. helleri* were also first introduced in 1920–22 on O‘ahu as an ornamental aquarium fish and later on for mosquito control (Mainland, 1939; Brock, 1952; Brock, 1960; Devick, 1991; Yamamoto and Tagawa, 2000). *X. helleri* were observed at three sites on one stream in West Maui. These observations were all made at sites in the lower reaches of the Waihe‘e River. *P. reticulata* were also observed at these sites.

Poeciliids were observed at 29 sites in 24 streams on O‘ahu. This included *X. helleri* (17 sites), *G. affinis* (11 sites), *P. sphenops* (9 sites), and *P. reticulata* (7 sites). Two species of poeciliids were observed at 10 sites, and three species were observed at 2 sites. Poeciliids were rarely, one of eight sites, observed coexisting with smallmouth bass.

Development of Community Indexes

The development of an invertebrate community index (ICI) of stream quality followed a multistep process of multivariate analyses, metric screening, metric selection, and metric scoring (Karr and others, 1986; DeShon, 1995; Hughes and others, 1998; Klemm and others, 2003). Initially, the Maui data were analyzed using the existing metrics that constitute the P–HBIBI developed by Wolff (2005). The success or failure of an existing metric to differentiate among the sites along a disturbance gradient could indicate the inclusion or exclusion of the metric from a revised index. For a metric to be considered as successful at differentiating among the sites, the results must show a reasonable distribution of the metric scores throughout the study region. Secondly, multivariate statistical analyses were used to examine the structural similarities and differences among the macroinvertebrate assemblages by investigating factors such as islands (Maui relative to O‘ahu) and regions (East relative to West Maui). Nonmetric multidimensional scaling (nMDS), multiresponse permutation procedures (MRPP), and detrended correspondence analysis (DCA) were used to examine the relations among the assemblages and to identify taxa that may account for some of the observed differences. These relations were assessed using the abundance (organisms/m^2) dataset, which were $\log(x + 1)$ transformed prior to the analysis, and the relative abundance (proportional) dataset, which were arcsine–square root transformed prior to the analysis. Variables (species) identified in fewer than three samples were removed from the dataset prior to performing DCA. Principal components analysis (PCA) was used to examine the significance of environmental variables including habitat and water-quality measurements to facilitate the selection of reference or “least disturbed” sites. The software used for the multivariate analyses included: Plymouth Routines In Multivariate Ecological Research (PRIMER) version 6.1 (Clarke and Gorley, 2006); MultiVariate Statistical Package (MVSP) version 3.1 (http://www.kovcomp.co.uk/mvsp/index.html) and; PC-ORD version 6.0 (McCune and Grace, 2002; Peck, 2010).

Metric screening began with an evaluation of candidate metrics identified from the data, including measures of taxonomic richness, trophic guilds, relative abundances, and absolute abundances. These candidate metrics were screened using the range test of Klemm and others (2003), in which percentage metrics were required to have a range greater than 10 percent; and for any of the metrics, no more than 90 percent of the values could be 0. Candidate metrics were then screened using Spearman rank correlations to examine the response of each candidate along one or more disturbance gradients such as water-quality conditions, land use, and sedimentation. The candidate metrics were then screened for redundancy using Spearman rank correlations to identify metrics that were contributing the same information. For example, the ratio of Trichoptera to Diptera metric was highly correlated with the abundance and relative abundance metrics for *Cheumatopsyche* and *Cricotopus*, so only one metric from this group should be used. Another example of redundancy was the percentage of Insecta metric being highly negatively correlated with the percentage of Oligochaeta metric. Although the Insecta metric responded to a decrease in disturbance and the Oligochaeta metric responded to an increase in disturbance, they both provided the same information, so only one was included in the index. The metrics that were selected from groups of redundant metrics demonstrated either a stronger response to a single disturbance gradient or stronger responses to multiple disturbance gradients as compared to the other redundant metrics in the group.

Metrics that were selected to be in the final indexes were then scored. The scoring process began with the selection of 10 reference-condition sites. These sites were selected to characterize the “least disturbed” condition from the various regions and elevations on each island. Reference site selection for each index is discussed later in this report. For metrics whose value increased with decreasing disturbance (positive metrics), the upper cutoff values (top tier) were determined as the 75th percentile of the cumulative distribution of the reference sites and the lower cutoff (bottom tier) was determined as the 25th percentile of the cumulative distribution of the nonreference sites. A score of 1 was assigned to values greater than or equal to the top tier, a score of 3 was assigned to values greater than or equal to the bottom tier but less than the top tier, and a score of 5 was assigned to values less than the bottom tier. An additional score of 7 was used in the total macroinvertebrate abundance metric, retained from the earlier P–HBIBI, and included in the ICI’s because the total abundances in the quantitative samples from the most impaired sites were less than the minimum fixed-count conducted by the contract laboratory.

For metrics whose value increased with increasing disturbance (negative metrics), the bottom tier values were determined as the 25th percentile of the cumulative distribution of the reference sites and the top tier values were determined as the 75th percentile of the cumulative distribution of the nonreference sites. In these cases, a score of 1 was assigned to values less than or equal to the bottom tier, a score of 3 was assigned to values less than or equal to the top tier but greater than the bottom tier, and a score of 5 was assigned to values greater than the top tier. Additionally, presence/absence metrics were scored as 1 if the native species was present or the nonnative species was absent, and 3 if the native species was absent or the nonnative species was present. Some departures to this scoring process are discussed in the individual metric descriptions below.

The final index scores were determined using a dataset composed of the reference sites and nonreference sites. Only one sample per site was used in the calculations for sites where replicate or re-sorted samples were collected. Each site was evaluated using the set of core metrics and the metrics scores were summed. The cumulative distribution and percentiles of the metric score sums were then calculated. The higher quality sites (low scores) were determined as less than or equal to the 25th percentile of the cumulative distribution and the lower quality sites (high scores) were determined as greater than the 75th percentile of the cumulative distribution.

Maui Metrics and Index Development

Following the procedures outlined in the previous section, potential macroinvertebrate metrics for Maui were analyzed, screened, selected, and scored. This process and the results are described in this section.

Evaluation with the Preliminary–Hawaiian Benthic Index of Biotic Integrity

Each of the Maui samples was evaluated using the Preliminary–Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) developed by Wolff (2005). The concept behind a multimetric index is that each individual metric displays a trend as defined by the biotic conditions observed at reference sites. The greater the difference between conditions (or a specified charateristic) at a reference site and those (that characteristic) at the sampling site, the higher the metric score will be. The reference sites of the P-HBIBI were selected using a set of parameters including bed sediment and fish tissue contaminants, land use, and physical habitat characteristics (Wolff, 2005). None of the individual metrics are expected to define the biotic condition on their own, but when added together, the results should display a trend of similarity or difference from the reference condition. For each site, a value is calculated for each metric. These values are then compared to the P–HBIBI conditional values and then scored accordingly. The conditional values and scores are shown in table 8.

Table 8. Conditional scoring for the Preliminary–Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) metrics (modified from Wolff (2005).

[m^2, square meter; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

Metric	Condition	Score	
Total abundance, in organisms/m^2	> 3,000	1	
	≤ 3,000 and > 700	3	
	≤ 700 and > 200	5	
	≤ 200	7	
Nonnative mollusk abundance (includes cryptogenic), in organisms/m^2	0	1	
	> 0 and ≤ 90	3	
	> 90	5	
Amphipod abundance, in organisms/m^2	0	1	
	> 0 and ≤ 35	3	
	> 35	5	
Percent Insecta	> 90	1	
	≤ 90 and > 75	3	
	≤ 75	5	
Atyoida bisulcata (‘ōpaekala‘ole or mountain ‘ōpae)	Present	1	
	Absent	3	
Crayfish (*Procambarus clarkii*)	Absent	1	
	Present	3	
Total number of taxa (taxa richness)	< 21	1	
	≥ 21 and < 30	3	
	≥ 30	5	
	Index score	**Category**	
		Original[1]	**Revised**
Final P–HBIBI (sum of metric scores)	≤ 14	Mild	Good
	> 14 and ≤ 22	Moderate	Fair
	> 22	Severe	Poor

[1]From Wolff (2005).

In general, the scores for each metric are 1, 3, or 5, with lower scores indicating less impairment. The index score is the sum of the individual metrics scores, with lower scores indicating less impairment.

Maui P–HBIBI Scores

To determine the efficiency of the P–HBIBI and each individual metric at differentiating among the Maui benthic macroinvertebrate samples, all of the Maui samples, including the replicates, repeats, and recounts were evaluated using the P–HBIBI. The results of these analyses are shown in table 9. Some of the individual metrics performed better than others at differentiating among the study sites. The results of these evaluations are discussed in this section.

Total Macroinvertebrate Abundance Metric

The total abundance metric is based on the results of the quantitative samples. The macroinvertebrates in each sample were sorted and counted and a subsample factor was determined if subsampling was performed. A total abundance was calculated for each sample and then standardized to abundance per square meter (figs. B27–B28). Recognizing that an equal effort was made to sample similar streambed substrates, these areal values were not standardized for the rugosity of each individually sampled streambed. Variation in substrate complexity, streamflow, and the variable macroalgal and moss coverage on the substrate may affect the species diversity and abundances in the individual samples. The abundance per square meter values were then compared to the P–HBIBI conditional values and scored. The conditional values and scores are shown in table 8. In continental settings, the total abundance of invertebrates typically is predicted to decrease with an increase in human disturbance (Fore and others, 1996; Black and MacCoy, 1999). Similarly, in Hawai‘i, the P–HBIBI predicts that decreasing total invertebrate abundances indicates increasing human disturbance (Wolff, 2005). This metric makes no differentiation as to which taxa are present or their relative abundances.

The distribution of total abundance metric scores for the Maui sampling sites are shown in figures B29–B30. Of the 54 samples, 27 (50 percent) had a score of 1, with total abundances greater than 3,000/m^2, and 23 (42.6 percent) had a score of 3, with total abundances between 700 and 3,000/m^2. Three samples (5.6 percent) had a score of 5 (200–700/m^2), including West Wailua Iki-B, Honomanū, and North Waiehu-C below the diversion, and one sample (1.9 percent), Nua‘ailua, had a score of 7 (<200/m^2) with a total macroinvertebrate abundance of only 163.5/m^2. The additional score of 7 was included in the P–HBIBI because the total macroinvertebrate abundances in quantitative samples from the most impaired sites were less than the minimum fixed-count conducted by the contract laboratory.

Overall, the total abundance metric scores successfully differentiated among the Maui study sites; however, some of the differences were not necessarily due to stream-quality issues. For example, Honomanū scored poorly even though it is in a relatively pristine watershed. The substratum at Honomanū was predominantly bedrock (57.5 percent) and boulder (11.5 percent), with scattered patches of cobble. This type of habitat, which by chance was not included in the development of the P–HBIBI, is not hospitable to fauna that are not adapted to torrential flow (Nielsen, 1950). Species such as the endemic torrent midge, *Telmatogeton,* are well adapted to this environment and were common, composing 9.2 percent (the highest percentage for this species) of the quantitative sample. Honomanū still had an overall P–HBIBI score of 13, which placed it in the “good” quality category.

Taxonomic Richness Metric

The richness metric is based on the results of the quantitative and qualitative samples as well as being supplemented by observational data. This metric counts the number of distinct taxonomical groups. It predicts that species richness will increase with increasing disturbance (Wolff, 2005), a prediction that is counter to that of most, if not all, of the studies on continental streams (Kerans and Karr, 1994; Fore and others, 1996; Black and MacCoy, 1999; Weigel and others, 2002; Weigel, 2003). However, as discussed by Howarth and Polhemus (1991), the native Hawaiian stream insect fauna is depauperate compared to that of continental streams, with major orders such as Ephemeroptera, Plecoptera, and Trichoptera nonexistent in the native biota. Additionally, habitat loss and alteration, pollution, and the introduction of numerous nonnative species, both competitors and consumers, have impacted the native insect assemblages (Howarth and Polhemus, 1991). Also, the noninsect taxa, similar to the native stream fish, are not numerous. There are relatively few native freshwater mollusks, only two native decapods, and one native sponge. This metric is also sensitive to the editing process used to resolve the occurrences of ambiguous taxa and to standardize for laboratory taxonomic resolution. As more of the data is grouped into higher taxonomic categories, fewer numbers of distinct taxa are counted.

The distribution of richness metric scores for the Maui sampling sites is shown in figures B31–B32. The fifty samples with less than 21 taxonomical groups had a score of 1, and four samples with 22–30 taxonomical groups had a score of 3, including East Wailua Nui-A and Haipua‘ena in East Maui, and Makamaka‘ole-B and one of the two Waihe‘e-B open canopy samples in West Maui. The richness metric scores failed to successfully differentiate among the Maui study sites.

Relative Abundance of Insecta Metric

The relative abundance of Insecta metric is based on the quantitative samples. The P–HBIBI predicted the relative abundance of insects (the percentage of the total abundance that comprises insects) to decrease with an increase in the level of disturbance. Wolff (2005) found that insects accounted for greater than 90 percent of the total invertebrate abundances at each of the Oʻahu reference sites and accounted for fewer than 65 percent of the total invertebrate abundances at the impaired sites. Additionally, nonnative mollusks were either the first or second numerically dominant group at all of the severely impaired sites, and mollusks or oligochaetes (figs. D35–D36) were the second-dominant taxa at many of the moderately impaired sites.

The dominant and second-dominant taxa of the Maui quantitative samples are shown in table 10. A nonnative insect species was the dominant taxon at 36 of the 40 sampling sites (90 percent) and in 49 of the 54 samples (90.7 percent). These same species were the second-dominant taxon at 36 sites and in 49 of the samples. Insecta as a class were numerically dominant in 53 of the 54 samples, with only the Nuaʻailua sample having a higher percentage of worms (Class: Clitellata) (50.6 percent) than insects (29.9 percent), although insects were the second-dominant group in that sample.

The distribution of relative abundance of Insecta metric scores is shown in figures B33–B34. The relative abundance of Insecta metric assessed 28 samples (51.9 percent) a score of 1, with relative abundances greater than 90 percent, 15 samples (27.8 percent) a score of 3, >75 and ≤90 percent Insecta, and 11 samples (20.4 percent) a score of 5, with less than 75 percent Insecta. The 28 samples that scored 1 averaged 97 percent Insecta, and the 15 samples that scored 3 averaged 86 percent Insecta. The 11 samples that scored 5 averaged 60 percent Insecta, with a low value of only 29.9 percent at the Nuaʻailua site.

The relative abundance of Insecta metric scores successfully differentiated among the Maui study sites. In 11 samples, the abundance of worms was high enough to restrict the relative abundance of insects to below 90 percent, and in 6 samples worm abundance was high enough to restrict the percentage of insects to less than 75 percent. In four samples, Physidae snail abundances limited the relative abundance of insects to below 90 percent, and in two samples snail abundances limited the relative abundance of insects to below 75 percent. The abundances of the native shrimp limited the relative abundance of insects in three samples, especially the Makamakaʻole-B site, and the relative abundance of insects at two sites were limited by abundances of the native snail *Neritina granosa*.

Variability in the sampling and sorting was a factor at the Hanawī-A, North Waiehu-A above the diversion, and Olowalu sites. Both Hanawī-A samples scored a 3, with 89.7 percent and 86.4 percent insects, and the re-sorts of the same samples scored a 1, with 98.3 percent and 95.9 percent insects, respectively. The two samples collected at the North Waiehu-A above the diversion site scored a 1 with 97.9 percent and a 3 with 85.6 percent. The most dramatic difference was at the Olowalu-B site, where the two samples differed from 94.6 percent (1) to 74.4 percent (5) because of an abundance of physid snails in the latter sample. In other cases, the sampling and sorting variability was not a factor, as both Honolua samples scored 5, with 63.4 percent and 73.2 percent, and both the Kopiliʻula-B sample and the re-sort of that sample scored 5, with 66.9 percent and 66.8 percent, respectively. The three Waiheʻe-A repeat samples were also very similar, all scoring a 1 with 99.2 percent, 99.2 percent, and 99.1 percent insects.

Abundance of Nonnative or Cryptogenic Mollusks Metric

The mollusk metric is based on the quantitative samples, standardized to the number of mollusks per square meter. The mollusks used in this metric include the Thiaridae, Physidae, Planorbidae, Corbiculidae, Hydrobiidae, and the nonnative Lymnaeidae *Pseudosuccinea columella* (fig. D37). These mollusks were listed as either nonnative or cryptogenic by Cowie (1997, 1998, 2001). Abundances of these mollusks were predicted to increase with increasing disturbance (Wolff, 2005). This is not wholly because they are better equipped to survive in polluted water, but also because people have accidentally or purposefully introduced them to these streams. Unlike many aquatic insects, these animals are rarely transported from stream to stream without assistance. Because more people live in urban areas, one might expect a trend that more aquarium fauna, such as the nonnative mollusks, would be dumped into urban streams than in streams in other, less developed areas. Consequently, because urban streams tend to be more environmentally impaired, the correlation can be made between an increase in nonnative fauna with an increase in impairment. Other nonnative mollusks, such as apple snails, were not collected in the quantitative samples. Mollusks of the Sphaeriidae family and the Ancylidae *Ferrissia* were not included in this metric. These mollusks are very small and easily overlooked. The relation between stream habitat characteristics and *Ferrissia* was investigated separately.

The distribution of nonnative or cryptogenic mollusk metric scores is shown in figures B35–B36. None of the East Maui samples contained these mollusks. Thirty-nine Maui samples scored 1, where none of the listed mollusks were collected, nine West Maui sites scored 3, where less than 90/m^2 were collected, and six West Maui sites scored 5, where greater than 90/m^2 were collected. The highest density of these mollusks, 742.4/m^2, was collected at Waikapū-A, accounting for 14.8 percent of total the sample. These were all identified as a species of *Physa*, commonly known as pouch snails (fig. D38). These snails have a world-wide distribution, and it is not known when or how they arrived in Hawaiʻi (Cowie, 1997). *Physa* sp. was also abundant at Launiupoko (581.6/m^2), Olowalu-B (364.8/m^2 and 42.4/m^2), Olowalu-A (174.4/m^2), Kauaʻula (316/m^2), and Waikapū-C (294.4/m^2). The only other mollusk collected in the quantitative samples was the Thiaridae *Melanoides tuberculata*, a cryptogenic species common in Hawaiian streams (fig. D39) but collected only in the sample from Makamakaʻole-B (15.9/m^2). In 2008, USGS investigators observed mollusks, including the thiarid *Melanoides tuberculata*, the planorbid *Planorbella duryi* (fig. D40), and many physids, in a shallow slow moving pool in a channelized, urbanized, section of ʻĪao Stream (Oki and others, 2010).

Table 9. Preliminary–Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) scores for benthic macroinvertebrate samples from streams on the Island of Maui.

[rst, re-sorted sample; rep, replicate sample; rpt, repeat sample; Abundance in number per square meter; X, species present; –, species absent; P/A, Presence/Absence; No./m^2, number per square meter]

Station ID	Site name	Sample type	Total abundance metric		Taxonomic richness metric[1]		Relative abundance of Insecta metric	
			No./m^2	Score	No. of taxa	Score	Percentage of total	Score
HI MAUI 09-001	Kopiliʻula-A		1,231	3	16	1	87.7	3
HI MAUI 09-002	W. Wailua Iki-B		330	5	18	1	64.6	5
HI MAUI 09-003	Wailua Nui-B		1,418	3	19	1	97	1
HI MAUI 09-004	Hanawī-A		7,911	1	15	1	89.5	3
HI MAUI 09-004	Hanawī-A	rst	10,478	1	14	1	98.1	1
HI MAUI 09-004	Hanawī-A	rep	6,662	1	11	1	86.3	3
HI MAUI 09-004	Hanawī-A	rep, rst	7,525	1	10	1	95.7	1
HI MAUI 09-005	W. Wailua Iki-A		4,499	1	17	1	75.2	3
HI MAUI 09-006	Haipuaʻena		3,196	1	23	3	73.3	5
HI MAUI 09-007	Pālauhulu-C		6,241	1	19	1	91.1	1
HI MAUI 09-008	E. Wailua Nui-A		2,571	3	23	3	88.4	3
HI MAUI 09-009	Pālauhulu-A		9,365	1	14	1	88.5	3
HI MAUI 09-010	Honomanū		323	5	21	1	89.1	3
HI MAUI 09-011	Kōlea		23,137	1	14	1	94.3	1
HI MAUI 09-011	Kōlea	rst	9,869	1	12	1	96	1
HI MAUI 09-012	Hanawī-C		5,305	1	12	1	92.7	1
HI MAUI 09-013	Waiohue		1,675	3	17	1	84.5	3
HI MAUI 09-014	Kopiliʻula-B		3,758	1	17	1	66.7	5
HI MAUI 09-014	Kopiliʻula-B	rst	2,271	3	15	1	66.7	5
HI MAUI 09-015	Hanawī-B		6,812	1	16	1	96	1
HI MAUI 09-015	Hanawī-B	rep	4,234	1	13	1	98.5	1
HI MAUI 09-016	Nuaʻailua		166	7	16	1	29.5	5
HI MAUI 09-017	Waikapū-C		7,053	1	13	1	95.1	1
HI MAUI 09-018	Waikapū-A		5,012	1	18	1	83.5	3
HI MAUI 09-019	Kanahā		3,224	1	13	1	97.3	1
HI MAUI 09-020	Honolua		1,129	3	16	1	73.4	5
HI MAUI 09-020	Honolua	rep	984	3	11	1	63.3	5
HI MAUI 09-021	Honokōwai		4,146	1	17	1	97.6	1
HI MAUI 09-022	Olowalu-B		1,690	3	15	1	74.4	5
HI MAUI 09-022	Olowalu-B	rep	1,523	3	14	1	94.5	1

Table 9. —Continued

Nonnative mollusk abundance metric		Amphipoda abundance metric		‘Ōpae P/A metric[1]		Crayfish P/A metric[1]		P-HBIBI score	P-HBIBI category
No./m²	Score	No./m²	Score	P/A	Score	P/A	Score		
0	1	0	1	X	1	–	1	11	Good
0	1	0	1	X	1	–	1	15	Fair
0	1	0	1	X	1	–	1	9	Good
0	1	0	1	X	1	–	1	9	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	9	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	9	Good
0	1	0	1	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	9	Good
0	1	0	1	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	7	Good
0	1	2.7	3	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	11	Good
0	1	0	1	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	17	Fair
294.4	5	0	1	–	3	X	3	15	Fair
742.8	5	0	1	X	1	–	1	13	Good
76.8	3	0	1	–	3	–	1	11	Good
0	1	0	1	–	3	–	1	15	Fair
0	1	0	1	–	3	–	1	15	Fair
0	1	0	1	–	3	–	1	9	Good
364.8	5	0	1	X	1	–	1	17	Fair
42.7	3	0	1	X	1	–	1	11	Good

Table 9. Preliminary–Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) scores for benthic macroinvertebrate samples from streams on the Island of Maui.—Continued

[rst, re-sorted sample; rep, replicate sample; rpt, repeat sample; Abundance in number per square meter; X, species present ; –, species absent; P/A, Presence/Absence; No./m^2, number per square meter]

Station ID	Site name	Sample type	Total abundance metric		Taxonomic richness metric[1]		Relative abundance of Insecta metric	
			No./m^2	Score	No. of taxa	Score	Percentage of total	Score
HI MAUI 09-023	Waiheʻe-B open		740	3	25	3	96.9	1
HI MAUI 09-023	Waiheʻe-B open	rep	1,313	3	12	1	94.7	1
HI MAUI 09-024	Waiheʻe-B closed		1,207	3	20	1	81.3	3
HI MAUI 09-025	Waiheʻe-C		1,619	3	21	1	50	5
HI MAUI 09-026	Waiheʻe-A		9,453	1	13	1	99.2	1
HI MAUI 09-026	Waiheʻe-A	rpt-1	4,061	1	12	1	99.2	1
HI MAUI 09-026	Waiheʻe-A	rpt-2	10,476	1	10	1	99.1	1
HI MAUI 09-027	N. Waiehu-C		657	5	20	1	89.2	3
HI MAUI 09-028	N. Waiehu-A		1,195	3	17	1	97.8	1
HI MAUI 09-028	N. Waiehu-A	rep	1,431	3	11	1	85.6	3
HI MAUI 09-029	S. Waiehu-C		2,300	3	13	1	97.5	1
HI MAUI 09-030	S. Waiehu-A		1,640	3	15	1	96	1
HI MAUI 09-030	S. Waiehu-A	rep	1,598	3	8	1	98.4	1
HI MAUI 09-031	ʻĪao-C		2,028	3	12	1	95.5	1
HI MAUI 09-031	ʻĪao-C	rep	4,161	1	11	1	94.8	1
HI MAUI 09-032	ʻĪao-A		5,311	1	17	1	99.1	1
HI MAUI 09-033	Kauaʻula		4,542	1	16	1	86.7	3
HI MAUI 09-034	Launiupoko		2,019	3	12	1	64.2	5
HI MAUI 09-035	Ukumehame-B		3,992	1	14	1	95	1
HI MAUI 09-036	Waiehu		1,276	3	17	1	87.4	3
HI MAUI 09-037	Makamakaʻole-A		4,161	1	11	1	98.7	1
HI MAUI 09-038	Makamakaʻole-B		1,508	3	22	3	35	5
HI MAUI 09-039	Ukumehame-A		3,271	1	16	1	96.3	1
HI MAUI 09-040	Olowalu-A		1,857	3	15	1	88.5	3

[1] Metric determined using instream samples and observations.

Table 9. —Continued

Nonnative mollusk abundance metric		Amphipoda abundance metric		‘Ōpae P/A metric[1]		Crayfish P/A metric[1]		P-HBIBI score	P-HBIBI category
No./m²	Score	No./m²	Score	P/A	Score	P/A	Score		
0	1	0	1	X	1	–	1	11	Good
0	1	0	1	X	1	–	1	9	Good
4.8	3	0	1	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	X	1	–	1	7	Good
10.2	3	0	1	X	1	–	1	15	Fair
0	1	0	1	X	1	–	1	9	Good
0	1	0	1	X	1	–	1	11	Good
4.5	3	0	1	X	1	–	1	11	Good
18.8	3	0	1	X	1	–	1	11	Good
6.3	3	0	1	X	1	–	1	11	Good
0	1	0	1	X	1	–	1	9	Good
0	1	0	1	X	1	–	1	7	Good
0	1	0	1	–	3	–	1	9	Good
315.9	5	0	1	–	3	–	1	15	Fair
581.7	5	0	1	–	3	–	1	19	Fair
69.1	3	0	1	–	3	–	1	11	Good
0	1	0	1	X	1	–	1	11	Good
0	1	0	1	–	3	–	1	9	Good
21.2	3	0	1	X	1	–	1	17	Fair
0	1	0	1	X	1	–	1	7	Good
174.4	5	0	1	X	1	–	1	15	Fair

Table 10. Dominant and second-dominant taxa collected in the Maui quantitative samples.

[sp., species; gr., group; –, not applicable]

Taxa	Group	Status	Main sample		All samples[1]	
			Dominant	Second-dominant	Dominant	Second-dominant
Cheumatopsyche sp.	Trichoptera	Nonnative	18	15	26	18
Cricotopus bicinctus gr.	Chironomidae	Nonnative	9	12[a]	14	15[a]
Eukiefferiella claripennis gr.	Chironomidae	Nonnative	5	4[a]	5	10[a]
Hydroptila sp.	Trichoptera	Nonnative	4	5[b]	4	6[b]
Oligochaeta	(Worms)	Cryptogenic	3	4[b]	3	5[b]
Atyoida bisulcata	Decapoda	Native	1[c]	–	1[c]	–
Lymnaeidae	Mollusca	Undetermined	–	–	1	–
Physa sp.	Mollusca	Nonnative	–	2	–	2
Total No. of Samples			40	42	54	56

[1]Includes repeat, replicate, and re-sorted samples.

[a] Shared codominance at 1 site.

[b] Shared codominance at 1 site.

[c] Occurred during a recruitment event.

Although most sites scored low, the metric scores did differentiate among the sites. The biggest difference was between West Maui and East Maui sites. There was no variability in the scoring between all of the paired replicate, re-sorts, and repeat samples.

Abundance of Amphipoda Metric

Amphipods, commonly called scuds, are found around the world. Although much work has been done on the Hawaiian marine, brackish, and terrestrial species of amphipods, little research has been done on the Hawaiian freshwater species (Barnard, 1970; Barnard, 1971; Brusca, 1973; Barnard, 1977). The one species collected from freshwater systems in Hawai‘i has been identified as *Hyalella* sp. or *Hyalella azteca* Saussure, 1858 (fig. D41; Barnard, 1971; Ibara and Conant, 1972; Yee and Ewart, 1986; Englund and others, 2000b; Wolff and Koch, 2009). Amphipods superficially resemble Collembola, or springtails, another inhabitant of Hawaiian streams. The abundance of amphipods typically is predicted to increase with increasing disturbance in continental settings (Weigel, 2003).

Only one of the Maui quantitative samples, collected from Waiohue Stream, contained any amphipods, which was a single amphipod with a calculated density of 2.7/m^2 (figs. B37–B38). This metric was unsuccessful at differentiating among the Maui study sites. In a previous study, amphipods had been collected in benthic samples from ‘Īao Stream; however, they were not identified during this study in the samples from nearby sites (McIntosh and others, 2002). This may be an artifact of the subsampling and sorting process, in which taxa may go unnoticed if they are rare in the samples. This metric did, however, successfully differentiate between O‘ahu sites and Maui sites. It also successfully differentiated among the sites from the O‘ahu WSA study, with 67.7 percent of the sites scored as 1, 25.8 percent as 3, and 6.5 percent as 5.

‘Ōpae Presence/Absence Metric

This metric is based on the presence or absence of the native mountain shrimp, *Atyoida bisulcata*, in either the quantitative or qualitative samples, as well as supplemental information provided by visual observations. The failure to collect an individual of this species during the sampling does not conclusively show that the species was not present, but rather suggests there may have been too few in the study reach to observe. The presence of *Atyoida bisulcata*, the endemic mountain shrimp locally known as ‘ōpaekala‘ole, is believed to be an indicator of higher water quality (Kido and Smith, 1997; Kido and others, 1999b). Adult *A. bisulcata* are more common in middle and upper stream reaches, whereas recruiting juveniles can be observed as low as the stream mouth during their upstream migration.

The distribution of *A. bisulcata* on Maui is shown in figures B3–B4. *A. bisulcata* were collected or observed at 31 of the 40 Maui sites (77.5 percent), including all 16 sampling sites in East Maui. *A. bisulcata* was the only amphidromous species collected or observed at East Maui sites located upstream of the Ko‘olau Ditch. Stream segments immediately downstream of the ditch diversions generally are dry except during periods of storm runoff. Some of these streams gain flow from groundwater farther downstream and can have permanent flow in the lower reaches to the ocean. *A. bisulcata* were present at 15 of the 24 sampling sites on West Maui. The longer distances of dry streambed, the lack of gaining surface-water flow at lower elevations, and less overall rain on the Lahaina side all serve to create a barrier for the upstream migration of *A. bisulcata* to some of the upper West Maui sites as compared to the upper East Maui sites.

The metric scores for the presence or absence of *A. bisulcata* did not successfully differentiate among the Maui study sites but do differentiate the Maui sites from the Oʻahu sites. The absence of *A. bisulcata* was most likely due to the diversion of streamflow and not necessarily related to the quality of the streams themselves. As mentioned earlier, the diversion of water can be a factor in influencing stream quality and can impair the ability of amphidromous species in their upstream and downstream migrations; however, the goals of this study are not the same as an instream flow study. On Oʻahu, other factors have been identified as barriers to the upstream/downstream migration of the native amphidromous species such as nonnative fish. Sampling sites upstream from the Wahiawa Reservoir, for example, were also devoid of *A. bisulcata* as well as the native fish species. However, these sites were rated as some of the most nearly pristine sites on Oʻahu, with forested watersheds and clear, fast-flowing, relatively uncontaminated water, with good habitat for the native species apart from an abundance of smallmouth bass. The manmade Wahiawa Reservoir has been stocked with gamefish, including largemouth and smallmouth bass, tucunare, tilapia, snakehead, and bluegill sunfish. This assemblage of fishes serves as a barrier to the amphidromous species by preying on the recruiting juveniles and perhaps the drifting larvae. The distribution of nonnative fish on Oʻahu is shown in figure C11.

Crayfish Presence/Absence Metric

Like the ʻōpae metric, this metric is based on the presence or absence of a species, the nonnative crayfish *Procambarus clarkii*, in either the quantitative or qualitative samples as well as supplemented by visual observations. Also, like the ʻōpae metric, the apparent absence of *P. clarkii* indicates that although it was not observed, it may have been present in small numbers. The presence of *P. clarkii* metric has similarities with the mollusk metric in that the presence of the crayfish in impaired streams is not entirely because they are better equipped to survive in polluted waters, but also because they were released into those waters. There is no evidence that the crayfish does not thrive when released into “pristine” waters.

This metric did not successfully differentiate among the Maui study sites. *P. clarkii* was not collected in any of the benthic samples on Maui and was only observed during snorkeling surveys at the Waikapū-C site in West Maui (fig. B3). *P. clarkii* has often been associated with taro fields but was not observed at any of the sites located downstream of return flows from any taro field. Snorkeling surveys determined that *P. clarkii* was abundant at the Waikapū-C site, coexisting with the native damselflies *Megalagrion nigrohamatum nigrohamatum* and *M. blackburni*. Crayfish were present at 61 percent of the sampling sites used to develop the metrics and at 29 percent of the Oʻahu WSA sampling sites (Wolff, 2005).

Final P–HBIBI Score

The final index score for each sampling site, the sum of the 7 individual metric scores, ranged from 7 to 37, with higher index scores indicating increasingly higher levels of impairment (Wolff, 2005). Sampling sites with P–HBIBI scores less than or equal to 14 were categorized as “good” quality (mildly impaired). Sites with index scores greater than 14 but less than or equal to 22 were categorized as “fair” quality (moderately impaired), and sites with index scores greater than 22 were categorized as “poor” quality (severely impaired).

The distribution of the P–HBIBI scores for the Maui samples is shown in figures B39–B40. The majority of the Maui samples, 43 of 54, were evaluated to be in the “good” quality category and the 11 remaining samples were categorized as “fair”. None of the Maui samples were evaluated as “poor”. Seven of the 11 “fair” quality samples scored 15, the lower limit of the category. The highest P–HBIBI score was 19 at the Launiupoko site in West Maui, heavily influenced by a high abundance of Physidae mollusks, which in turn resulted in a lower overall percentage of insects. Only 2 of the 16 sites on East Maui and 7 of the 24 sites on West Maui were categorized as “fair” and 1 West Maui site had one replicate sample categorized as “fair” and the other replicate sample categorized as “good”. Nuaʻailua and West Wailua Iki-B in East Maui were both small streams with low flow. The average water velocities measured at the sampling points were the lowest of all the Maui sites, 0.26 and 0.45 ft/sec, respectively.

At one site, Olowalu-B on West Maui, where two replicate samples were collected, one sample was categorized as “good” with a score of 11 and the other sample categorized as “fair” with a score of 17. This was due to a lower percentage of insects (74.4 percent as compared to 94.6 percent) caused by a higher abundance of nonnative or cryptogenic Physidae mollusks (364.8/m^2 as compared to 42.7/m^2) in the “fair” sample, demonstrating some of the variability in the sampling and sorting. Although there were some slight differences, the samples from all of the other sites, where replicate samples and re-sorted samples were evaluated, were rated in the same category.

The P–HBIBI scores performed well in contrasting the quality of Maui streams as compared to the quality of streams on Oʻahu. None of the Maui sites rated in the “poor” category, indicative of the lesser extent of urbanization and industrialization and the smaller population on Maui as compared to that on Oʻahu. Native species, including the fish, shrimp, and insects, were more common and more abundant in the Maui streams than on Oʻahu. Additionally, the extensive systems of surface-water diversions and ditches greatly reduced the number of perennially flowing streams draining the larger agricultural and urban areas. The sites that were rated as “fair” were, with some exceptions, in agreement with the on-site assessments performed by the research team. The “fair” rating of the Makamakaʻole-B site was due, in part, to the extremely large number of recruiting ‘ōpaekala‘ole, the endemic mountain shrimp, captured in the sampling nets.

New Maui Metrics and Index

The procedure of selecting new, appropriate metrics to develop an invertebrate community index for streams on Maui followed the process described in the “Index Development” section. This process consisted of multivariate analysis, metric screening, metric selection, and metric scoring. The results of the nMDS analysis showed that there is somewhat of a separation between East and West Maui assemblages (figs. 6A–6B). This clustering is visually more apparent using the log(x + 1) transformed abundance data (fig. 6B). The MRPP analysis confirmed the nMDS results, showing that the samples within each region are more similar to each other than was expected by chance (Euclidian distance measure; proportional data: $A = 0.0593$, $p < 0.00005$; abundance data: $A = 0.0590$, $p < 0.00005$; where A is the chance-corrected within-group agreement; McCune and Grace, 2002). This clustering indicates that although there is some overlapping similarity between the regional community structures, the diversity, relative abundances, and abundances of the taxa are being influenced by regional differences. The results of the DCA performed on the log(x + 1) transformed abundance data displayed a similar clustering of the East and West Maui assemblages (fig. 7). West Maui sites were influenced by physid snails and *Megalagrion* damselfly naiad abundances whereas East Maui sites were more influenced by hīhīwai, ‘ōpae, and lymnaeid snail abundances.

Maui Reference “Least Disturbed” Site Selection

The scoring process of these new metrics required the selection of reference condition “least disturbed” sites. The selection of reference sites began with an examination of the results of a PCA of the habitat characteristics (fig. 8). Sites plotted in the upper right quadrant represent streams that tended to be larger, more turbulent West Maui streams, whereas sites that plotted in the lower left quadrant were small, slower flowing, streams with higher percentages of sedimentation. Sites in the upper left quadrant were all on streams in West Maui, with many from the Lahaina side. These sites tended to have higher percentages of cobble and gravel substratum and higher specific conductance values, whereas sites in the lower right quadrant tended to have higher percentages of large boulder and bedrock substratum with higher percentages of fast flowing riffles. Most of these sites were from East Maui streams. The site evaluations also included an examination of land use in the contributing basin and the overall quality of the sites as determined by the best professional judgment of the field crew and leader. The final reference sites were selected to represent the “least disturbed” conditions on both East and West Maui over a range of altitudes. A set of 10 sites were chosen, 5 representing East Maui and 5 representing West Maui; 6 from higher altitudes, 3 from middle altitudes, and 1 from lower altitudes (table 11). Fewer lower altitude sites were included because they tended to be more disturbed than the higher altitude sites. Scoring of the core metrics proceeded as described earlier.

The conditional values and scores are shown in table 12. In general, the scores for each metric are 1, 3, or 5, with lower scores indicating less impairment. The index score is the sum of the individual metrics scores, with lower scores indicating less impairment. The results of these analyses are shown in table 13 and are discussed in this section.

Total Macroinvertebrate Abundance Metric (Revised)

The P–HBIBI total abundance metric successfully differentiated among the Maui study sites and was retained in the current index as a 4-tiered metric. The conditional scores, however, were revised to reflect the greater abundances of macroinvertebrates collected in the Maui samples. The top tier limit, indicating better conditions, was increased from 3,000/m^2 to 7,900/m^2; the second tier limit was increased from 700/m^2 to 4,000/m^2; the third tier limit increased from 200/m^2 to 1,200/m^2. The data also indicated that some samples from high quality sites contained lower total abundances due in part to higher percentages of these study reaches being composed of large boulders and bedrock substratum. This was most notable at the Honomanū and North Waiehu-A sampling sites.

The distributions of these metric scores are shown in figures B41–B42. The distributions of the abundances per square meter are shown in figures B27–B28. A total of 7 of the 54 samples (13 percent) scored in the top tier, 15 samples (27.8 percent) in the second tier, 24 samples (44 percent) in the third tier, and 8 samples (14.8 percent) scored in the bottom tier with total abundances < 1,200/m^2. Three of the paired replicate samples scored in different tiers in this metric, and in two of these cases the final index categories were different as well. The second of the repeat samples from Waihe‘e-A scored lower than the others in this metric. The differences among these samples are discussed in the “Repeat Samples” section of appendix A. None of the re-sorted samples scored in different tiers with this metric.

Relative Abundance of Insecta Metric (Revised)

The P–HBIBI relative abundance of Insecta metric successfully differentiated among the Maui study sites. To improve this metric, the insect relative abundance was recalculated from the total macroinvertebrate abundance, subtracting out the abundances of the native shrimp (‘ōpae), and the native snail (hīhīwai). This was done to ensure that sites would not be mischaracterized in the scoring for having healthy populations of these native, noninsect species. The condition values were slightly revised for the Maui data, retaining the top tier at 90 percent but lowering the bottom tier limit from 75 to 73 percent. The actual 75th percentile of the reference sites was 99 percent, but this was considered to be too restrictive; so the original limit, which worked well, was retained.

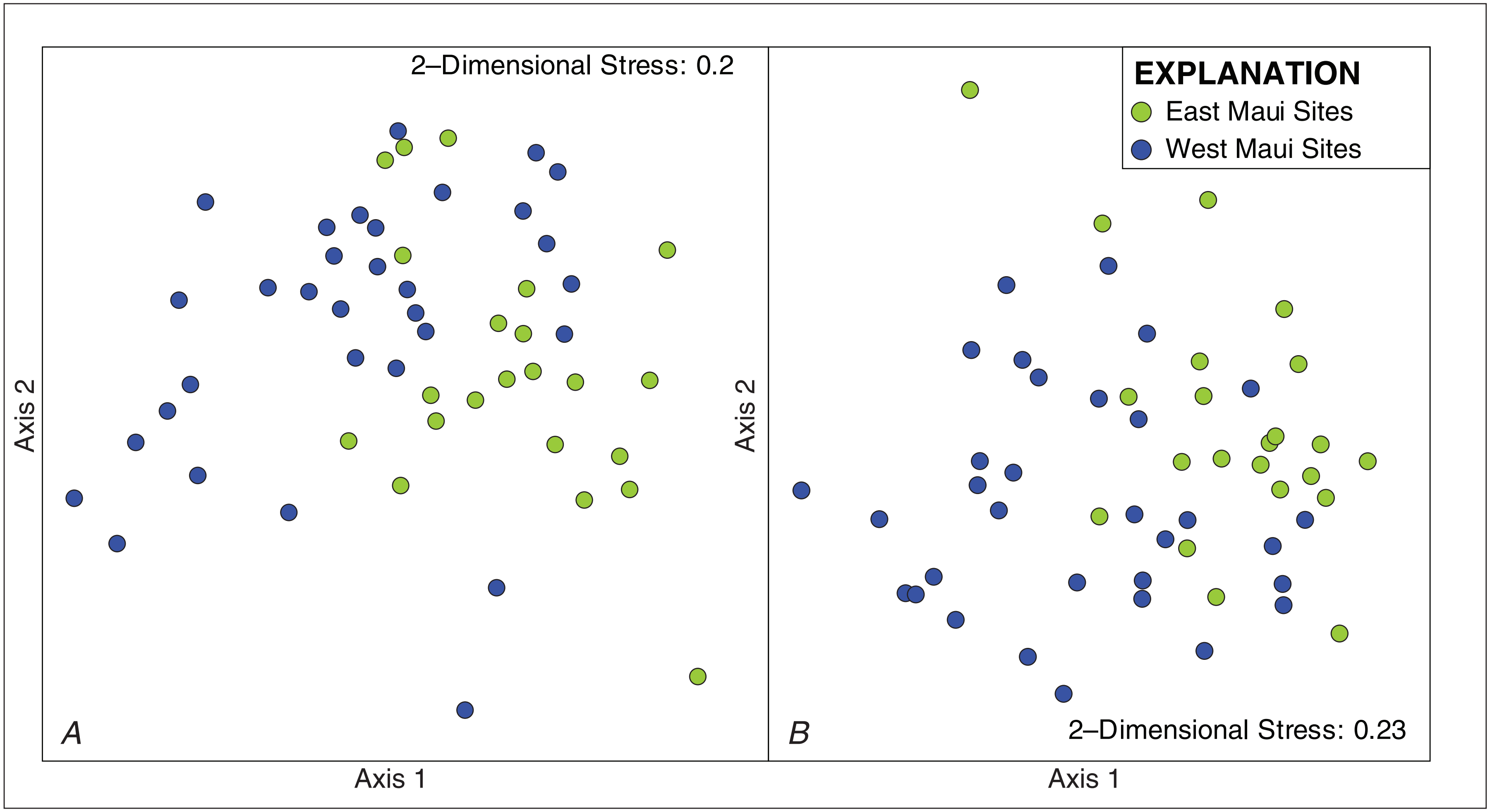


Figure 6. Nonmetric multidimensional scaling (nMDS) ordination of the Maui quantitative macroinvertebrate samples using (*A*) arcsine-square root transformed proportional data and (*B*) log(x+1) transformed abundance data (logarithm of the sum of the abundance plus one, with abundance in number of organisms per square meter).

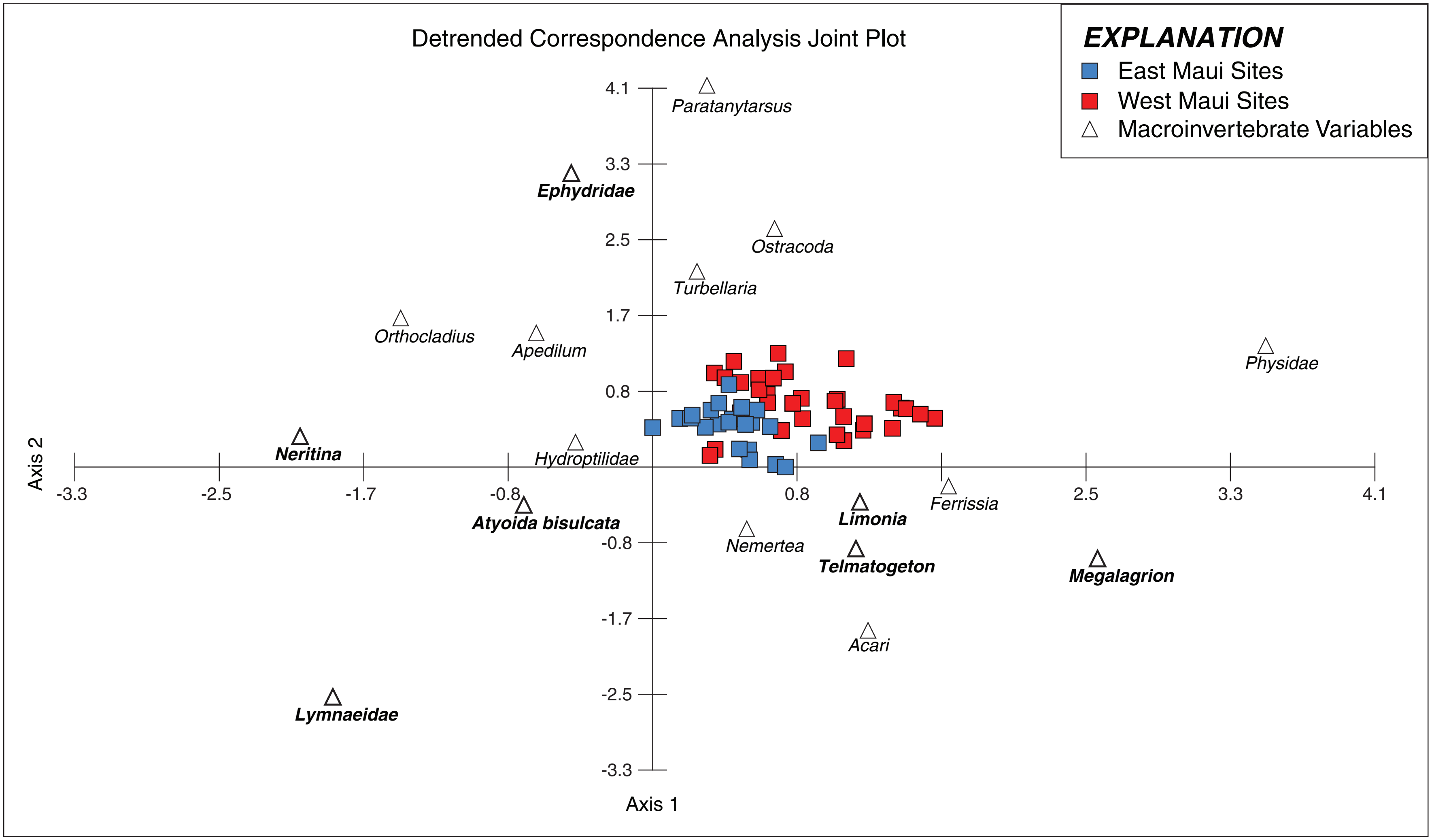


Figure 7. Detrended correspondence analysis (DCA) joint plot ordination of the Maui quantitative macroinvertebrate samples using log(x+1) transformed abundance data (logarithm of the sum of the abundance plus one, with abundance in number of organisms per square meter). Variables in **bold** are, or possibly are, native species.

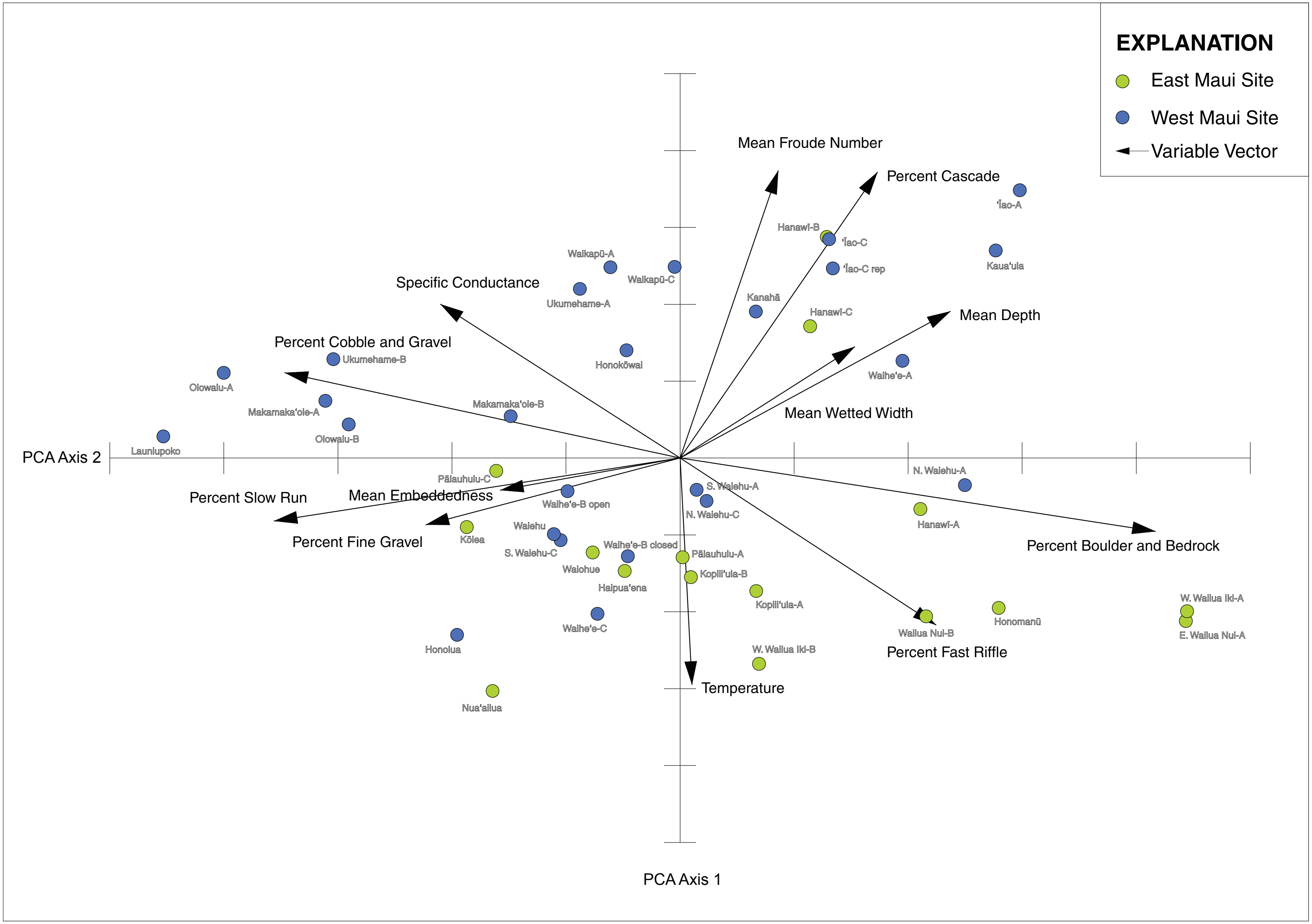


Figure 8. Principal components analysis (PCA) ordination of Maui study sites habitat characteristics.

Table 11. Maui reference condition “least disturbed” sites.

Station ID	Stream name	Region	Altitude, in feet	Site name
HI_MAUI_09-004	Hanawī Stream	East Maui	1,364	Hanawī-A
HI_MAUI_09-009	Pālauhulu Stream	East Maui	153	Pālauhulu-A
HI_MAUI_09-012	Hanawī Stream	East Maui	661	Hanawī-C
HI_MAUI_09-013	Waiohue Stream	East Maui	28	Waiohue
HI_MAUI_09-015	Hanawī Stream	East Maui	130	Hanawī-B
HI_MAUI_09-019	Kanahā Stream	West Maui	1,122	Kanahā
HI_MAUI_09-026	Waihe‘e River	West Maui	600	Waihe‘e-A
HI_MAUI_09-030	South Waiehu Stream	West Maui	676	S. Waiehu-A
HI_MAUI_09-032	‘Īao Stream	West Maui	975	‘Īao-A
HI_MAUI_09-037	Makamaka‘ole Stream	West Maui	751	Makamaka‘ole-A

Table 12. Conditional scoring for Invertebrate Community Index (ICI) metrics and index for Maui.

[m^2, square meter; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

Metric	Condition	Score
Total abundance, in organisms/m^2	≥ 7,900	1
	< 7,900 and ≥ 4,000	3
	< 4,000 and ≥ 1,200	5
	< 1,200	7
Insecta relative abundance, in percent of Insecta from the total abundance minus the abundances of the native shrimp and snail	≥ 90	1
	< 90 and ≥ 73	3
	< 73	5
Trichoptera:Diptera ratio (Trichoptera abundance:nonnative Diptera abundance)	≥ 2.5	1
	< 2.5 and ≥ 0.5	3
	< 0.5	5
Native species richness	**Presence/Absence**	**Score**
Atyoida bisulcata (‘ōpaekala‘ole or mountain ‘ōpae)	Present	1
	Absent	2
Neritina granosa (hīhīwai)	Present	1
	Absent	2
Telmatogeton spp. (torrent midges)	Present	1
	Absent	3
Megalagrion damselflies (adults and/or naiads) (pinao ‘ula)	Present	1
	Absent	3
	Index score	**Category**
Final Maui Invertebrate Community Index (sum of metric scores)	≤14	Good
	> 14 and ≤18	Fair
	> 18	Poor

This metric was highly negatively correlated with the relative abundance of Oligochaeta (worms) metric. The distribution of these metric scores is shown in figures B43–B44. A total of 31 of the 54 samples (57.4 percent) scored in the top tier, 16 samples (29.6 percent) scored in the second tier, and 7 samples (13 percent) scored in the bottom tier. A review of the paired replicate samples showed that four of seven pairs scored in different tiers; the largest difference, 21 percent, was in the Olowalu-B samples due to a high abundance of physid snails in one of the samples. One of the pairs of re-sorted samples scored in different tiers, with a difference of only 3 percent. None of the repeat samples scored in different tiers.

Ratio of the Nonnative Trichoptera and Diptera

This metric compared the proportions of the insect families of Trichoptera and Diptera in each sample. In continental streams, many of the trichopteran species are more sensitive to disturbance than many of the dipteran species, so that larger proportions of trichopterans indicate less disturbance. For this metric, only those specimens that could be confirmed as nonnative dipterans were used in the calculations. Specimens were not included if they could only be identified to a family level if that family contained both native and nonnative species. Although there are no native trichopterans in Hawai‘i, as discussed earlier, there are a number of native species of dipterans. The native species were excluded from this metric because: (1) tolerance values have not been developed for the native dipterans and, (2) unlike many of the introduced species, studies in Hawaiian streams have demonstrated that the native species are especially sensitive to habitat disturbances.

This metric was calculated by summing the abundances of the trichopterans (*Cheumatopsyche*, *Hydroptila* spp. and *Oxyethira*) and dividing by the sum of the abundances of the nonnative dipterans (predominantly chironomids: *Eukiefferiella*, *Cricotopus*, *Apedilum*, and *Paratanytarsus*). The distribution of these metric scores is shown in figures B45–B46. The distribution of the actual ratios is shown in figures B47–B48. This metric was highly correlated with the relative abundances of the trichopteran *Cheumatopsyche* and the dipteran *Cricotopus* and the ratio of these two taxa (figs. B49–B50). A total of 13 of the 54 samples (24.1 percent) scored in the top tier, 30 samples (55.6 percent) scored in the middle tier, and 11 samples (20.4 percent) scored in the bottom tier with < 0.5 Trichoptera/Diptera.

A review of the paired replicate samples showed that three of the pairs scored in different tiers, with the largest difference, 9.7, in the South Waiehu-A samples. This difference was enough to decrease the replicate sample from a “good” to a “fair” rating. The second repeat sample from Waihe‘e-A scored better than the other two repeat samples. As discussed in the “Repeat Samples” section of appendix A, this was mainly due to much lower abundances of the chironomids *Cricotopus* (73 and 76 percent fewer respectively) and *Eukiefferiella* (71 and 70 percent fewer, respectively) in the second sample. None of the re-sorted samples scored in different tiers.

Native Macroinvertebrate Presence/Absence

The presence or absence of four of the native macroinvertebrates was determined using the quantitative, qualitative, and observational data and scored individually. The amphidromous species, *Atyoida bisulcata* (‘ōpae) and *Neritina granosa* (hīhīwai), were scored as either 1 if present and 2 if not observed. Because these species are amphidromous, they are more susceptible to alterations in stream flow and may be absent from sites due to anthropogenic impediments such as diversions, and for that reason the difference in the scoring is only 1 point. However, due to their habitat requirements of clean, fast-flowing water, the presence of either of these native species may be an indicator of better quality streams (Ford, 1979; Brasher, 1997, Kido and Smith, 1997). The ‘ōpae metric was retained because the hīhīwai metric, in general, scores better at lower elevations while the ‘ōpae metric, in general, scores better at higher elevations and the two together balance out the elevational differences. *Telmatogeton* (torrent midges), and *Megalagrion* damselflies (adults and (or) naiads of any species) were given a score as either 1 if present or 3 if not observed. These species are not amphidromous and as adults can move freely about upstream and downstream, and for that reason the difference in the scoring is 2 points.

The distribution of these metric scores is shown in figures B51–B58. Because this metric is based on all the available data collected at a site, the resultant score is for the site and is therefore the same for the replicate and re-sorted samples. Of the 40 sampling sites, ‘ōpae were present at 31 (77.5 percent), hīhīwai were present at 11 (27.5 percent), *Megalagrion* damselflies were present at 29 (72.5 percent) and *Telmatogeton* were present at 20 (50 percent). All four species were present at only the Hanawī-B site, while three of the species were present at 15 sites, two were present at 18 sites, and only one of the species was present at 6 sites.

Final Index Score

The final community index was calculated as the sum of the eight individual metric scores (table 13). This ICI is not meant to be a measure of the native biotic integrity, but a comparison to the macroinvertebrate communities found at reference “least disturbed” sites. The distribution of these index scores is shown in figures B59–B60. Samples scoring ≤14 were categorized as ”good” quality invertebrate communities. The assemblages in these samples were evaluated to be at or near the reference condition. A total of 22 of the 54 samples (40.7 percent) were evaluated to be ”good” quality communities. Samples scoring >14 but ≤18 were categorized as “fair” quality communities. Communities in these samples were evaluated to deviate to some extent from the reference condition but were still considered to be in an acceptable state. A total of 22 (40.7 percent) of the samples were evaluated to be “fair” quality communities. Samples with a final index score >18 were categorized as “poor” communities.

Table 13. New metric scores and Maui Invertebrate Community Index (ICI) ratings for the Maui benthic macroinvertebrate samples.

[rst, re-sorted sample; rep, replicate sample; rpt, repeat sample; Abundance in number per square meter; X, species present; –, species absent; P/A, Presence/Absence; No./m^2, number per square meter]

Station ID	Site name	Sample type	Total abundance metric		Trichoptera: Diptera metric		Relative abundance of Insecta metric[3]	
			No./m^2	Score	Ratio	Score	Percentage	Score
HI_MAUI_09-001	Kopili‘ula-A		1,231	5	1.7	3	89	3
HI_MAUI_09-002	W. Wailua Iki-B		330	7	1.2	3	73	3
HI_MAUI_09-003	Wailua Nui-B		1,418	5	1.2	3	97	1
HI_MAUI_09-004	Hanawī-A[2]		7,911	1	1.6	3	90	1
HI_MAUI_09-004	Hanawī-A	rst	10,478	1	2.3	3	99	1
HI_MAUI_09-004	Hanawī-A	rep	6,662	3	1	3	87	3
HI_MAUI_09-004	Hanawī-A	rep, rst	7,525	3	1.1	3	96	1
HI_MAUI_09-005	W. Wailua Iki-A		4,499	3	1.4	3	76	3
HI_MAUI_09-006	Haipua‘ena		3,196	5	0.3	5	73	3
HI_MAUI_09-007	Pālauhulu-C		6,241	3	1.4	3	91	1
HI_MAUI_09-008	E. Wailua Nui-A		2,571	5	0.5	3	88	3
HI_MAUI_09-009	Pālauhulu-A[2]		9,365	1	2.5	1	89	3
HI_MAUI_09-010	Honomanū		323	7	2.6	1	95	1
HI_MAUI_09-011	Kōlea		23,137	1	0.2	5	94	1
HI_MAUI_09-011	Kōlea	rst	9,869	1	0.2	5	96	1
HI_MAUI_09-012	Hanawī-C[2]		5,305	3	0.6	3	93	1
HI_MAUI_09-013	Waiohue2		1,675	5	3.6	1	97	1
HI_MAUI_09-014	Kopili‘ula-B		3,758	5	4	1	67	5
HI_MAUI_09-014	Kopili‘ula-B	rst	2,271	5	4.8	1	68	5
HI_MAUI_09-015	Hanawī-B[2]		6,812	3	2.1	3	97	1
HI_MAUI_09-015	Hanawī-B	rep	4,234	3	4	1	99	1
HI_MAUI_09-016	Nua‘ailua		166	7	5	1	32	5
HI_MAUI_09-017	Waikapū-C		7,053	3	1.4	3	95	1
HI_MAUI_09-018	Waikapū-A		5,012	3	0.9	3	83	3
HI_MAUI_09-019	Kanahā[2]		3,224	5	0.6	3	97	1
HI_MAUI_09-020	Honolua		1,129	7	0.4	5	73	3
HI_MAUI_09-020	Honolua	rep	984	7	0.8	3	63	5
HI_MAUI_09-021	Honokōwai		4,146	3	0.5	3	98	1
HI_MAUI_09-022	Olowalu-B		1,690	5	4.2	1	74	3
HI_MAUI_09-022	Olowalu-B	rep	1,523	5	6.4	1	95	1
HI_MAUI_09-023	Waihe‘e-B open		740	7	0.4	5	97	1
HI_MAUI_09-023	Waihe‘e-B open	rep	1,313	5	0.4	5	95	1
HI_MAUI_09-024	Waihe‘e-B closed		1,207	5	0.4	5	81	3
HI_MAUI_09-025	Waihe‘e-C		1,619	5	0.8	3	50	5

Table 13.—Continued

Megalagrion P/A Metric[1]		‘Ōpae P/A Metric[1]		Hīhīwai P/A Metric[1]		Telmatogeton P/A Metric[1]		Invertebrate Community Index	
P/A	Score	P/A	Score	P/A	Score	P/A	Score	Index score	Category
X	1	X	1	–	2	X	1	16	Fair
X	1	X	1	X	1	–	3	19	Poor
–	3	X	1	X	1	–	3	17	Fair
X	1	X	1	–	2	X	1	10	Good
X	1	X	1	–	2	X	1	10	Good
X	1	X	1	–	2	X	1	14	Good
X	1	X	1	–	2	X	1	12	Good
X	1	X	1	–	2	X	1	14	Good
X	1	X	1	–	2	X	1	18	Fair
–	3	X	1	X	1	–	3	15	Fair
X	1	X	1	–	2	X	1	16	Fair
–	3	X	1	X	1	–	3	13	Good
X	1	X	1	–	2	X	1	14	Good
X	1	X	1	–	2	X	1	12	Good
X	1	X	1	–	2	X	1	12	Good
X	1	X	1	–	2	–	3	14	Good
–	3	X	1	X	1	–	3	15	Fair
X	1	X	1	X	1	–	3	17	Fair
X	1	X	1	X	1	–	3	17	Fair
X	1	X	1	X	1	X	1	11	Good
X	1	X	1	X	1	X	1	9	Good
X	1	X	1	X	1	–	3	19	Poor
X	1	–	2	–	2	–	3	15	Fair
X	1	X	1	–	2	X	1	14	Good
X	1	–	2	–	2	X	1	15	Fair
X	1	–	2	–	2	X	1	21	Poor
X	1	–	2	–	2	X	1	21	Poor
X	1	–	2	–	2	X	1	13	Good
X	1	X	1	–	2	–	3	16	Fair
X	1	X	1	–	2	–	3	14	Good
X	1	X	1	–	2	–	3	20	Poor
X	1	X	1	–	2	–	3	18	Fair
X	1	X	1	–	2	–	3	20	Poor
–	3	X	1	–	2	–	3	22	Poor

Table 13. New metric scores and Maui Invertebrate Community Index (ICI) ratings for the Maui benthic macroinvertebrate samples.—Continued

[rst, re-sorted sample; rep, replicate sample; rpt, repeat sample; Abundance in number per square meter; X, species present; –, species absent; P/A, Presence/Absence; No./m^2, number per square meter]

Station ID	Site name	Sample type	Total abundance metric		Trichoptera: Diptera metric		Relative abundance of Insecta metric[3]	
			No./m^2	Score	Ratio	Score	Percentage	Score
HI_MAUI_09-026	Waihe‘e-A[2]		9,453	1	0.3	5	99	1
HI_MAUI_09-026	Waihe‘e-A	rpt-1	4,061	3	1	3	99	1
HI_MAUI_09-026	Waihe‘e-A	rpt-2	10,476	1	0.3	5	99	1
HI_MAUI_09-027	N. Waiehu-C		657	7	0.4	5	89	3
HI_MAUI_09-028	N. Waiehu-A		1,195	7	0.8	3	98	1
HI_MAUI_09-028	N. Waiehu-A	rep	1,431	5	0.6	3	86	3
HI_MAUI_09-029	S. Waiehu-C		2,300	5	0.5	3	98	1
HI_MAUI_09-030	S. Waiehu-A[2]		1,640	5	11.9	1	96	1
HI_MAUI_09-030	S. Waiehu-A	rep	1,598	5	2.3	3	98	1
HI_MAUI_09-031	‘Īao-C		2,028	5	1.7	3	95	1
HI_MAUI_09-031	‘Īao-C	rep	4,161	3	1.6	3	95	1
HI_MAUI_09-032	‘Īao-A[2]		5,311	3	1.3	3	99	1
HI_MAUI_09-033	Kaua‘ula		4,542	3	0.4	5	87	3
HI_MAUI_09-034	Launiupoko		2,019	5	1.1	3	64	5
HI_MAUI_09-035	Ukumehame-B		3,992	5	0.8	3	95	1
HI_MAUI_09-036	Waiehu		1,276	5	3.1	1	88	3
HI_MAUI_09-037	Makamaka‘ole-A[2]		4,161	3	0.7	3	99	1
HI_MAUI_09-038	Makamaka‘ole-B		1,508	5	0.8	3	53	5
HI_MAUI_09-039	Ukumehame-A		3,271	5	4.9	1	96	1
HI_MAUI_09-040	Olowalu-A		1,857	5	3	1	89	3

[1] Metric determined using instream samples and observations.

[2] Sample used as reference sample in calculating the metrics.

[3] Relative abundance calculated from total abundance minus the abundance of native shrimp and snails.

Table 13.—Continued

Megalagrion P/A Metric[1]		ʻŌpae P/A Metric[1]		Hīhīwai P/A Metric[1]		Telmatogeton P/A Metric[1]		Invertebrate Community Index	
P/A	Score	P/A	Score	P/A	Score	P/A	Score	Index score	Category
X	1	X	1	–	2	X	1	12	Good
X	1	X	1	–	2	X	1	12	Good
X	1	X	1	–	2	X	1	12	Good
X	1	X	1	–	2	X	1	20	Poor
X	1	X	1	–	2	X	1	16	Fair
X	1	X	1	–	2	X	1	16	Fair
–	3	X	1	–	2	–	3	18	Fair
X	1	X	1	–	2	–	3	14	Good
X	1	X	1	–	2	–	3	16	Fair
–	3	X	1	–	2	X	1	16	Fair
–	3	X	1	–	2	X	1	14	Good
X	1	–	2	X	1	X	1	12	Good
X	1	–	2	–	2	X	1	17	Fair
X	1	–	2	–	2	X	1	19	Poor
–	3	–	2	X	1	–	3	18	Fair
–	3	X	1	–	2	–	3	18	Fair
–	3	–	2	–	2	X	1	15	Fair
–	3	X	1	X	1	–	3	21	Poor
X	1	X	1	–	2	–	3	14	Good
X	1	X	1	–	2	–	3	16	Fair

These samples deviated enough from the reference condition to indicate that further investigation may be needed to determine the cause or causes of the deviation. A total of 10 samples (18.5 percent) were evaluated to be “poor” macroinvertebrate communities. The cause or causes of the deviation might be naturally occurring conditions, or anthropogenically generated reductions in streamflow, or adverse water quality or physical habitat disturbances that should be addressed by land managers.

A review of the replicate samples showed that four of the seven paired samples were categorized in different tiers. In all four instances, the paired samples straddled a cutoff condition value with only 2 points separating the index scores. All of the re-sorted samples were categorized the same as the original samples. All of the repeat samples from the Waihe‘e-A site were categorized the same.

O‘ahu Metrics and Index Refinement

The procedure of selecting new metrics and refining existing, appropriate metrics to develop an invertebrate community index for streams on O‘ahu followed the process described in the “Index Development” section. Data for benthic macroinvertebrate samples collected in 2006–07 in an earlier study (Wolff and Koch, 2009) were used to refine and revise the O‘ahu P–HBIBI. These samples were collected as part of the USEPA’s probability-based Wadeable Stream Assessment (WSA) program.

Evaluation with the Preliminary–Hawaiian Benthic Index of Biotic Integrity

O‘ahu WSA P–HBIBI Scores

The O‘ahu WSA-targeted riffle habitat samples were evaluated using the P–HBIBI developed by Wolff (2005). The results of these analyses are shown in table 14. Targeted riffle habitat samples were not collected from 9 of the 40 O‘ahu WSA study reaches; 7 sites had only pool habitat, 4 of which were substantially diverted upstream of the sampling site, and 2 sites were flat-bottomed concrete-lined channels. This analysis will consider only the 31 targeted riffle samples. The conditional values and scores for each metric are shown in table 8.

Total Macroinvertebrate Abundance Metric

The distribution of total abundance metric scores for the O‘ahu WSA sampling sites are shown in figure C13. These scores were based on the total abundance of macroinvertebrates per square meter determined at each site (fig. C12). Of the 31 sites where quantitative samples were collected, 7 sites (22.6 percent) had a score of 1, 14 sites (45.2 percent) had a score of 3, 9 sites (29 percent) had a score of 5, and 1 site (3.2 percent) scored a 7 with less than 200/m^2. The total abundance of macroinvertebrates ranged from a high of 5,850.4/m^2 at the Waiāhole-B site to a low of 53.6/m^2 at the ‘Āhuimanu site. Total abundance was positively correlated with the abundance of trichopterans ($p<0.0001$, Spearman’s rho = 0.88) and dipterans ($p<0.0001$, Spearman’s rho = 0.77). This metric successfully differentiated among the sites.

Taxonomic Richness Metric

The distribution of the taxa richness metric scores for the O‘ahu WSA sampling sites is shown in figure C14. Taxa richness ranged from a high of 25 taxa at three sites to a low of 13 at two sites. A majority of sites, 24 of 31, had a score of 1 (≤ 21 taxa), with 7 sites with a score of 3 (22–30 taxa). Taxa richness tended to decrease with an increase in flow, and exhibited a negative correlation with discharge measured at the time of sampling ($p=0.0003$, Spearman’s rho =-0.61). Taxa richness also tended to decrease as the percentage of insects in the samples increased ($p=0.0015$, Spearman’s rho =-0.55). The richness metric scores failed to differentiate among the O‘ahu sites.

Relative Abundance of Insecta Metric

The dominant and second-dominant taxa of the O‘ahu WSA quantitative samples are shown in table 15. A nonnative insect species was the dominant taxon at 27 of the 31 sampling sites (87.1 percent). These same species were the second-dominant taxa at 14 sites (45.2 percent). Insecta as a class were numerically dominant in 30 of the 31 samples, with only the Kalihi-C site having a higher percentage of worms (Class: Clitellata) than insects, although insects were the second-dominant group.

The distribution of the relative abundance of Insecta metric scores for the O‘ahu WSA sampling sites is shown in figure C15. The relative abundance of Insecta metric rated 11 sites (35.5 percent) a score of 1, with relative abundances greater than 90 percent, 7 sites (22.6 percent) a score of 3, between 76 and 90 percent Insecta, and 13 sites (41.9 percent) a score of 5, with less than 75 percent Insecta. The relative abundance of insects in the quantitative samples ranged from a high of 96.8 percent at the South Fork Kaukonahua-A site to a low of 24.7 percent at the Kalihi-C site. The Kalihi-C site was dominated by worms, which accounted for 71.8 percent of the sample.

On O‘ahu, the abundances of a variety of other classes of organisms were high enough to wholly or partially limit the relative abundance of insects, including worms, crustaceans, snails, flatworms, ostracods, and mites. In contrast to the results on Maui, the native mountain ‘ōpae and the native snail *Neritina granosa* were not abundant enough to affect the relative abundance of insects on O‘ahu.. The high relative abundance of worms (Class: Clitellata) constrained the relative abundance of insects at two sites to less than 90 percent and at three sites to less than 75 percent. Crustaceans and snails included the introduced shrimp *Neocaridina denticulata sinensis,* amphipods, *Melanoides tuberculata*, *Ferrissia sharpi*, and Physidae. This metric successfully differentiated among the O‘ahu WSA sites, but required an adjustment to balance out the scores.

Abundance of Nonnative or Cryptogenic Mollusks Metric

The mollusks considered in this metric include the Thiaridae, Physidae, Planorbidae, Corbiculidae, Hydrobiidae, and the nonnative Lymnaeidae *Pseudosuccinea columella*. The distribution of the nonnative or cryptogenic mollusk metric scores for the O‘ahu WSA sampling sites are shown in figure C16. A total of 16 sites (51.6 percent), at which none of the listed mollusks were collected, scored 1; 13 sites (41.9 percent), at which abundance was less than 90/m^2 scored 3; and 2 sites (6.5 percent), at which abundance was greater than 90/m^2, scored 5. The highest density of these mollusks, 109.6/m^2, was collected at Anahulu-B, and they accounted for 27.8 percent of the total sample. These mollusks included *Physa* sp. (22.1 percent), *Melanoides tuberculata* (5.5 percent), and Planorbidae (0.2 percent). The second highest density, 108.8/m^2, consisting entirely of *P. columella*, was collected at the North Fork Kaukonahua-A site, where they accounted for only 3.1 percent of the sample because of the greater total abundance in the North Fork Kaukonahua-A sample. This metric successfully differentiated among the O‘ahu WSA sites.

Abundance of Amphipoda Metric

The distribution of the Amphipoda abundance metric scores for the O‘ahu WSA sampling sites are shown in figure C17. A total of 21 sites (67.7 percent) scored 1, indicating no amphipods were identified in the samples, 7 sites (22.6 percent) scored 3, indicating less than 35/m^2 were collected, and 3 sites (9.7 percent) scored 5, with abundances greater than 35/m^2. The highest density of amphipods (all identified as *Hyalella* sp.), 155.2/m^2, was collected at Nu‘uanu-C, accounting for 28.1 percent of the total sample. The other sites to score 5 were Pauoa, where 44.8/m^2 were collected, accounting for 11.5 percent of the total sample, and Kahana Iki, where 35.2/m^2 (7.4 percent) were collected. This metric, in general, differentiated among the sites.

‘Ōpae Presence/Absence Metric

The distribution and abundance of *Atyoida bisulcata* or ‘ōpae on O‘ahu are shown in figures C1–C2. Of the 31 sites where quantitative samples were collected, 12 (38.7 percent) scored 1, where ‘ōpae were observed (in the samples or visually), and 19 (61.3 percent) scored 3, where ‘ōpae were not observed. *A. bisulcata* were not observed at the nine sites where quantitative samples were not collected. In total, ‘ōpae were observed at 12 of the 40 (30 percent) O‘ahu WSA sites. This is a much lower percentage of sites than on Maui, where ‘ōpae were observed at 77.5 percent of the sites. On O’ahu, *A. bisulcata* were collected in only five quantitative samples and in only three qualitative samples. The other observations were made visually during snorkel surveys or during general data collections.

No *A. bisulcata* or any other decapods were observed at any of the North or South Fork Kaukonahua sites, even though these sites were ascertained to have good instream habitat and good water quality. These sites are all upstream from the Wahiawā Reservoir, which has long been stocked with a variety of gamefish, including largemouth bass, smallmouth bass, peacock bass, bluegill, and catfish. Smallmouth bass were observed in high numbers at each of these sampling sites. These gamefish have likely affected the amphidromous species of fish and shrimp to some degree. The presence of other nonnative fish, such as the predaceous *Hemichromis* and *Gambusia*, in other O‘ahu streams has likely also had an effect on the native species (Yamamoto, 1992). For these reasons, this metric failed to successfully differentiate among the sites. It could however be a useful indicator for interisland comparisons.

Crayfish Presence/Absence Metric

The distribution of *Procambarus clarkii* observed at O‘ahu WSA sites is shown in figure C2. Of the sites where quantitative samples were collected, 23 (74.2 percent) scored 1, where *P. clarkii* were not observed, and 8 (25.8 percent) scored 3, where *P. clarkii* were observed. Of all 40 sites, *P. clarkii* were observed at 9 (22.5 percent). Crayfish were observed at 4 of 10 windward sites, 5 of 8 leeward sites, and were not observed at any of the central O‘ahu sites. Crayfish were observed at 1 of the 15 upper elevation sites, 8 of the 18 middle elevation sites, and were not observed at any of the 7 lower elevation sites. This metric, in general, successfully differentiated among the sites.

Final P–HBIBI Score

The final index score was calculated as the sum of the seven individual metric scores, ranging from 7 to 37, with higher index scores indicating increased levels of impairment (Wolff, 2005). P–HBIBI scores less than or equal to 14 were categorized as “good” (mildly impaired). P–HBIBI scores greater than 14 but less than or equal to 22 were categorized as “fair” (moderately impaired), while index scores greater than 22 were categorized as “poor” (severely impaired).

The distribution of the P–HBIBI scores for the O‘ahu WSA sampling sites is shown in figure C18. Of the 31 sites where quantitative samples were collected, 16 sites (51.6 percent) were evaluated as “good,” 11 sites (35.5 percent) were evaluated as “fair,” and 4 sites (12.9 percent) were evaluated as “poor.” Two sites on the windward side and two sites on the leeward side were evaluated as “poor” sites. None of the 6 leeward sites were rated as “good,” whereas 9 of the 13 windward sites (69.2 percent) and 7 of the 12 central sites (58.3 percent) were rated in the “good” quality category. None of the 10 higher elevation sites were rated as “poor,” while 1 mid elevation site and 3 low elevation sites were evaluated in the “poor” category. Two of the 11 “fair” sites, North Fork Kaukonahua-B and South Fork Kaukonahua-B, scored 15, the lower limit of the category.

The highest P–HBIBI score was 27, at the Pauoa site in leeward O‘ahu and at Kahana Iki in windward O‘ahu. The Pauoa site scored poorly in most of the individual metrics, with

Table 14. Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) scores for the O‘ahu Wadeable Stream Assessment (WSA) benthic macroinvertebrate samples.

[Abundance in number per square meter; X, species present; –, species absent; NF, North Fork; SF, South Fork; P/A, Presence/Absence; No./m^2, number per square meter; P–HBIBI, Preliminary–Hawaiian Benthic Index of Biotic Integrity]

Station ID	Site name	Total abundance metric		Taxonomic richness metric[1]		Relative abundance of insecta metric	
		No./m^2	Score	No. of taxa	Score	Percentage of total	Score
HIO05518-002	Nu‘uanu-C	552	5	20	1	51.8	5
HIO05518-003	N. Hālawa-A	710	3	21	1	96.5	1
HIO05518-010	SF Kaukonahua-A	3,182	1	23	3	96.8	1
HIO05518-011	Waiāhole-B	5,849	1	17	1	74.7	5
HIO05518-013	Kamananui-B	730	3	16	1	90.2	1
HIO05518-018	Kalihi-C	346	5	25	3	24.7	5
HIO05518-023	Kahana-A	4,832	1	13	1	83.4	3
HIO05518-026	Kīpapa-A	1,229	3	18	1	91.5	1
HIO05518-027	Waikāne-B	3,686	1	20	1	94.4	1
HIO05518-029	Kamananui-A	982	3	25	3	83.3	3
HIO05518-035	Ha‘ikū	2,331	3	21	1	76.1	3
HIO05518-037	Anahulu-B	394	5	25	3	60.8	5
HIO05518-038	SF Kaukonahua-C	1,962	3	17	1	93.5	1
HIO05518-039	Waikāne-C	1,126	3	20	1	64.4	5
HIO05518-151	Kahana-C	2,463	3	18	1	76.2	3
HIO05518-160	Kahana-B	2,836	3	16	1	91.5	1
HIO05518-162	Kalihi-A	598	5	20	1	74.2	5
HIO05518-163	‘Āhuimanu	54	7	14	1	29.9	5
HIO05518-164	Kamo‘oali‘i	4,676	1	20	1	96.7	1
HIO05518-166	Kīpapa-C	2,948	3	24	3	49	5
HIO05518-171	Mānoa	1,521	3	15	1	86.6	3
HIO05518-175	Kahana Iki	474	5	24	3	43.8	5
HIO05518-177	SF Kaukonahua-B	533	5	13	1	85.3	3
HIO05518-181	Anahulu-C	5,675	1	19	1	83.6	3
HIO05518-182	NF Kaukonahua-B	700	5	16	1	90.1	1
HIO05518-183	Waiāhole-C	2,036	3	19	1	95.1	1
HIO05518-186	NF Kaukonahua-A	3,488	1	20	1	93.2	1
HIO05518-187	Lulumahu	209	5	16	1	39.1	5
HIO05518-191	Waimānalo	715	3	21	1	51.1	5
HIO05518-194	Pauoa	389	5	22	3	71.8	5
HIO05518-203	Hakipu‘u	893	3	19	1	60.8	5

[1] Metric determined using instream samples and observations.

Table 14.—Continued

Alien mollusk abundance metric		Amphipoda abundance metric		‘Ōpae P/A metric[1]		Crayfish P/A metric[1]		P-HBIBI score	P-HBIBI category
No./m²	Score	No./m²	Score	P/A	Score	P/A	Score		
28	3	155.2	5	–	3	X	3	25	Poor
0	1	1.2	3	–	3	–	1	13	Good
0	1	0	1	–	3	–	1	11	Good
0	1	0	1	X	1	–	1	11	Good
0	1	0	1	X	1	–	1	9	Good
0	1	1.6	3	–	3	–	1	21	Fair
0	1	0	1	X	1	–	1	9	Good
21.6	3	0	1	–	3	–	1	13	Good
0	1	0	1	X	1	–	1	7	Good
15.2	3	1.8	3	X	1	–	1	17	Fair
0	1	0	1	–	3	–	1	13	Good
109.6	5	0	1	X	1	–	1	21	Fair
4	3	0	1	–	3	–	1	13	Good
0	1	0	1	X	1	–	1	13	Good
0	1	0	1	X	1	–	1	11	Good
0	1	0	1	X	1	–	1	9	Good
0.8	3	1.2	3	X	1	X	3	21	Fair
10.4	3	2.4	3	–	3	X	3	25	Poor
0	1	8.5	3	–	3	X	3	13	Good
11.2	3	0	1	X	1	–	1	17	Fair
0	1	26.6	3	–	3	X	3	17	Fair
15.2	3	35.3	5	–	3	X	3	27	Poor
0	1	0	1	–	3	–	1	15	Fair
51.2	3	0	1	–	3	–	1	13	Good
10.4	3	0	1	–	3	–	1	15	Fair
0	3	0	1	X	1	–	1	9	Good
108.8	5	0	1	–	3	–	1	13	Good
0	1	0	1	–	3	X	3	19	Fair
3.2	3	0	1	–	3	–	1	17	Fair
3.2	3	44.8	5	–	3	X	3	27	Poor
75.2	3	0	1	–	3	–	1	17	Fair

Table 15. Dominant and second-dominant taxa collected in the O‘ahu Wadeable Stream Assessment (WSA) quantitative samples.

[sp., species; gr., group; –, not applicable]

Taxa	Group	Status	Dominant	Second-dominant
Cheumatopsyche analis	Trichoptera	Nonnative	21	5
Cricotopus bicinctus gr.	Chironomidae	Nonnative	2	7
Oligochaeta	(Worms)	Cryptogenic	2	3
Hydroptila sp.	Trichoptera	Nonnative	2	2
Neocaridina denticulata sinensis	Decapoda	Nonnative	1	1
Hemerodromia stellaris	Empididae	Nonnative	1	–
Melanoides tuberculata	Mollusca	Cryptogenic	1	–
Polypedilum sp.	Chironomidae	Nonnative	1	–
Ferrissia sharpi	Mollusca	Cryptogenic	–	4
Turbellaria	Flatworms	Cryptogenic	–	4
Hyalella sp.	Amphipoda	Cryptogenic	–	2
Eukiefferiella claripennis gr.	Chironomidae	Nonnative	–	1
Ostracoda	–	Cryptogenic	–	1
Physa sp.	Mollusca	Nonnative	–	1

a low total abundance, high amphipod abundance, and a low relative abundance of insects. Pauoa is a relatively small stream with high embeddedness (52 percent) and some of the poorest water quality of the Oʻahu sites, with the highest concentrations of dissolved inorganic carbon, calcium, acid neutralizing capacity, and the highest specific conductance. The Kahana Iki site scored similar to the Pauoa site and is also a relatively small, unappealing stream, congested with dense thickets of the indigenous Hau tree, *Hibiscus tiliaceus*, with a discharge of only 0.2 ft^3/s and the highest sulfate concentration measured.

In general, the P–HBIBI performed well in evaluating the Oʻahu WSA macroinvertebrate samples. This analysis highlighted some of the strengths and weaknesses of the index. Using this new information, some of the existing metrics were adjusted to improve their performance, other metrics were dropped, and new metrics were incorporated into a revised invertebrate community index for Oʻahu streams.

Refined Oʻahu Metrics and Index

The procedure of selecting new, appropriate metrics for Oʻahu followed the process described in the "Index Development" section. This process consisted of multivariate analysis, metric screening, metric selection, and metric scoring. The results of the nMDS analysis showed somewhat of a separation among leeward, central, and windward assemblages (figs. 9A–9B). This clustering is more apparent using the $\log(x + 1)$ transformed abundance data (fig. 9B), indicating that, although the community structures are basically the same among the regions, the abundances of the taxa are being influenced by regional differences. The results of the MRPP analyses also showed that the clusters of sites were statistically significant (Euclidean distance measure: proportional data: $A = 0.0393$, $p = 0.00999$; abundance data: $A = 0.0687$, $p = 0.000003$). The results of the DCA performed on the $\log(x + 1)$ transformed abundance data shows a similar clustering among leeward, central, and windward assemblages (fig. 10). Leeward sites were influenced by greater abundances of nonnative *Neocaridina* cherry shrimp, amphipods, and the nonnative chironomid *Corynoneura* sp., whereas central sites were more influenced by greater abundances of ʻōpae, Ephydridae, and the nonnative chironomid *Thienemanniella* sp.

Oʻahu Reference "Least Disturbed" Site Selection

The subset of "least disturbed" reference sites was selected from the initial 31 sampling sites using a series of screening procedures described in Wolff and Koch (2009). In essence, the sites were screened on the basis of on-site evaluations and objective criteria, including contributing basin land use, water-quality parameters, and physical-habitat characteristics. The final list of 10 reference sites included 6 central and 4 windward sites representing a range of elevations (table 16). None of the leeward Oʻahu sites were included as reference sites because of the generally poor water quality and degradation to the physical habitat (figs. 11–12). Scoring of the core metrics proceeded as described earlier.

The revised Oʻahu Invertebrate Community Index was developed using the same methods as described for the Maui ICI. The conditional values and scores are shown in table 17. In general, the scores for each metric are 1, 3, or 5, with lower scores indicating less impairment. The index score for each site is the sum of the individual metrics scores, with lower scores indicating less impairment. The results of these analyses are shown in table 18. The distributions of the metric scores and final ICI scores are shown in appendix C.

Total Macroinvertebrate Abundance Metric (Revised)

This metric was retained from the original P–HBIBI; however, the conditional scoring was revised accordingly. The top tier limit, indicative of sites with the greatest abundances of macroinvertebraes, was increased from 3,000/m^2 to 3,600/m^2. This is still well below the top tier limit for Maui of 7,900/m^2. The second tier limit was decreased from 700/m^2 to 475/m^2, again well below the Maui limit of 4,000/m^2. The additional tier indicative of the worst conditions (least abundance), < 200/m^2, was retained.

The distribution of the total macroinvertebrate abundance metric scores is shown in figure C19. The distribution of the actual total abundances is shown in figure C12. A total of 5 of the 31 sites (16.1 percent) scored in the top tier, 20 sites (64.5 percent) scored in the second tier, 5 sites scored in the third tier, and only 1 site (3.2 percent) scored in the bottom tier with only 53.6/m^2 at the ʻĀhuimanu site. This revision reduced the number of P–HBIBI top tier sites from 7 to 5, increased the number of second tier sites from 14 to 20, and reduced the number of third tier sites from 9 to 5.

Relative Abundance of Insecta Metric (Revised)

As described earlier in the Maui index, this metric was revised by subtracting the abundances of the native shrimp, ʻōpae, from the total abundance before calculating the percentage of Insecta. No hīhīwai were collected during the Oʻahu field studies, but they would have also been subtracted from the total abundance before the calculation. The conditional scoring was modified, retaining the top tier limit at 90 percent, but the bottom tier limit was reduced from 75 percent to 51 percent. This is lower than the Maui bottom tier limit of 73 percent.

The distribution of these metric scores is shown in figure C20. A total of 10 sites (32.3 percent) scored in the top tier, 16 sites (51.6 percent) scored in the middle tier, and 5 sites (16.1 percent) scored in the bottom tier. This revised metric reduced the number of P–HBIBI bottom tier sites from 13 to 5 and increased the number of P–HBIBI middle tier sites from 8 to 16.

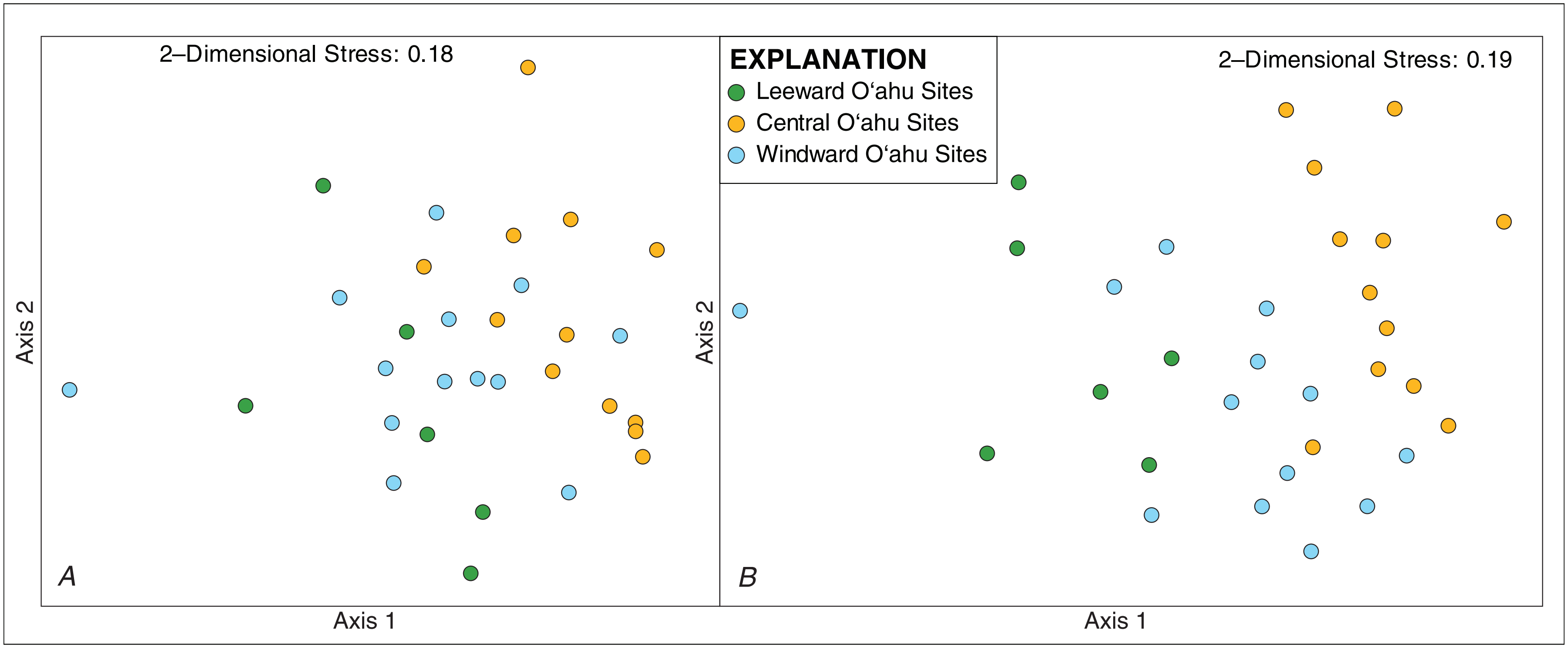


Figure 9. Nonmetric multidimensional scaling (nMDS) ordination of the O’ahu Wadeable Stream Assessment (WSA) quantitative macroinvertebrate samples using (*A*) arcsine-square root transformed proportional data and (*B*) log(x+1) transformed abundance data (logarithm of the sum of the abundance plus one, with abundance in number of organisms per square meter).

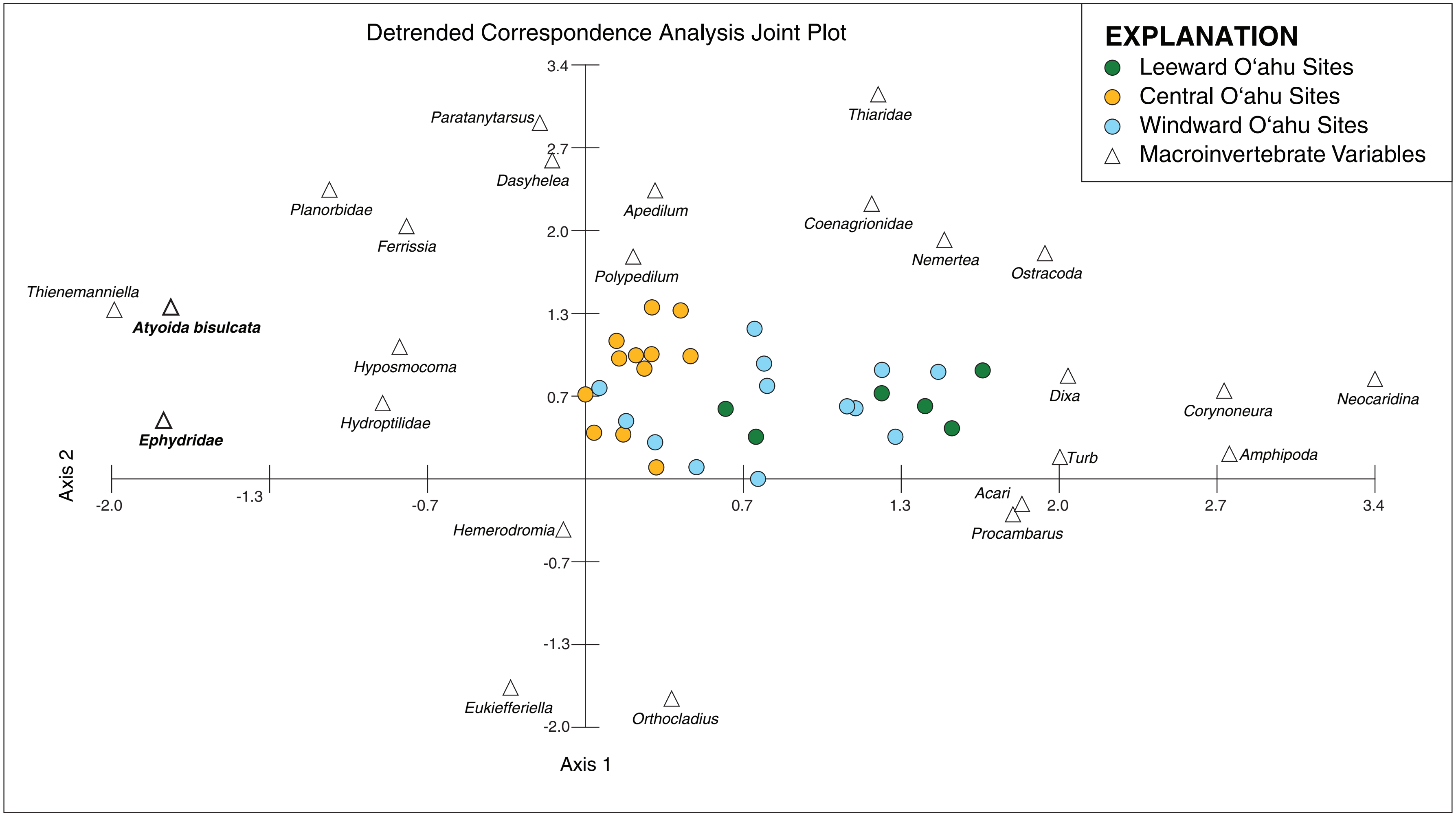


Figure 10. Detrended correspondence analysis (DCA) joint plot ordination of the O‘ahu Wadeable Stream Assessment (WSA) quantitative macroinvertebrate samples using log(x+1) transformed abundance data (logarithm of the sum of the abundance plus one, with abundance in number of organisms per square meter). Variables in **bold** are, or possibly are, native species.

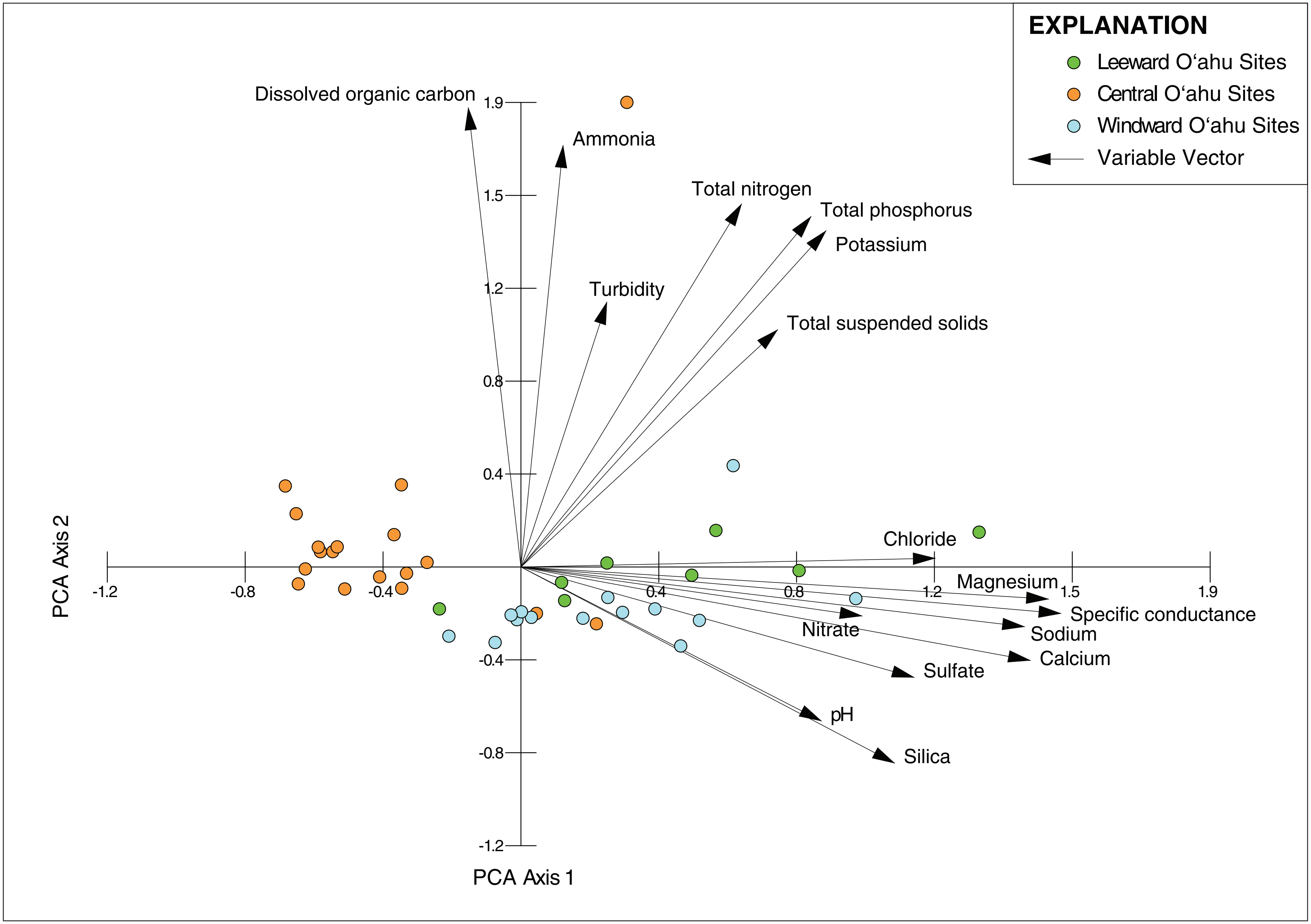


Figure 11. Principal components analysis (PCA) ordination of O‘ahu Wadeable Stream Assessment (WSA) study sites water-quality parameters. Eigenvalues: axis 1= 8.693, axis 2 = 5.041; percentage of variance: axis 1= 45.75, axis 2 = 26.53.

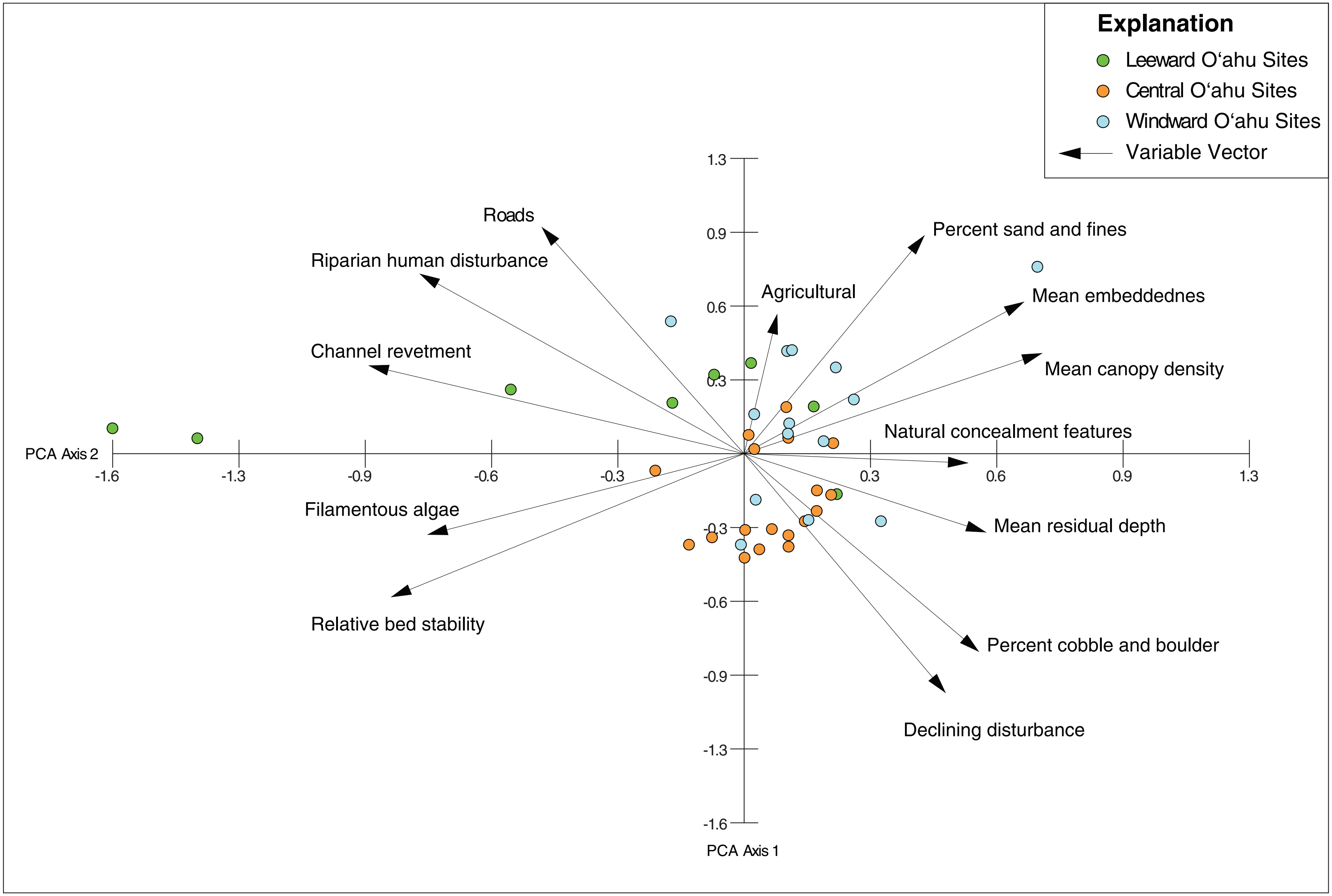


Figure 12. Principal components analysis (PCA) ordination of O‘ahu Wadeable Stream Assessment (WSA) study sites habitat characteristics. Eigenvalues: axis 1 = 6.09, axis 2 = 3.83; percentage of variance: axis 1 = 26.47, axis 2 = 16.63.

Table 16. O‘ahu Wadeable Stream Assessment (WSA) reference condition “least disturbed” sites.

Station ID	Stream name	Region	Altitude, in feet	Site name
HIO05518-010	South Fork Kaukonahua Stream	Central	984	SF Kaukonahua-A
HIO05518-011	Waiāhole Stream	Windward	13	Waiāhole-B
HIO05518-013	Kamananui Stream	Central	207	Kamananui-C
HIO05518-023	Kahana Stream	Windward	705	Kahana-A
HIO05518-026	Kīpapa Stream	Central	991	Kīpapa-A
HIO05518-027	Waikāne Stream	Windward	10	Waikāne-B
HIO05518-029	Kamananui Stream	Central	472	Kamananui-A
HIO05518-038	South Fork Kaukonahua Stream	Central	912	SF Kaukonahua-C
HIO05518-151	Kahana Stream	Windward	253	Kahana-C
HIO05518-186	North Fork Kaukonahua Stream	Central	1,194	NF Kaukonahua-A

Table 17. Conditional scoring for revised Invertebrate Community Index (ICI) metrics and index for O‘ahu.

[m^2, square meter; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

Metric	Condition	Score
Total abundance, in organisms/m^2	≥ 3,600	1
	< 3,600 and ≥ 475	3
	< 475 and ≥ 200	5
	< 200	7
Insecta relative abundance, in percent of Insecta from the total abundance minus the abundances of the native shrimp and snail	≥ 90	1
	< 90 and ≥ 51	3
	< 51	5
Trichoptera:Diptera ratio (Trichoptera abundance:nonnative Diptera abundance)	≥ 16.5	1
	< 16.5 and ≥ 0.6	3
	< 0.6	5
Revised alien mollusk abundance, in organisms/m^2	0	1
	> 0 and <11	3
	≥ 11	5
Amphipoda relative abundance, in percent	0	1
	> 0 and <0.5	3
	≥ 0.5	5
Turbellaria relative abundance, in percent	0	1
	> 0 and <6	3
	≥ 6	5
Alien crustacean presence/absence (for Red cherry shrimp (*Neocaridina denticulata sinensis*) and (or) Crayfish (*Procambarus clarkii*))	Absent	1
	Present	3
	Index score	**Category**
Final O‘ahu Invertebrate Community Index (sum of metric scores)	≤ 13	Good
	14–21	Fair
	> 21	Poor

Ratio of Nonnative Trichoptera and Diptera Metric (New)

As described in the Maui index, this metric compares the ratio of the insect families Trichoptera and Diptera and uses only nonnative species in the calculations. This metric was calculated by summing the abundances of the trichopterans (*Cheumatopsyche*, *Hydroptila* spp. and *Oxyethira*) and dividing by the sum of the abundances of the nonnative dipterans (predominantly chironomids: *Cricotopus*, *Paratanytarsus*, and *Eukiefferiella*; and the empidid: *Hemerodromia*). The top tier value, 16.5, is much higher than the top tier value on Maui at 2.5, showing that trichopterans outnumber nonnative dipterans at the “least disturbed” sites by a much wider margin on O‘ahu.

The distribution of these metric scores is shown in figure C21. A total of 8 sites (25.8 percent) scored in the top tier, 18 sites (58.1 percent) scored in the middle tier, and 5 sites (16.1 percent) scored in the bottom tier.

Relative Abundance of Amphipoda Metric (Revised)

This metric was revised in the new ICI by using the relative abundance rather than the absolute abundance of amphipods. As with the Insecta metric, the abundances of the native shrimp and snail were subtracted from the total abundance before calculating the relative abundance of the amphipods. The distribution of these metric scores is shown in figure C22. A total of 21 sites (67.7 percent) scored in the top tier, 4 sites (12.9 percent) scored in the middle tier, and 6 sites (19.4 percent) scored in the bottom tier. This revision increased the number of P–HBIBI bottom tier sites from 3 to 6 and decreased the number of middle tier sites from 7 to 4; the number of top tier sites was unchanged. Most of the bottom tier sites were located in leeward O‘ahu.

Relative Abundance of Turbellaria Metric (New)

This new metric was added to the O‘ahu ICI. Turbellarians are a class of organisms from the phylum Platyhelminthes and are commonly known as planaria or flatworms. Although the specimens from these studies were not identified below the class level, the planaria commonly found in Hawai‘i are of the genus *Dugesia* (fig. D42). Studies suggest that these organisms are not native to the Hawaiian Islands (Englund and others, 2000b). As with the other percentage-based metrics, the abundances of the native shrimp and snail were subtracted from the total abundance before the calculations. The distribution of these metric scores is shown in figure C23. A total of 12 sites (38.7 percent) scored in the top tier, 12 sites scored in the middle tier, and 7 sites (22.6 percent) scored in the bottom tier. The majority of the middle and bottom tier sites were in the windward and leeward regions.

Abundance of Nonnative or Cryptogenic Mollusks Metric (Revised)

This metric was revised by removing the nonnative Lymnaeidae *Pseudosuccinea columella* from the list of nonnative mollusks. An analysis of the distribution and abundance of this species did not show a relation with any of the disturbance gradients. The mollusks included in this metric were the Thiaridae, Physidae, Planorbidae, Corbiculidae, and Hydrobiidae. The bottom condition of this negative metric, indicative of disturbed sites, was lowered from 90/m^2 to 11/m^2.

The distribution of these metric scores is shown in figure C24. A total of 18 sites (58.1 percent) scored in the top tier, 6 sites (19.4 percent) scored in the middle tier, and 7 sites (22.6 percent) scored in the bottom tier. This revision increased the number of P–HBIBI bottom tier sites from 2 to 7, reduced the number of middle tier sites from 13 to 6, and increased the number of top tier sites from 16 to 18.

Nonnative Shrimp and Crayfish Presence/Absence Metric (Revised)

This presence/absence metric was revised by including the relatively recently introduced shrimp *Neocaridina denticulata sinensis* together with the much earlier introduced crayfish *Procambarus clarkii*. This nonnative shrimp, as discussed earlier, has been invading streams on O‘ahu and Kaua‘i since 1991. High densities of this shrimp were collected at a few of the O‘ahu WSA study sites. Both of these introduced species are considered pests and can negatively impact the native stream biota. This metric scored a 3 if either species was present at a site in the qualitative, quantitative, or observational data (table 18). In any future revisions of the ICI, these species might be split into separate metrics.

The distribution of the scores is shown in figure C25. A total of 19 sites (61.3 percent) scored 1 (where neither species was present), and 12 sites (38.7 percent) scored 3 (where at least 1 of the species was present). Both of these species were present at five sites, the crayfish was the only species present at three sites, and the shrimp was the only species present at four sites. This revision therefore increased the number of P–HBIBI bottom tier sites by 4.

Final O‘ahu Index Score

As in the P–HBIBI, the final community index was calculated as the sum of the individual metric scores (table 17). The distribution of the final O‘ahu ICI ratings for the O‘ahu WSA sites is shown in figure C26. A total of 10 sites (32.3 percent) were categorized as “good” quality streams, 16 sites (51.6 percent) were categorized as ”fair” quality streams, and 5 sites (16.1 percent) were categorized as ”poor” quality streams. Eleven of the 31 O‘ahu WSA sites were categorized differently using the revised O‘ahu ICI as compared to the P–HBIBI: the ratings of 2 sites dropped from “fair” to ”poor”;

Table 18. Revised metric and Oʻahu Invertebrate Community Index (ICI) scores for the Oʻahu Wadeable Stream Assessment (WSA) benthic macroinvertebrate samples.

[Abundance in number per square meter; Pct, percent; P/A, presence/absence; X, species present; –, species absent; NF, North Fork; SF, South Fork; No./m^2, number per square meter; italics, denotes change in category assignment; P–HBIBI, Preliminary–Hawaiian Benthic Index of Biotic Integrity]

Station ID	Site name	Total abundance metric		Trichoptera: Diptera metric		Relative abundance of Insecta metric		Revised mollusk abundance metric	
		No./m^2	Score	Ratio	Score	Pct	Score	No./m^2	Score
HIO05518-002	Nuʻuanu-C	552	3	37.7	1	52	3	28	5
HIO05518-003	N. Hālawa-A	710	3	0.6	3	96	1	0	1
HIO05518-010	SF Kaukonahua-A[2]	3,182	3	3.9	3	97	1	0	1
HIO05518-011	Waiāhole-B[2]	5,849	1	3.6	3	75	3	0	1
HIO05518-013	Kamananui-B[2]	730	3	7.6	3	91	1	0	1
HIO05518-018	Kalihi-C	346	5	0.2	5	25	5	0	1
HIO05518-023	Kahana-A[2]	4,832	1	2.1	3	84	3	0	1
HIO05518-026	Kīpapa-A[2]	1,229	3	16.5	1	91	1	21	5
HIO05518-027	Waikāne-B[2]	3,686	1	20.2	1	94	1	0	1
HIO05518-029	Kamananui-A[2]	982	3	4.1	3	84	3	16	5
HIO05518-035	Haʻikū	2,331	3	1.7	3	76	3	0	1
HIO05518-037	Anahulu-B	394	5	13.6	3	61	3	110	5
HIO05518-038	SF Kaukonahua-C[2]	1,962	3	117.8	1	94	1	4	3
HIO05518-039	Waikāne-C	1,126	3	2.3	3	64	3	0	1
HIO05518-151	Kahana-C[2]	2,463	3	4.2	3	76	3	0	1
HIO05518-160	Kahana-B	2,836	3	49.7	1	92	1	0	1
HIO05518-162	Kalihi-A	598	3	2	3	74	3	1	3
HIO05518-163	ʻĀhuimanu	54	7	0	5	30	5	10	3
HIO05518-164	Kamoʻoaliʻi	4,676	1	0.4	5	97	1	0	1
HIO05518-166	Kīpapa-C	2,948	3	3.3	3	49	5	11	3
HIO05518-171	Mānoa	1,520	3	0.8	3	87	3	0	1
HIO05518-175	Kahana Iki	474	5	2	3	44	5	15	5
HIO05518-177	SF Kaukonahua-B	533	3	63.1	1	85	3	0	1
HIO05518-181	Anahulu-C	5,675	1	0.1	5	84	3	51	5
HIO05518-182	NF Kaukonahua-B	700	3	51.2	1	90	3	6	3
HIO05518-183	Waiāhole-C	2,036	3	0.7	3	95	1	0	1
HIO05518-186	NF Kaukonahua-A[2]	3,488	3	0.8	3	93	1	0	1
HIO05518-187	Lulumahu	209	5	0.3	5	39	5	0	1
HIO05518-191	Waimānalo	715	3	2.5	3	51	3	3	3
HIO05518-194	Pauoa	389	5	19.3	1	72	3	0	1
HIO05518-203	Hakipuʻu	893	3	2.6	3	61	3	75	5

[1] Metric determined using instream samples and observations.

[2] Sample used as reference sample in calculating the metrics.

Table 18.—Continued

Relative abundance of Amphipoda metric		Relative abundance of Turbellaria metric		Nonnative Crustacea P/A metric[1]			Invertebrate Community Index		P–HBIBI category
Pct	Score	Pct	Score	Neocaridina	Crayfish	Score	Score	Category	
28.1	5	4.2	3	X	X	3	23	Poor	Poor
0.2	3	0	1	–	–	1	13	Good	Good
0	1	0	1	–	–	1	11	Good	Good
0	1	12.8	5	–	–	1	15	*Fair*	*Good*
0	1	0	1	–	–	1	11	Good	Good
0.5	5	0.7	3	–	–	1	25	*Poor*	*Fair*
0	1	0	1	–	–	1	11	Good	Good
0	1	0	1	X	–	3	15	*Fair*	*Good*
0	1	3.7	3	–	–	1	9	Good	Good
0.2	3	0	1	–	–	1	19	Fair	Fair
0	1	9.2	5	X	–	3	19	*Fair*	*Good*
0	1	0	1	–	–	1	19	Fair	Fair
0	1	0	1	–	–	1	11	Good	Good
0	1	7.7	5	–	–	1	17	*Fair*	*Good*
0	1	2.4	3	–	–	1	15	*Fair*	*Good*
0	1	0.7	3	–	–	1	11	Good	Good
0.2	3	1.6	3	–	X	3	21	Fair	Fair
4.5	5	17.9	5	–	X	3	33	Poor	Poor
0.2	3	1.5	3	–	X	3	17	*Fair*	*Good*
0	1	0	1	X	–	3	19	Fair	Fair
1.8	5	1.2	3	X	X	3	21	Fair	Fair
7.4	5	0.8	3	X	X	3	29	Poor	Poor
0	1	0	1	–	–	1	11	*Good*	*Fair*
0	1	0	1	–	–	1	17	*Fair*	*Good*
0	1	0.2	3	–	–	1	15	Fair	Fair
0	1	3.6	3	–	–	1	13	Good	Good
0	1	0	1	–	–	1	11	Good	Good
0	1	23.4	5	X	X	3	25	*Poor*	*Fair*
0	1	16.2	5	X	-	3	21	Fair	Fair
11.5	5	1.6	3	X	X	3	21	*Fair*	*Poor*
0	1	6.1	5	–	–	1	21	Fair	Fair

7 sites dropped from "good" to "fair"; 1 site increased from "poor" to "fair"; and 1 site increased from "fair" to "good" (table 18). The Oʻahu ICI categorized the sites more accurately based on the ranking of the sites using the habitat and water-quality information.

Other Changes to the P–HBIBI

Two metrics from the P–HBIBI were not included in the revised Oʻahu Invertebrate Community Index. This included the taxa richness metric and the native shrimp presence/absence metric. The richness metric was difficult to calculate because many specimens were indentified only to the family level. Within some of these families are a mixture of native and nonnative species; the native species tend to be more sensitive to disturbance whereas the nonnatives tend to be more tolerant of disturbances. This dichotomy made it difficult to use this metric in any meaningful way. A test of nonnative chironomid species richness was also unsuccessful at differentiating among the sites, but may become more effective in making such distinctions as more data are collected. The presence/absence of the native shrimp metric was not considered in the revised ICI because many of the "least disturbed" stream sites on Oʻahu had impediments, such as gamefish, that may have prevented the shrimp from inhabiting these sites. This metric may be useful in a statewide index, as it successfully differentiated between streams on Oʻahu and Maui, where ʻōpae were much more abundant.

Evaluation of the P–HBIBI Sites

The Oʻahu NAWQA sites from which data were used to develop the P–HBIBI were evaluated with the revised Oʻahu ICI (table 19; fig. 13). Only 3 of the 18 Oʻahu samples (16 sites) were categorized differently with the revised index: 2 repeat samples from1 site, Waiheʻe B, dropped from "good" to "fair" because of higher percentages of Turbellaria in 1999 and an abundance of nonnative mollusks in 2001; and 1 site, Nuʻuanu, which was a "fair" site in the P–HBIBI, dropped to "poor" in the new ICI. Only 1 site, Waiakeakua, scored in the top tier in the Trichoptera–Diptera ratio metric whereas 5 sites scored in the bottom tier. The distribution of the individual metric scores and the final ICI scores are shown in figures C27–C34.

Combined Invertebrate Community Index

The considerable differences among the benthic macroinvertebrate assemblages on Maui and Oʻahu limit the capability of developing rigorous metrics and a multimetric index that effectively assesses the stream quality of each of the streams on both islands. A statewide ICI would, as the name implies, also require sampling of macroinvertebrates and habitats on all of the main Hawaiian Islands. As a starting point, however, metrics from both the Maui and Oʻahu ICI's were tested, scored, and combined into an index. In general, this combined index highlights some of the differences between the stream communities on each island. This combined ICI is intended to provide information that can be used, in conjunction with other available information, to help HIDOH prioritize their efforts to identify problem areas on a statewide basis. After these problem areas are identified, the island-wide ICIs can be used to more accurately assess the quality of individual stream reaches so that the HIDOH can prioritize their management efforts on the most impaired streams.

Comparison of Oʻahu and Maui Benthic Invertebrate Communities

Comparisons between the benthic macroinvertebrate assemblages from Maui and Oʻahu illustrated some noticeable differences. The results of an nMDS analysis illustrates a separation between the Oʻahu and Maui assemblages (figs. 14*A*–14*B*). The relatively tight clustering in both the percentage and abundance datasets indicated that both the structure (taxa present and the relative abundances of those taxa) and taxa abundances of the assemblages were heavily influenced by differences between the islands. Additionally, the Maui samples clustered much more tightly together than did the Oʻahu samples, indicating that the Maui macroinvertebrate assemblages, species diversity, and abundances were more similar to each other than were the Oʻahu assemblages. The results of the MRPP analyses showed that the clusters were significantly different (Euclidean distance measure: proportional data, $A = 0.0694$, $p < 0.0000$; abundance data, $A = 0.0868$, $p < 0.0000$).The results of the DCA performed on the $\log(x + 1)$ transformed abundance data also illustrated a similarly tight clustering among Oʻahu and Maui assemblages (fig. 15). The Maui assemblages were influenced by greater abundances of many of the native species, including *Megalagrion* damselfly naiads, *Telmatogeton* midges, hīhīwai, and ʻōpae. Except for the ʻōpae, these native species were not observed in any of the Oʻahu WSA samples. The snail family Lymnaeidae and the insect family Ephydridae both contain native and nonnative species, so that without finer taxonomic resolution, it would be speculation to say that there were more natives of these families on Maui; however, they were both more abundant on Maui than on Oʻahu.

An obvious difference between the faunal assemblages of the Oʻahu WSA sites and the Maui sites is that the entire native faunal assemblage was more nearly intact at the Maui streams sites. The native gobies *Lentipes concolor* (ʻoʻopu ʻalamoʻo), *Sicyopterus stimpsoni* (ʻoʻopu nōpili), and *Awaous guamensis* (ʻoʻopu nākea) were much more widely distributed and were far more abundant in Maui streams than in Oʻahu streams. So too were the native mountain shrimp *Atyoida bisulcata* (ʻōpaekalaʻole), the native mollusk *Neritina granosa* (hīhīwai), the native damselflies *Megalagrion* spp. (pinao ʻula), the native midge *Telmatogeton* spp., and the likely native Ephydridae. Some of these species, including ʻoʻopu ʻalamoʻo, hīhīwai, and *Telmatogeton* are rarely seen in Oʻahu

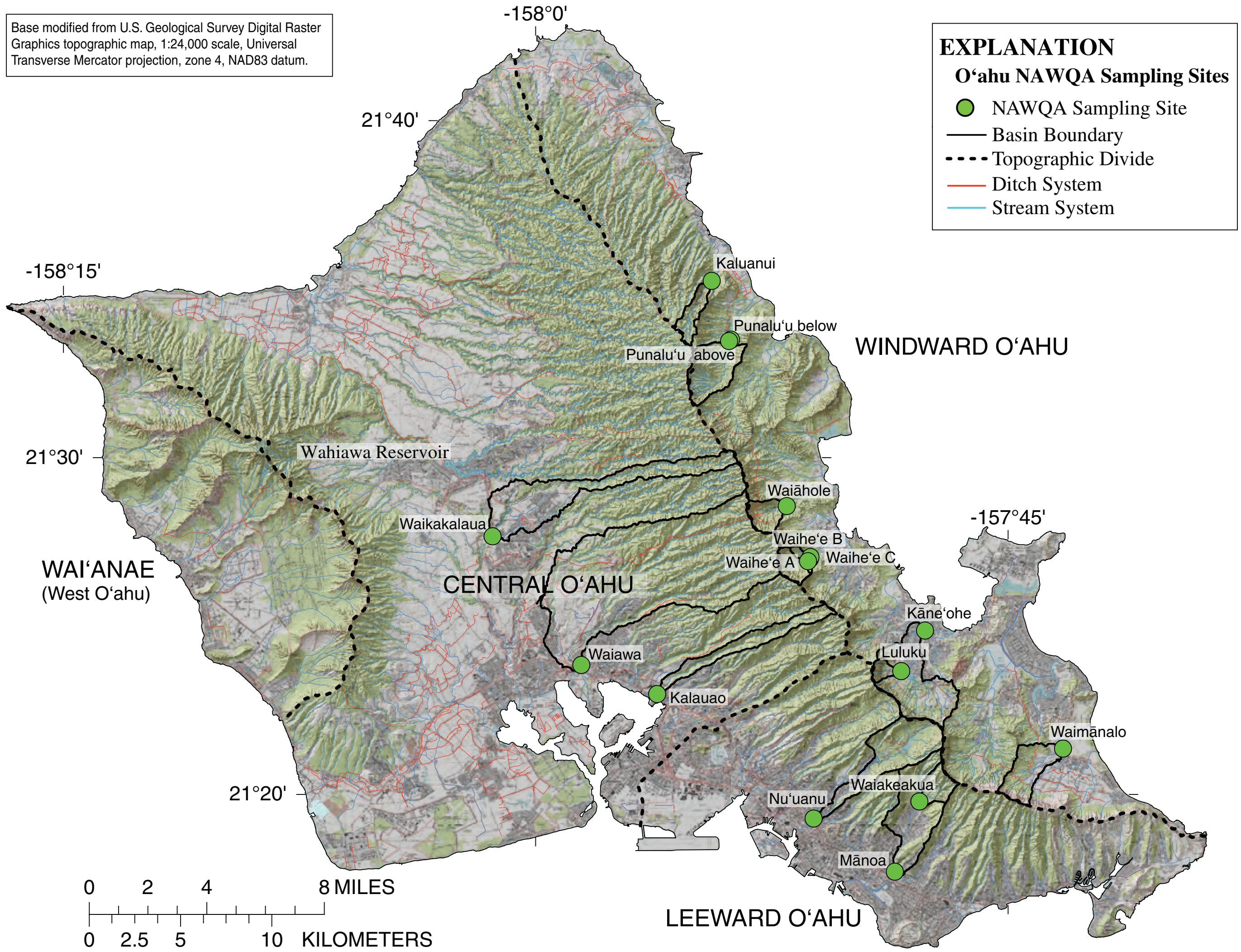


Figure 13. Locations of the National Water-Quality Assessment (NAWQA) program sampling sites on O‘ahu.

Table 19. Revised metric and Oʻahu Invertebrate Community Index (ICI) scores for the Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) Oʻahu benthic macroinvertebrate samples.

[Abundance in number per square meter; Pct, percent; P/A, presence/absence; X, species present; –, species absent; No./m^2, number per square meter; italics, denotes change in category assignment; P–HBIBI, Preliminary–Hawaiian Benthic Index of Biotic Integrity]

Station ID	Site name	Total abundance metric		Trichoptera: Diptera metric		Relative abundance of Insecta metric		Revised mollusk abundance metric	
		No./m^2	Score	Ratio	Score	Pct	Score	No./m^2	Score
DOHINV001	Waimānalo	9,532	1	8.5	3	84	3	185	5
DOHINV002	Kalauao	2,207	3	0	5	87	3	238	5
DOHINV003	Nuʻuanu	3,821	1	0.3	5	71	3	56	3
DOHINV004	Luluku	773	3	0.8	3	89	3	0	1
DOHINV005	Waiawa	1,729	3	0.1	5	91	1	90	3
NAWQA-0010	Mānoa	302	5	0.8	3	50	5	102	5
NAWQA-0020	Waiheʻe B–99	3,618	1	2.8	3	88	3	0	1
NAWQA-0040	Waiāhole	2,421	3	4.4	3	96	1	0	1
NAWQA-0050	Punaluʻu above weir	10,355	1	6	3	97	1	0	1
NAWQA-0060	Punaluʻu below weir	4,216	1	6.3	3	89	3	0	1
NAWQA-0070	Waikakalaua	254	5	0.5	5	47	5	53	3
NAWQA-0080	Waiakeakua	273	5	27.2	1	93	1	0	1
NAWQA-0090	Kāneʻohe	1,022	3	1.6	3	36	5	375	5
NAWQA-0100	Kaluanui	3,374	3	0.2	5	23	5	1	3
NAWQA-0200	Waiheʻe A–00	10,354	1	3.3	3	93	1	0	1
NAWQA-0300	Waiheʻe B–00	6,472	1	5.6	3	95	1	0	1
NAWQA-0400	Waiheʻe C–00	5,594	1	11.9	3	99	1	0	1
NAWQA-0500	Waiheʻe B–01	6,146	1	7.3	3	99	1	16	3

Table 19.—Continued

Relative abundance of Amphipoda metric		Relative abundance of Turbellaria metric		Nonnative Crustacea P/A metric[1]			Invertebrate Community Index		P–HBIBI category
Pct	Score	Pct	Score	Neocaridina	Crayfish	Score	Score	Category	
5.1	5	0	1	X	–	3	21	Fair	Fair
0	1	0	1	–	–	1	19	Fair	Fair
0.6	5	1.5	3	X	X	3	25	*Poor*	*Fair*
1.6	5	0	1	X	X	3	19	Fair	Fair
0	1	0.4	3	–	X	3	21	Fair	Fair
7.4	5	4	3	–	X	3	29	Poor	Poor
0	1	7.7	5	–	X	3	17	*Fair*	*Good*
0	1	0.6	3	–	–	1	13	Good	Good
0	1	0.8	3	–	–	1	11	Good	Good
0	1	2.7	3	–	–	1	13	Good	Good
0.6	5	0	1	X	X	3	29	Poor	Poor
0	1	0.3	3	X	X	3	15	Fair	Fair
0.7	5	3.3	3	–	X	3	27	Poor	Poor
0	1	0	1	–	–	1	19	Fair	Fair
0	1	0.6	3	–	X	3	13	Good	Good
0	1	0.6	3	–	X	3	13	Good	Good
0	1	0.3	3	–	X	3	13	Good	Good
0	1	0	1	X	X	3	15	*Fair*	*Good*

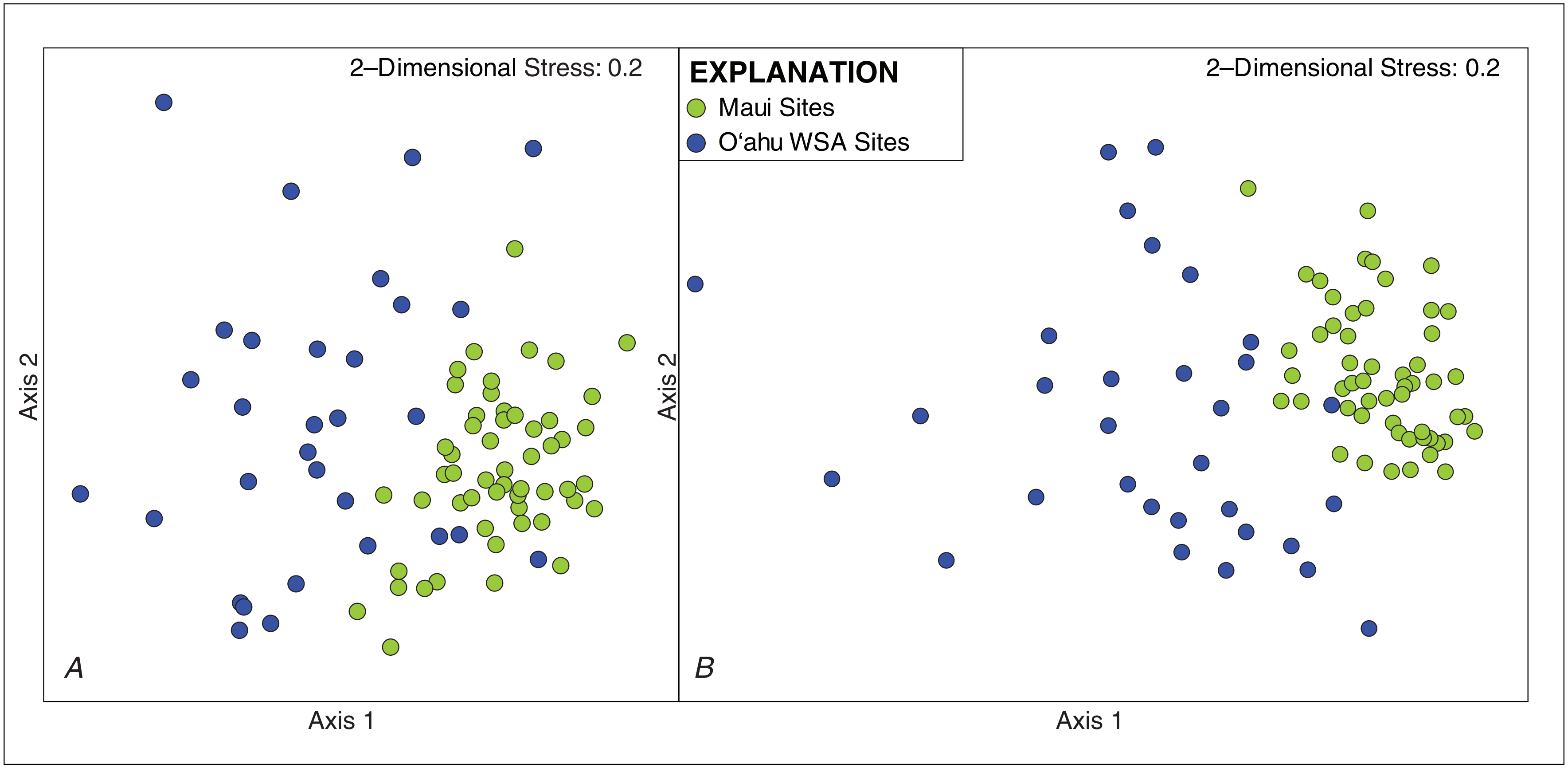


Figure 14. Nonmetric multidimensional scaling (nMDS) ordination of the Maui and O’ahu Wadeable Stream Assessment (WSA) quantitative macroinvertebrate samples using (*A*) arcsine-square root transformed proportional data and (*B*) log(x+1) transformed abundance data (logarithm of the sum of the abundance plus one, with abundance in number of organisms per square meter).

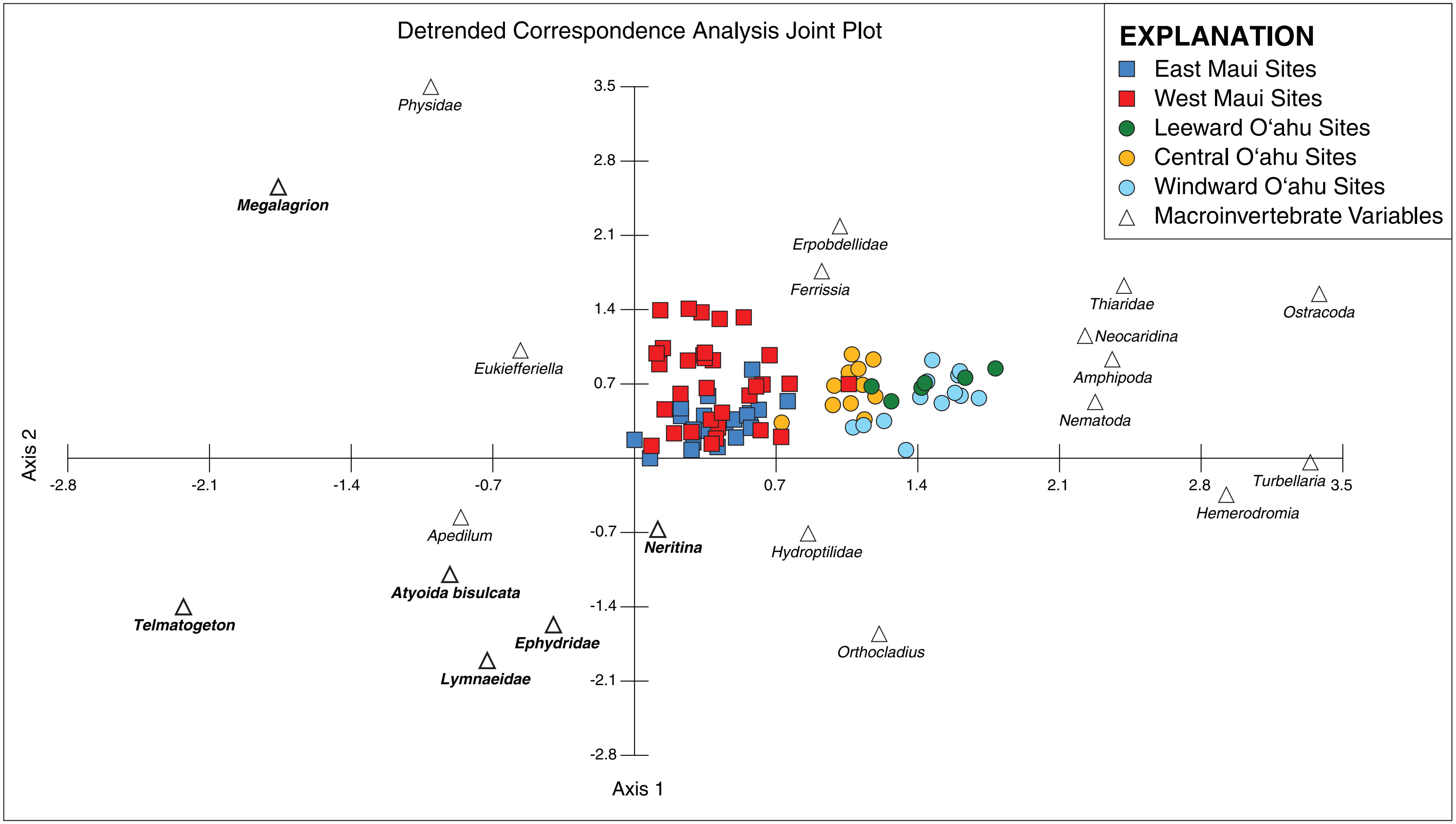


Figure 15. Detrended correspondence analysis (DCA) joint plot ordination of the Maui and O‘ahu Wadeable Stream Assessment (WSA) quantitative macroinvertebrate samples using log(x+1) transformed abundance data (logarithm of the sum of the abundance plus one, with abundance in number of organisms per square meter). Variables in **bold** are, or possibly are, native species.

streams, although small populations have been observed on occasion in the more “pristine” streams.

Another obvious difference between the O‘ahu and Maui faunal assemblages was that the nonnative faunal assemblage was much more diverse, more widely distributed, and more abundant in O‘ahu streams. This included a wide assortment of nonnative fish, mollusks, and crustaceans that were observed in O‘ahu streams but were either absent from or less frequently observed in Maui streams. This also included the nonnative Empididae (aquatic dance fly) *Hemerodromia stellaris,* the cherry shrimp, *Neocaridina denticulata sinensis,* the crayfish *Procambarus clarkii*, and a number of chironomid species all of which were commonly found in O‘ahu streams, but were absent from or not commonly observed in the streams on Maui.

Combined ICI Development

The development of the combined ICI followed the same basic procedures as those used for the island-wide ICI’s. The list of metrics was narrowed to the existing metrics from both the Maui and O‘ahu ICI’s. The set of “least impaired” reference condition sites from both islands were combined and used to calculate the top or bottom tier values. The rest of the sites were combined and used to calculate the middle tier values. The conditions and scores for each metric and the ICI conditions and stream-quality categories are shown in table 20. The combined ICI metrics and index scores are shown in tables 21–23. The distributions of the combined ICI final scores are shown in figures B61–B62 and C35–C36.

Total Macroinvertebrate Abundance Metric

This metric was retained from the original P–HBIBI and used in both island-wide ICI’s, but the conditional values were modified accordingly. Greater total macroinvertebrate abundances are associated with higher stream quality. The conditional values for the combined index set the top tier limit, indicative of the best sites, as greater than or equal to 5,580/m^2 (table 20). This is less than the 7,900/m^2 determined in the Maui ICI and greater than the 3,600/m^2 determined for the O‘ahu ICI. The second tier limit was set at less than 5,580/m^2 and greater than or equal to 657/m^2. The additional bottom tier limit, < 200/m^2, indicative of the worst conditions, was retained.

A total of 7 of the 40 Maui sites (17.5 percent; 12 of the 54 samples) and 2 of the 31 O‘ahu WSA sites (6.5 percent) scored in the top tier; 30 Maui sites (75 percent; 39 samples) and 20 O‘ahu WSA sites (64.5 percent) scored in the second tier; 2 Maui sites (5 percent; 2 samples) and 8 O‘ahu WSA sites (25.8 percent) scored in the third tier; and 1 Maui site (2.5 percent; 1 sample) and 1 O‘ahu WSA site (3.2 percent) scored in the bottom tier (tables 21–22).

Relative Abundance of Insecta Metric

This metric, in its modified format, subtracting the abundances of the native shrimp, ‘ōpae, and the native snail, hīhīwai, from the total sample abundances before the calculation, was used in both the Maui and O‘ahu ICI’s and was included in the combined index. Greater relative abundances of insects in the samples are associated with higher stream quality. The conditional values retained the top tier at 90 percent but adjusted the bottom tier to 64 percent.

A total of 21 of the 40 Maui sites (52.5 percent; 31 samples) and 11 of the 31 O‘ahu WSA sites (35.5 percent) scored in the upper tier; 16 Maui samples (40 percent; 19 samples) and 11 O‘ahu WSA samples (35.5 percent) scored in the second tier; and 3 Maui sites (7.5 percent; 4 samples) and 9 O‘ahu WSA sites (29.0 percent) scored in the bottom tier (tables 21–22).

Relative Abundance of Amphipoda Metric

This metric was modified from its original format in the P–HBIBI from abundance to relative abundance, again subtracting the abundances of the native shrimp, ‘ōpae, and the native snail, hīhīwai, from the total sample abundances before the calculation, and used in the O‘ahu ICI. Increasing relative abundances of amphipods are associated with decreasing stream quality. This metric was not used in the Maui ICI because amphipods were present in only one quantitative sample.

This metric highlights one of the differences between the Maui stream biota and the O‘ahu stream biota, with a majority of Maui sites scoring in the top tier. A total of 39 of the 40 Maui sites (97.5 percent; 53 samples) and 21 of the 31 O‘ahu WSA sites (67.7 percent) scored in the upper tier; 1 Maui site (2.5 percent; 1 sample) and 4 O‘ahu WSA sites (12.9 percent) scored in the second tier; and no Maui sites and 6 O‘ahu WSA sites (19.4 percent) scored in the bottom tier (tables 21–22).

Relative Abundance of Turbellaria Metric

This new metric was added to the O‘ahu ICI but was not included in the Maui ICI because of the rarity of turbellarians, commonly known as planaria or flatworms, in the Maui quantitative samples (table 21). Again, the relative abundances were calculated after subtracting the abundances of the native shrimp, ‘ōpae, and the native snail, hīhīwai, from the total sample abundances. Greater relative abundances of turbellarians were associated with decreasing stream quality.

This metric highlights another of the differences between the Maui and O‘ahu stream assemblages. A total of 37 of the 40 Maui sites (92.5 percent; 50 samples) and 12 of the 31 O‘ahu WSA sites (38.7 percent) scored in the top tier; 1 Maui site (2.5 percent; 1 sample) and 6 O‘ahu WSA sites (19.3 percent) scored in the second tier; and 2 Maui sites (5.0 percent; 3 samples) and 13 O‘ahu WSA sites (41.9 percent) scored in the bottom tier (tables 21–22).

Native Macroinvertebrate Presence/Absence

The presence or absence metrics of four of the native aquatic macroinvertebrates, determined on the basis of the quantitative, qualitative, and observational data, that were included in the Maui ICI were slightly modified and included

Table 20. Conditional scoring for combined Invertebrate Community Index (ICI) metrics and index for Maui and O‘ahu

[m^2, square meter; <, less than; ≤, less than or equal to; >, greater than; ≥, greater than or equal to]

Metric	Condition	Score
Total abundance, in organisms/m^2	≥ 5,580	1
	< 5,580 and ≥ 657	3
	< 657 and ≥ 200	5
	< 200	7
Insecta relative abundance, in percent of Insecta from the total abundance minus the abundances of the native shrimp and snail	≥ 90	1
	< 90 and ≥ 64	3
	< 64	5
Amphipoda relative abundance, in percent	0	1
	> 0 and <0.5	3
	≥ 0.5	5
Turbellaria relative abundance, in percent	0	1
	> 0 and <1.5	3
	≥ 1.5	5
Native species richness	**Presence/Absence**	**Score**
Atyoida bisulcata	Present	1
(‘ōpaekala‘ole or mountain ‘ōpae)	Absent	2
Neritina granosa	Present	1
(hīhīwai)	Absent	2
Telmatogeton spp.	Present	1
(torrent midges)	Absent	2
Megalagrion damselflies (adults and/or naiads)	Present	1
(pinao ‘ula)	Absent	2
	Index score	**Category**
Final Combined Invertebrate Community Index for Maui and O‘ahu (sum of metric scores)	≤ 13	Good
	14–18	Fair
	> 18	Poor

Table 21. Combined Invertebrate Community Index (ICI) metric and index scores for the Maui benthic macroinvertebrate samples.

[Abundance in number per square meter; Pct, percent; P/A, presence/absence; X, species present; –, species absent; No./m^2, number per square meter; rst, re-sorted; rep, replicate; rpt, repeat]

Station ID	Site name	Sample type	Total abundance metric		Relative abundance of Insecta metric		Relative abundance of Amphipoda metric	
			No./m^2	Score	Pct	Score	Pct	Score
HI_MAUI_09-001	Kopiliʻula-A		1,231	3	89	3	0	1
HI_MAUI_09-002	W. Wailua Iki-B		330	5	73	3	0	1
HI_MAUI_09-003	Wailua Nui-B		1,418	3	97	1	0	1
HI_MAUI_09-004	Hanawī-A[2]		7,911	1	90	1	0	1
HI_MAUI_09-004	Hanawī-A	rst	10,478	1	99	1	0	1
HI_MAUI_09-004	Hanawī-A	rep	6,662	1	87	3	0	1
HI_MAUI_09-004	Hanawī-A	rep, rst	7,525	1	96	1	0	1
HI_MAUI_09-005	W. Wailua Iki-A		4,499	3	76	3	0	1
HI_MAUI_09-006	Haipuaʻena		3,196	3	73	3	0	1
HI_MAUI_09-007	Pālauhulu-C		6,241	1	91	1	0	1
HI_MAUI_09-008	E. Wailua Nui-A		2,571	3	88	3	0	1
HI_MAUI_09-009	Pālauhulu-A[2]		9,365	1	89	3	0	1
HI_MAUI_09-010	Honomanū		323	5	95	1	0	1
HI_MAUI_09-011	Kōlea		23,137	1	94	1	0	1
HI_MAUI_09-011	Kōlea	rst	9,869	1	96	1	0	1
HI_MAUI_09-012	Hanawī-C[2]		5,305	3	93	1	0	1
HI_MAUI_09-013	Waiohue2		1,675	3	97	1	0.2	3
HI_MAUI_09-014	Kopiliʻula-B		3,758	3	67	3	0	1
HI_MAUI_09-014	Kopiliʻula-B	rst	2,271	3	68	3	0	1
HI_MAUI_09-015	Hanawī-B[2]		6,812	1	97	1	0	1
HI_MAUI_09-015	Hanawī-B	rep	4,234	3	99	1	0	1
HI_MAUI_09-016	Nuaʻailua		166	7	32	5	0	1
HI_MAUI_09-017	Waikapū-C		7,053	1	95	1	0	1
HI_MAUI_09-018	Waikapū-A		5,012	3	83	3	0	1
HI_MAUI_09-019	Kanahā2		3,224	3	97	1	0	1
HI_MAUI_09-020	Honolua		1,129	3	73	3	0	1
HI_MAUI_09-020	Honolua	rep	984	3	63	5	0	1
HI_MAUI_09-021	Honokōwai		4,146	3	98	1	0	1
HI_MAUI_09-022	Olowalu-B		1,690	3	74	3	0	1
HI_MAUI_09-022	Olowalu-B	rep	1,523	3	95	1	0	1
HI_MAUI_09-023	Waiheʻe-B open		740	3	97	1	0	1
HI_MAUI_09-023	Waiheʻe-B open	rep	1,313	3	95	1	0	1
HI_MAUI_09-024	Waiheʻe-B closed		1,207	3	81	3	0	1

Table 21.—Continued

Relative abundance of Turbellaria metric		ʻŌpae P/A metric[1]		Megalgrion P/A metric[1]		Hīhīwai P/A metric[1]		Telmatogeton P/A metric[1]		Combined Invertebrate Community Index	
Pct	Score	P/A	Score	P/A	Score	P/A	Score	P/A	Score	Score	Category
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	X	1	X	1	X	1	–	2	15	Fair
0	1	X	1	–	2	X	1	–	2	12	Good
0	1	X	1	X	1	–	2	X	1	9	Good
0	1	X	1	X	1	–	2	X	1	9	Good
0	1	X	1	X	1	–	2	X	1	11	Good
0	1	X	1	X	1	–	2	X	1	9	Good
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	X	1	–	2	X	1	–	2	10	Good
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	X	1	–	2	X	1	–	2	12	Good
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	X	1	X	1	–	2	X	1	9	Good
0	1	X	1	X	1	–	2	X	1	9	Good
0	1	X	1	X	1	–	2	–	2	12	Good
0	1	X	1	–	2	X	1	–	2	14	Fair
0	1	X	1	X	1	X	1	–	2	13	Good
0	1	X	1	X	1	X	1	–	2	13	Good
0	1	X	1	X	1	X	1	X	1	8	Good
0	1	X	1	X	1	X	1	X	1	10	Good
0	1	X	1	X	1	X	1	–	2	19	Poor
0	1	–	2	X	1	–	2	–	2	11	Good
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	–	2	X	1	–	2	X	1	12	Good
0	1	–	2	X	1	–	2	X	1	14	Fair
0	1	–	2	X	1	–	2	X	1	16	Fair
0	1	–	2	X	1	–	2	X	1	12	Good
0	1	X	1	X	1	–	2	–	2	14	Fair
0	1	X	1	X	1	–	2	–	2	12	Good
0	1	X	1	X	1	–	2	–	2	12	Good
0	1	X	1	X	1	–	2	–	2	12	Good
0.8	3	X	1	X	1	–	2	–	2	16	Fair

Table 21. Combined Invertebrate Community Index (ICI) metric and index scores for the Maui benthic macroinvertebrate samples..—Continued

[Abundance in number per square meter; Pct, percent; P/A, presence/absence; X, species present; –, species absent; No./m^2, number per square meter; rst, re-sorted; rep, replicate; rpt, repeat]

Station ID	Site name	Sample type	Total abundance metric		Relative abundance of Insecta metric		Relative abundance of Amphipoda metric	
			No./m^2	Score	Pct	Score	Pct	Score
HI_MAUI_09-025	Waihe‘e-C		1,619	3	50	5	0	1
HI_MAUI_09-026	Waihe‘e-A[2]		9,453	1	99	1	0	1
HI_MAUI_09-026	Waihe‘e-A	rpt-1	4,061	3	99	1	0	1
HI_MAUI_09-026	Waihe‘e-A	rpt-2	10,476	1	99	1	0	1
HI_MAUI_09-027	N. Waiehu-C		657	3	89	3	0	1
HI_MAUI_09-028	N. Waiehu-A		1,195	3	98	1	0	1
HI_MAUI_09-028	N. Waiehu-A	rep	1,431	3	86	3	0	1
HI_MAUI_09-029	S. Waiehu-C		2,300	3	98	1	0	1
HI_MAUI_09-030	S. Waiehu-A[2]		1,640	3	96	1	0	1
HI_MAUI_09-030	S. Waiehu-A	rep	1,598	3	98	1	0	1
HI_MAUI_09-031	‘Īao-C		2,028	3	95	1	0	1
HI_MAUI_09-031	‘Īao-C	rep	4,161	3	95	1	0	1
HI_MAUI_09-032	‘Īao-A[2]		5,311	3	99	1	0	1
HI_MAUI_09-033	Kaua‘ula		4,542	3	87	3	0	1
HI_MAUI_09-034	Launiupoko		2,019	3	64	3	0	1
HI_MAUI_09-035	Ukumehame-B		3,992	3	95	1	0	1
HI_MAUI_09-036	Waiehu		1,276	3	88	3	0	1
HI_MAUI_09-037	Makamaka‘ole-A[2]		4,161	3	99	1	0	1
HI_MAUI_09-038	Makamaka‘ole-B		1,508	3	53	5	0	1
HI_MAUI_09-039	Ukumehame-A		3,271	3	96	1	0	1
HI_MAUI_09-040	Olowalu-A		1,857	3	89	3	0	1

[1] Metric determined using instream samples and observations.

[2] Sample used as reference sample in calculating the metrics.

Table 21.—Continued.

Relative abundance of Turbellaria metric		‘Ōpae P/A metric[1]		Megalgrion P/A metric[1]		Hīhīwai P/A metric[1]		Telmato-geton P/A metric[1]		Combined Invertebrate Community Index	
Pct	Score	P/A	Score	P/A	Score	P/A	Score	P/A	Score	Score	Category
0	1	X	1	–	2	–	2	–	2	17	Fair
0	1	X	1	X	1	–	2	X	1	9	Good
0	1	X	1	X	1	–	2	X	1	11	Good
0	1	X	1	X	1	–	2	X	1	9	Good
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	X	1	X	1	–	2	X	1	11	Good
0	1	X	1	X	1	–	2	X	1	13	Good
0	1	X	1	–	2	–	2	–	2	13	Good
0	1	X	1	X	1	–	2	–	2	12	Good
0	1	X	1	X	1	–	2	–	2	12	Good
1.5	5	X	1	–	2	–	2	X	1	16	Fair
1.7	5	X	1	–	2	–	2	X	1	16	Fair
0	1	–	2	X	1	X	1	X	1	11	Good
0	1	–	2	X	1	–	2	X	1	14	Fair
0	1	–	2	X	1	–	2	X	1	14	Fair
0	1	–	2	–	2	X	1	–	2	13	Good
3.6	5	X	1	–	2	–	2	–	2	19	Poor
0	1	–	2	–	2	–	2	X	1	13	Good
0	1	X	1	–	2	X	1	–	2	16	Fair
0	1	X	1	X	1	–	2	–	2	12	Good
0	1	X	1	X	1	–	2	–	2	14	Fair

Table 22. Combined Invertebrate Community Index (ICI) metric and index scores for the O‘ahu Wadeable Stream Assessment (WSA) benthic macroinvertebrate samples.

[Abundance in number per square meter; Pct, percent; P/A, presence/absence; X, species present; –, species absent; No./m^2, number per square meter]

Station ID	Site name	Total abundance metric		Relative abundance of Insecta metric		Relative abundance of Amphipoda metric		Relative abundance of Turbellaria metric	
		No./m^2	Score	Pct	Score	Pct	Score	Pct	Score
HIO05518-002	Nu‘uanu-C	552	5	52	5	28.1	5	4.2	5
HIO05518-003	N. Hālawa-A	710	3	96	1	0.2	3	0	1
HIO05518-010	SF Kaukonahua-A[2]	3,182	3	97	1	0	1	0	1
HIO05518-011	Waiāhole-B[2]	5,849	1	75	3	0	1	12.8	5
HIO05518-013	Kamananui-B[2]	730	3	91	1	0	1	0	1
HIO05518-018	Kalihi-C	346	5	25	5	0.5	5	0.7	3
HIO05518-023	Kahana-A[2]	4,832	3	84	3	0	1	0	1
HIO05518-026	Kīpapa-A[2]	1,229	3	91	1	0	1	0	1
HIO05518-027	Waikāne-B[2]	3,686	3	94	1	0	1	3.7	5
HIO05518-029	Kamananui-A[2]	982	3	84	3	0.2	3	0	1
HIO05518-035	Ha‘ikū	2,331	3	76	3	0	1	9.2	5
HIO05518-037	Anahulu-B	394	5	61	5	0	1	0	1
HIO05518-038	SF Kaukonahua-C[2]	1,962	3	94	1	0	1	0	1
HIO05518-039	Waikāne-C	1,126	3	64	3	0	1	7.7	5
HIO05518-151	Kahana-C[2]	2,463	3	76	3	0	1	2.4	5
HIO05518-160	Kahana-B	2,836	3	92	1	0	1	0.7	3
HIO05518-162	Kalihi-A	598	5	74	3	0.2	3	1.6	5
HIO05518-163	‘Āhuimanu	54	7	30	5	4.5	5	17.9	5
HIO05518-164	Kamo‘oali‘i	4,676	3	97	1	0.2	3	1.5	3
HIO05518-166	Kīpapa-C	2,948	3	49	5	0	1	0	1
HIO05518-171	Mānoa	1,520	3	87	3	1.8	5	1.2	3
HIO05518-175	Kahana Iki	474	5	44	5	7.4	5	0.8	3
HIO05518-177	SF Kaukonahua-B	533	5	85	3	0	1	0	1
HIO05518-181	Anahulu-C	5,675	1	84	3	0	1	0	1
HIO05518-182	NF Kaukonahua-B	700	3	90	1	0	1	0.2	3
HIO05518-183	Waiāhole-C	2,036	3	95	1	0	1	3.6	5
HIO05518-186	NF Kaukonahua-A[2]	3,488	3	93	1	0	1	0	1
HIO05518-187	Lulumahu	209	5	39	5	0	1	23.4	5
HIO05518-191	Waimānalo	715	3	51	5	0	1	16.2	5
HIO05518-194	Pauoa	389	5	72	3	11.5	5	1.6	5
HIO05518-203	Hakipu‘u	893	3	61	5	0	1	6.1	5

[1] Metric determined using instream samples and observations.

[2] Sample used as reference sample in calculating the metrics.

Table 22.—Continued.

ʻŌpae P/A metric[1]		Megalagrion P/A metric[1]		Hīhīwai P/A metric[1]		Telmatogeton P/A metric[1]		Combined Invertebrate Community Index	
P/A	Score	P/A	Score	P/A	Score	P/A	Score	Score	Category
–	2	–	2	–	2	–	2	28	Poor
–	2	X	1	–	2	–	2	15	Fair
–	2	–	2	–	2	–	2	14	Fair
X	1	–	2	–	2	–	2	17	Fair
X	1	–	2	–	2	–	2	13	Good
–	2	–	2	–	2	–	2	26	Poor
X	1	X	1	–	2	–	2	14	Fair
–	2	X	1	–	2	–	2	13	Good
X	1	–	2	–	2	–	2	17	Fair
X	1	–	2	–	2	–	2	17	Fair
–	2	–	2	–	2	–	2	20	Poor
X	1	–	2	–	2	–	2	19	Poor
–	2	–	2	–	2	–	2	14	Fair
X	1	–	2	–	2	–	2	19	Poor
X	1	–	2	–	2	–	2	19	Poor
X	1	–	2	–	2	–	2	15	Fair
X	1	–	2	–	2	–	2	23	Poor
–	2	–	2	–	2	–	2	30	Poor
–	2	–	2	–	2	–	2	18	Fair
X	1	–	2	–	2	–	2	17	Fair
–	2	–	2	–	2	–	2	22	Poor
–	2	–	2	–	2	–	2	26	Poor
–	2	–	2	–	2	–	2	18	Fair
–	2	–	2	–	2	–	2	14	Fair
–	2	X	1	–	2	–	2	15	Fair
X	1	–	2	–	2	–	2	17	Fair
–	2	X	1	–	2	–	2	13	Good
–	2	–	2	–	2	–	2	24	Poor
–	2	–	2	–	2	–	2	22	Poor
–	2	–	2	–	2	–	2	26	Poor
–	2	–	2	–	2	–	2	22	Poor

Table 23. Combined Invertebrate Community Index (ICI) metric and index scores for the Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) O‘ahu benthic macroinvertebrate samples.

[Abundance in number per square meter; Pct, percent; P/A, presense/absenct; X, species present; –, species absent; No./m^2, number per square meter]

Station ID	Site name	Total abundance metric		Relative abundance of Insecta metric		Relative abundance of Amphipoda metric		Relative abundance of Turbellaria metric	
		No./m^2	Score	Pct	Score	Pct	Score	Pct	Score
HIO05518-002	Nu‘uanu-C	552	5	52	5	28.1	5	4.2	5
HIO05518-003	N. Hālawa-A	710	3	96	1	0.2	3	0	1
HIO05518-010	SF Kaukonahua-A[2]	3,182	3	97	1	0	1	0	1
HIO05518-011	Waiāhole-B[2]	5,849	1	75	3	0	1	12.8	5
HIO05518-013	Kamananui-B[2]	730	3	91	1	0	1	0	1
HIO05518-018	Kalihi-C	346	5	25	5	0.5	5	0.7	3
HIO05518-023	Kahana-A[2]	4,832	3	84	3	0	1	0	1
HIO05518-026	Kīpapa-A[2]	1,229	3	91	1	0	1	0	1
HIO05518-027	Waikāne-B[2]	3,686	3	94	1	0	1	3.7	5
HIO05518-029	Kamananui-A[2]	982	3	84	3	0.2	3	0	1
HIO05518-035	Ha‘ikū	2,331	3	76	3	0	1	9.2	5
HIO05518-037	Anahulu-B	394	5	61	5	0	1	0	1
HIO05518-038	SF Kaukonahua-C[2]	1,962	3	94	1	0	1	0	1
HIO05518-039	Waikāne-C	1,126	3	64	3	0	1	7.7	5
HIO05518-151	Kahana-C[2]	2,463	3	76	3	0	1	2.4	5
HIO05518-160	Kahana-B	2,836	3	92	1	0	1	0.7	3
HIO05518-162	Kalihi-A	598	5	74	3	0.2	3	1.6	5
HIO05518-163	‘Āhuimanu	54	7	30	5	4.5	5	17.9	5
HIO05518-164	Kamo‘oali‘i	4,676	3	97	1	0.2	3	1.5	3
HIO05518-166	Kīpapa-C	2,948	3	49	5	0	1	0	1
HIO05518-171	Mānoa	1,520	3	87	3	1.8	5	1.2	3
HIO05518-175	Kahana Iki	474	5	44	5	7.4	5	0.8	3
HIO05518-177	SF Kaukonahua-B	533	5	85	3	0	1	0	1
HIO05518-181	Anahulu-C	5,675	1	84	3	0	1	0	1
HIO05518-182	NF Kaukonahua-B	700	3	90	1	0	1	0.2	3
HIO05518-183	Waiāhole-C	2,036	3	95	1	0	1	3.6	5
HIO05518-186	NF Kaukonahua-A[2]	3,488	3	93	1	0	1	0	1
HIO05518-187	Lulumahu	209	5	39	5	0	1	23.4	5
HIO05518-191	Waimānalo	715	3	51	5	0	1	16.2	5
HIO05518-194	Pauoa	389	5	72	3	11.5	5	1.6	5
HIO05518-203	Hakipu‘u	893	3	61	5	0	1	6.1	5
HI_MAUI_09-040	Olowalu-A	1,857	3	89	3	0	1	0	1

[1] Metric determined using instream samples and observations.

[2] Sample used as reference sample in calculating the metrics.

Table 23.—Continued.

ʻŌpae P/A metric[1]		Megalagrion P/A metric[1]		Hīhīwai P/A metric[1]		Telmatogeton P/A metric[1]		Combined Invertebrate Community Index	
P/A	Score	P/A	Score	P/A	Score	P/A	Score	Score	Category
–	2	–	2	–	2	–	2	28	Poor
–	2	X	1	–	2	–	2	15	Fair
–	2	–	2	–	2	–	2	14	Fair
X	1	–	2	–	2	–	2	17	Fair
X	1	–	2	–	2	–	2	13	Good
–	2	–	2	–	2	–	2	26	Poor
X	1	X	1	–	2	–	2	14	Fair
–	2	X	1	–	2	–	2	13	Good
X	1	–	2	–	2	–	2	17	Fair
X	1	–	2	–	2	–	2	17	Fair
–	2	–	2	–	2	–	2	20	Poor
X	1	–	2	–	2	–	2	19	Poor
–	2	–	2	–	2	–	2	14	Fair
X	1	–	2	–	2	–	2	19	Poor
X	1	–	2	–	2	–	2	19	Poor
X	1	–	2	–	2	–	2	15	Fair
X	1	–	2	–	2	–	2	23	Poor
–	2	–	2	–	2	–	2	30	Poor
–	2	–	2	–	2	–	2	18	Fair
X	1	–	2	–	2	–	2	17	Fair
–	2	–	2	–	2	–	2	22	Poor
–	2	–	2	–	2	–	2	26	Poor
–	2	–	2	–	2	–	2	18	Fair
–	2	–	2	–	2	–	2	14	Fair
–	2	X	1	–	2	–	2	15	Fair
X	1	–	2	–	2	–	2	17	Fair
–	2	X	1	–	2	–	2	13	Good
–	2	–	2	–	2	–	2	24	Poor
–	2	–	2	–	2	–	2	22	Poor
–	2	–	2	–	2	–	2	26	Poor
–	2	–	2	–	2	–	2	22	Poor
X	1	X	1	–	2	–	2	14	Fair

in the combined index. These species included the amphidromous mountain shrimp, *Atyoida bisulcata* (‘ōpae), the amphidromous freshwater snail, *Neritina granosa* (hīhīwai), larvae of the torrent midges *Telmatogeton* spp., and adults and (or) naiads of any species of *Megalagrion* damselfly. Each of these native species metrics was scored as either 1 if present or 2 if not observed; therefore, if all four taxa were present the minimum score is 4 and if none of the taxa were present the maximum score is 8. The presence of any of these native species is associated with higher stream quality.

This metric highlights another of the differences between the Maui and O‘ahu stream assemblages, as the Maui streams were observed to have greater native macroinvertebrate biodiversity than streams on O‘ahu. Only 1 of the 40 Maui sites (2.5 percent) and none of the 31 O‘ahu WSA sites scored 4, the minimum score if all four native taxa were present; 15 Maui sites (37.5 percent) and none of the O‘ahu WSA sites scored 5, where 3 of the 4 taxa were present; 18 Maui sites (45.0 percent) and 1 O‘ahu WSA site (3.2 percent) scored 6, where 2 of the 4 taxa were present; 6 Maui sites (15.0 percent) and 15 O‘ahu WSA sites (48.4 percent) scored 7, where 1 of the 4 taxa were present; and none of the Maui sites and 15 O‘ahu WSA sites (48.4 percent) scored 8, where none of the 4 native taxa were present.

Final Combined ICI Score

As in the P–HBIBI and the Maui and O‘ahu ICI’s, the final invertebrate community index was calculated as the sum of the individual metric scores (table 20). The distributions of the final ICI scores are shown in figures B61–B62 (Maui) and C35–C36 (O‘ahu). A total of 28 of the 40 Maui sites (70 percent) but only 3 of the 31 O‘ahu WSA sites (9.7 percent) scored ≤13 and were designated as “good” quality sites; 10 Maui sites (25 percent) and 14 O‘ahu WSA sites (45.2 percent) scored >13 and ≤18 and were designated as “fair” quality sites; and 2 Maui sites (5 percent) and 14 O‘ahu WSA sites (45.2 percent) scored >18 and were designated as “poor” quality sites. Only 1 of the Maui paired replicates, Olowalu-B, was designated in different categories with scores of 12 (“good”) and 14 (“fair”).

The O‘ahu NAWQA sites used to develop the P–HBIBI were evaluated with the statewide ICI (table 23; fig. C36). A total of 5 of the 18 samples (27.8 percent) were designated as “good” quality sites. These included four of the five Waihe‘e Stream samples and the Punalu‘u above the diversion site. Six samples (33.3 percent) were designated as “fair” quality sites; and seven samples (38.9 percent) were designated as “poor” quality.

The ratio of Trichoptera to nonnative Diptera metric, included in both the Maui and O‘ahu ICI’s, was notably not incorporated into the combined index. Greater abundances of Trichoptera than nonnative Diptera were associated with higher stream quality for both island ICI’s. However, the composition of the nonnative dipterans was very different between the islands (tables 24–25). Most notably, the nonnative dipteran *Hemerodromia stellaris* (Family: Empididae) was not observed in any sample from Maui but was widespread and abundant around O‘ahu (fig. C8). The distribution and abundances of *H. stellaris* on O‘ahu did not appear to be associated with any of the habitat or water-quality parameters. *H. stellaris* on O‘ahu was identified in 25 of the 31 quantitative samples with densities as high as 503.5/m^2 at Kamo‘oali‘i Stream and relative abundances as high as 33.8 percent at the North Hālawa-A, where it was the dominant taxa. Additionally, the nonnative dipteran *Polypedilum* (Family Chironomidae) was also not present in any of the samples collected from Maui streams. This taxa was identified in 7 of the 31 quantitative samples collected on O‘ahu, with densities as high as 2,991/m^2 at the Anahulu-B site and relative abundances as high as 52.7 percent from the same site. In total, six nonnative dipterans were unique to O‘ahu WSA samples and two nonnative dipterans were unique to the Maui samples (tables 24–25).

Furthermore, there were some considerable differences in abundances between the Maui and O‘ahu trichopteran and dipteran assemblages. On average, the Maui samples contained greater total abundances as well as greater abundances of trichopterans and dipterans than did the O‘ahu samples (table 26). The maximum abundance of trichopterans in samples from Maui was more than twice as great as abundances in samples from O‘ahu, and the maximum abundance of dipterans was more than four times greater on Maui than on O‘ahu. However, the largest nine Trichoptera/Diptera ratios were in samples from O‘ahu, with a maximum ratio of 117.8, compared to a maximum of 11.9 for samples from Maui and a mean ratio of 14 compared to 1.8 for the Maui samples. Five of the nine O‘ahu sites had large populations of smallmouth bass, but the correlations between the presence of bass and dipteran abundance or dipteran relative abundance were not significant. Until further research reveals the factors influencing these differences, this metric is applicable only to the island-wide indexes.

Need for Additional Information

The results of this study highlighted the differences between the benthic macroinvertebrate communities from Maui and O‘ahu streams. The combined ICI developed for this study was based on the best available information from the two islands. Because of the paucity of data for other islands of Hawai‘i, the accuracy of the combined ICI for use on those islands has not been verified. Thus, although the use of the combined ICI on other islands may be useful for preliminary assessments, the results of such assessments will contain unquantified uncertainty. The development of a statewide ICI that can reliably assess the stream quality requires macroinvertebrate sampling from the other islands.

This study addressed some of the variability in the sampling and and in the sorting procedures used to collect and enumerate the macroinvertebrate assemblages. However, this study did not examine temporal or seasonal effects on the communities. A study designed to resample some of the established sampling sites at various times of the year for a number of years would provide much needed information on such temporal and seasonal variation.

Table 24. Composition of nonnative dipteran abundances collected in quantitative samples from Maui and O‘ahu Wadeable Stream Assessment (WSA) study sites.

[n, number of samples in which the taxon was identified; –, not identified in samples; WSA, Wadeable Stream Assessment]

Family	Subfamily	Taxon	Abundance, in number per square meter							
			Maui				O‘ahu WSA			
			n	Minimum	Maximum	Mean	n	Minimum	Maximum	Mean
Chironomidae	Chironominae	*Apedilum* sp.	38	0.8	768.2	80.0	5	0.8	348.3	71.2
Chironomidae	Chironominae	*Paratanytarsus* sp.	12	2.4	40.8	9.7	12	0.8	92.2	23.8
Chironomidae	Chironominae	*Polypedilum* sp.	–	–	–	–	7	0.8	2,991.0	434.9
Chironomidae	Chironominae	*Tanytarsus* sp.	1	1.5	1.5	1.5	2	1.4	5.2	3.3
Chironomidae	Orthocladiinae	*Corynoneura* sp.	–	–	–	–	7	0.8	49.0	12.6
Chironomidae	Orthocladiinae	*Cricotopus bicinctus* gr.	53	3.2	8,470.4	1,102.5	30	2.4	1,322.7	279.6
Chironomidae	Orthocladiinae	*Eukiefferiella* sp.	54	4.0	9,699.3	779.1	17	0.8	878.9	129.9
Chironomidae	Orthocladiinae	*Gymnometriocnemus* sp.	2	2.6	8.5	5.6	–	–	–	–
Chironomidae	Orthocladiinae	*Thienemanniella* sp.	–	–	–	–	6	5.9	140.6	29.5
Chironomidae	Tanypodinae	*Ablabesmyia* sp.	1	3.2	3.2	3.2	–	–	–	–
Dixidae	Dixinae	*Dixa* sp.	–	–	–	–	3	0.8	4.0	2.1
Empididae	Hemerodromiinae	*Hemerodromia* sp.	–	–	–	–	25	0.8	503.5	79.3
Tipulidae	Limoniinae	*Erioptera* sp.	–	–	–	–	1	1.2	1.2	1.2

Table 25. Composition of nonnative dipteran relative abundances collected in quantitative samples from Maui and Oʻahu Wadeable Stream Assessment (WSA) study sites.

[n, number of samples in which the taxon was identified; –, not identified in samples; WSA, Wadeable Stream Assessment]

Family	Subfamily	Taxon	Relative abundance, in percentage of sample abundance							
			Maui				Oʻahu WSA			
			n	Minimum	Maximum	Mean	n	Minimum	Maximum	Mean
Chironomidae	Chironominae	*Apedilum* sp.	38	0.2	19	2.7	5	0.2	6.1	1.5
Chironomidae	Chironominae	*Paratanytarsus* sp.	12	0.2	3.2	0.6	12	0.2	6.8	1.8
Chironomidae	Chironominae	*Polypedilum* sp.	–	–	–	–	7	0.2	52.7	8.3
Chironomidae	Chironominae	*Tanytarsus* sp.	1	0.2	0.2	0.2	2	0.2	0.5	0.4
Chironomidae	Orthocladiinae	*Corynoneura* sp.	–	–	–	–	7	0.2	12.3	2.9
Chironomidae	Orthocladiinae	*Cricotopus bicinctus* gr.	53	1.9	50.1	23.9	30	0.2	49.1	12.6
Chironomidae	Orthocladiinae	*Eukiefferiella* sp.	54	2	46.6	15.2	17	0.2	23.9	4.4
Chironomidae	Orthocladiinae	*Gymnometriocnemus* sp.	2	0.2	0.2	0.2	–	–	–	–
Chironomidae	Orthocladiinae	*Thienemanniella* sp.	–	–	–	–	6	0.2	5.7	1.3
Chironomidae	Tanypodinae	*Ablabesmyia* sp.	1	0.2	0.2	0.2	–	–	–	–
Dixidae	Dixinae	*Dixa* sp.	–	–	–	–	3	0.2	0.2	0.2
Empididae	Hemerodromiinae	*Hemerodromia* sp.	–	–	–	–	25	0.2	33.8	3.6
Tipulidae	Limoniinae	*Erioptera* sp.	–	–	–	–	1	0.2	0.2	0.2

Table 26. Summary statistics for nonnative Trichoptera and Diptera abundances from the Maui and Oʻahu Wadeable Stream Assessment (WSA) quantitative samples.

[n, number of samples; Min, minimum value; Max, maximum value; WSA, Wadeable Stream Assessment]

Project	n	Trichoptera:Diptera ratio			Trichopteran abundance, in number of trichopterans per square meter			Dipteran abundance, in number of dipterans per square meter			Total abundance, in number of invertebrates per square meter		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Maui	54	0.2	11.9	1.8	40	7,137	1,672	8	18,170	1,920	165.6	23,137	3,992
Oʻahu WSA	31	0	117.8	14	0	3,413	977	7.1	4,251	534	53.6	5,849	1,875

Summary and Conclusions

Data on benthic macroinvertebrates, physical habitat, and water quality were collected at 40 wadeable sites on 25 perennial streams on the island of Maui, Hawaiʻi, in 2009–10 to evaluate the relationships among the macroinvertebrate assemblages and environmental characteristics and to develop a multimetric invertebrate community index (ICI) that could be used as an indicator of stream quality. Additionally, quantitative macroinvertebrate data collected from 31 randomly selected sites on the Island of Oʻahu during a previous study, part of the U.S. Environmental Protection Agency's (USEPA) Wadeable Stream Assessment (WSA) was used to refine and develop a new ICI of stream quality for the Island of Oʻahu.

The 1972 Federal Clean Water Act requires states to restore and maintain the biological integrity of the Nation's surface waters. The Hawaiʻi Department of Health (HIDOH) is required to submit to the USEPA a list of all waterbodies (estuaries, harbors, coastal waters, and streams) that do not meet State water quality standards. The HIDOH is required to rank and prioritize the list of impaired waters according to the severity of the impairment and the instream and offstream uses of the waters. HIDOH currently uses two site evaluation protocols, the Hawaiʻi Stream Visual Assessment Protocol (HSVAP), based on habitat parameters, and the Hawaiʻi Stream Bioassessment Protocol (HSBP), based on habitat characteristics and macrofauna metrics, including fish, crustaceans, and mollusks. The goal of the study described in this report was to develop a multimetric invertebrate community index for Hawaiian streams based on attributes of the benthic macroinvertebrate assemblages. In the future, an ICI could be incorporated into the HIDOH site evaluations to better enable the HIDOH to prioritize the list of impaired waters.

The HIDOH currently uses the Hawaiʻi Stream Bioassessment Protocol (HSBP) to help evaluate streams on the basis of a number of habitat characteristics, aspects of the native and nonnative fish assemblages, and abundances of some of the more conspicuous native and nonnative benthic macroinvertebrates. The results of the HSBP assessments are currently not part of the official water quality criterion of the State Water Quality Standards, but are used to assess the attainment of designated and existing aquatic life uses protected by the Clean Water Act and used as evidence in the HIDOH weight-of-evidence decisionmaking process. Because the benthic-macroinvertebrate-based ICIs developed in this study are generally less affected by factors that may affect the native streamfish species, such as diversions, predaceous nonnative fish species, introduced fish parasites, and stream channelization, the use of the ICIs would provide the HIDOH an integrated and robust assessment of stream quality, especially in streams where the native streamfish assemblages are affected by natural or anthropogenic obstacles. Additional advantages of using benthic macroinvertebrates for stream assessments include: (1) they are found in all aquatic environments and, consequently, can be affected by environmental perturbations in a variety of aquatic systems and habitats; (2) the large diversity of species and the wide range of tolerances to disturbances offers a wide spectrum of responses to environmental stressors; (3) their basic sedentary nature allows effective spatial analyses of pollutants or disturbance effects; and (4) some have relatively long life cycles, which allows examination of temporal changes caused by perturbation. An ICI, statewide or island-wide, would complement the HSBP and provide the HIDOH another line of evidence to aid in their decisionmaking.

The Maui sampling sites were selected to represent a range of land-use and habitat characteristics and to represent the different climatic conditions around the island created by the effects of the prevailing trade winds and mountain ranges. Fieldwork was conducted from June 2009 through February 2010. Sixteen sites were sampled in East Maui, and 24 sites were sampled in West Maui. Additionally, replicate samples were collected at eight sites, three repeat samples were collected over the duration of the fieldwork from one site, and laboratory re-sorts of four previously sorted and enumerated samples were conducted.

Quantitative macroinvertebrates samples were collected from riffle habitats and qualitative samples were collected from all available habitats following National Water-Quality Assessment (NAWQA) protocols for the collection of such samples. Snorkel surveys and adult damselfly surveys also were conducted at each site. Physical habitat data, including canopy cover, substrate, riparian vegetation, embeddedness, and flow regime, were collected at each study reach.

Multivariate statistical analysis of the replicate, repeat, and re-sorted samples illustrated the variation among the samples. The percent similarity of the paired replicate samples ranged from 75 to 85 percent using the proportional data and from 70 to 90 percent using the abundance data. The percent similarity between the paired re-sorted and original sorts ranged from 85 to 90 percent similarity the using the proportional data and from 80 to 85 percent similarity using abundance data. The repeat samples collected at the Waiheʻe-A site on Maui showed an 85 percent similarity between the first and third samples, with both having only a 70 percent similarity with the second sample using the proportional data. The first and third samples had an 80 percent similarity, with both having a 75 percent similarity with the second sample using the abundance dataset. The second sample had 57 percent fewer macroinvertebrates than the first sample and 61 percent less than the third sample.

An evaluation of the Maui data using the P-HBIBI determined that four of the existing metrics were unsuccessful in differentiating among the sites and that the three metrics that were successful needed to be adjusted. A new multimetric invertebrate community index (ICI) was developed for Maui. Candidate invertebrate metrics were screened and tested and the individual metrics that proved the best at discerning among the sites along one or more disturbance gradients were combined into an ICI of stream quality. These metrics were: total invertebrate abundance, insect relative abundance (less the abundances of the native shrimp and snail), the ratio of Trichoptera to nonnative Diptera, native snail (hīhīwai) presence or absence, native mountain shrimp (‘ōpae) presence or absence, native torrent midge (*Telmatogeton* sp.) presence or absence, and native *Megalagrion* damselfly presence or absence. The Maui ICI classified 22 of the 54 Maui samples to represent “good” quality communities, or those at or near the reference condition; 22 of the samples to be “fair” quality communities; and 10 to be “poor” quality communities—a classification that may be used to trigger further investigation. The cause or causes of the low rating might be naturally occurring conditions, or anthropogenically generated reductions in streamflow, or water-quality or physical-habitat disturbances.

An evaluation of the O‘ahu WSA data using the P-HBIBI determined that two of the existing metrics were unsuccessful in differentiating among the sites and that the remaining five metrics that were successful needed to be adjusted. A new ICI was developed for O‘ahu. The set of metrics that were included in the revised ICI were: total invertebrate abundance, insect relative abundance (less the abundances of the native shrimp and snail), the ratio of Trichoptera to nonnative Diptera, turbellarian relative abundance (less the abundances of the native shrimp and snail), amphipod relative abundance (less the abundances of the native shrimp and snail), nonnative mollusk abundance, and nonnative crayfish (*Procambarus clarkii*) and (or) red cherry shrimp (*Neocaridina denticulata sinensis*) presence or absence. The O‘ahu ICI classified 10 of the 31 samples as ”good” quality communities, 16 of the samples as ”fair” quality, and 5 of the samples as ”poor” quality. A reanalysis of the 18 O‘ahu macroinvertebrate samples collected from 1999 to 2002 that were used to develop the P–HBIBI using the O‘ahu ICI resulted in the reclassification of 3 samples.

A comparison of the Maui and O‘ahu macroinvertebrate communities revealed that the communities differed dramatically in the taxa present and the abundances and relative abundances of those taxa. The native stream communities were more nearly intact on Maui than on O‘ahu, including the native fish, shrimp, snails, and insects. The first step in developing a statewide ICI was performed by merging the Maui and O‘ahu WSA macroinvertebrate datasets and selecting, testing, and scoring a set of metrics developed for the Maui and O‘ahu ICIs. The data from the reference condition sites from both islands were merged and used to derive the tier limits for the best conditions, and the data from the remaining sites were used to derive the tier limits for the worst conditions. The metrics that were integrated into the statewide ICI included: total invertebrate abundance, insect relative abundance (less the abundances of the native shrimp and snail), turbellarian relative abundance (less the abundances of the native shrimp and snail), amphipod relative abundance (less the abundances of the native shrimp and snail), and a native species richness metric based on the presence or absence of the amphidromous mountain shrimp, *Atyoida bisulcata* (‘ōpae), the amphidromous freshwater snail, *Neritina granosa* (hīhīwai), larvae of the torrent midges *Telmatogeton* spp., and adults and (or) naiads of any species of *Megalagrion* damselfly. Overall, this index highlighted a number of the differences between the stream communities observed on each island. A majority of the Maui samples, 39 of 54 (72.2 percent), and sites, 28 of 40 (70 percent), were designated as “good” quality sites, whereas only 3 of the 31 (9.7 percent) O‘ahu WSA sites were designated as “good” quality sites; 10 Maui sites (25 percent; 13 samples) and 14 O‘ahu WSA sites (45.2 percent) were designated as “fair” quality sites; and only 2 Maui sites (5 percent; 2 samples) and 14 O‘ahu WSA sites (45.2 percent) were designated as “poor” quality stream sites. An evaluation of the O‘ahu sites used in the development of the P–HBIBI, using the statewide ICI, designated 5 of the 18 samples (27.8 percent) as “good”, 6 samples (33.3 percent) as “fair”, and 7 samples (38.9 percent) as “poor” quality stream sites.

This study provides information critical to a comprehensive assessment of stream quality in Hawai‘i and the development of appropriate monitoring and management strategies. The preliminary statewide ICI developed in this study is intended to assist the HIDOH in prioritizing their stream management efforts by identifying broad problem areas on a statewide scale. Once these broad problem areas are identified, the HIDOH can use the island-wide ICIs to more accurately assess the quality of individual stream reaches. The ability of the Maui and O‘ahu ICIs to discern levels of impairment in streams could provide the HIDOH one more tool in their stream assessment toolbox. Further refinement and calibration would make the ICIs more robust resources for monitoring programs to rely on. Future refinements may reveal some of the forces that shape the invertebrate communities and may lead to predictive models that could be used to forecast the effects of anthropogenic activities on those communities.

References Cited

Adachi, M.S., 1958, Notes and Exhibitions: *Oxyethira maya*: Proceedings of the Hawaiian Entomological Society, v. 16, no. 3, p. 328.

Ancey, C.F., 1899, Some notes on the non-marine molluscan fauna of the Hawaiian Islands, with diagnoses of new species: Proceedings of the Malacological Society of London, v. 3, no. 521, p. 268–274, pls. 12–13.

Archer, K.M., 1984, Biological survey and quality rating of windward O‘ahu streams: Submitted to VTN Pacific, Inc, 43 p.

Archer, K.M., Timbol, A.S., and Parrish, J.D., 1980, Biological survey of Kahana Stream system: Hawaii Cooperative Fishery Research Unit Technical Report 80-2, 47 p.

Armstrong, R.W., 1983, Atlas of Hawai‘i (2nd ed.): University of Hawaii Press, Honolulu, 238 p.

Asquith, Adam, and Messing, R.H., 1992, Annotated insect distribution records for the island of Kauai: Proceedings of the Hawaiian Entomological Society, v. 31, p. 151–156.

Bae, Y.J., and McCafferty, W.P., 1991, Phylogenetic systematics of the Potamanthidae (Ephemeroptera): Transactions of the American Entomological Society, v. 117, no. 3, p. 1-–143.

Barbour, M.T., Gerritsen, J., Snyder, B.D., and Stribling, J.B., 1999, Rapid bioassessment protocols for use in wadeable streams and rivers; periphyton, benthic macroinvertebrates, and fish (2nd ed.): U.S. Environmental Protection Agency, Office of Water, Assessment and Watershed Protection Division, Washington, D.C., EPA 841-B-99-002, 336 p.

Barnard, J.L., 1970, Sublittoral Gammaridea (Amphipoda) of the Hawaiian Islands: Smithsonian Contributions to Zoology, v. no. 34, 286 p.

Barnard, J.L., 1971, Keys to the Hawaiian marine Gammaridea, 0-30 meters: Smithsonian Contributions to Zoology, v. no. 58, 135 p.

Barnard, J.L., 1977, The cavernicolous fauna of Hawaiian lava tubes 9. Amphipoda (Crustacea) from brackish lava ponds on Hawaii and Maui: Pacific Insects, v. 17, no. 2–3, p. 267–299.

Barnes, J.R., and Shiozawa, D.K., 1985, Drift in Hawaiian streams: Verhandlungen Internationale Vereinigung fūr Theoretische und Angewandte Limnologie, v. 22, p. 2119–2124.

Beardsley, J.W., 1960, Notes and exhibitions; *Oxyethira maya*: Proceedings of the Hawaiian Entomological Society, v. 17, no. 2, 181 p.

Beardsley, J.W., 1966, Notes and exhibitions; new Caddis-fly on Oahu: Proceedings of the Hawaiian Entomological Society, v. 19, no. 2, p. 145–146.

Beardsley, J.W., 1967a, Notes and exhibitions; *Cheumatopsyche analis*: Proceedings of the Hawaiian Entomological Society, v. 19, no. 3, p. 322.

Beardsley, J.W., 1967b, Notes and exhibitions; *Cheumatopsyche analis*: Proceedings of the Hawaiian Entomological Society, v. 19, no. 3, p. 328.

Beardsley, J.W., 1967c, Notes and exhibitions; *Cheumatopsyche analis*: Proceedings of the Hawaiian Entomological Society, v. 19, no. 3, p. 335.

Beardsley, J.W., 1971, Notes and exhibitions; *Hydroptila arctia*: Proceedings of the Hawaiian Entomological Society, v. 21, no. 1, p. 15–16.

Beardsley, J.W., 1993, Notes and exhibitions; new records of Diptera for the Hawaiian Islands: *Hemerodromia stellaris*: Proceedings of the Hawaiian Entomological Society, v. 32, p. 5.

Beckley, E.M., 1883, Hawaiian fishing implements and methods of fishing with an account of the fishing implements used by the natives of the Hawaiian Islands: Advertiser Steam Print, Honolulu, 19 p.

Bell, F.T., and Higgins, Elmer, 1939, A plan for the development of the Hawaiian fisheries: U.S. Department of Commerce, Bureau of Fisheries, Investigational Report No. 42, 25 p.

Benbow, M.E., Burky, A.J., and Way, C.M., 1997, Larval habitat preference of the endemic Hawaiian midge, *Telmatogeton torrenticola* (Telmatogetoninae): Hydrobiologia, v. 346, p. 129–136.

Benbow, M.E., Orzetti, L.L., McIntosh, M.D., and Burky, A.J., 2002, A note on cascade climbing of migrating goby and shrimp postlarvae in two Maui streams: Micronesica, v. 34, p. 243–248.

Benbow, M.E., Burky, A.J., and Way, C.M., 2003, Life cycle of a torrenticolous Hawaiian chironomid (*Telmatogeton torrenticola*); stream flow and microhabitat effects: Annales de Limnologie - International Journal of Limnology, v. 39, p. 103–114.

Benbow, M.E., Burky, A.J., and Way, C.M., 2004, The use of two modified Breder traps to quantitatively study amphidromous upstream migration: Hydrobiologia, v. 527, p. 139–151.

Benbow, M.E., McIntosh, M.D., Burky, A.J., and Way, C.M., 2005, The influence of stream flow reduction on the energetics of endemic Hawaiian torrenticolous aquatic insects, *Telmatogeton* Schiner and *Procanace* Hendel: Journal of Insect Conservation, v. 9, p. 175–185.

Benstead, J.P., March, J.G., Pringle, C.M., and Scatena, F.N., 1999, Effects of a low-head dam and water abstraction on migratory tropical stream biota: Ecological Applications, v. 9, p. 656–668.

Bishop, C.R., Halstead, Robert, and Dole, S.B., 1884, Report on forestry: The Planters' Monthly, v. 3, no. 8, p. 574–575.

Black, R.W., and MacCoy, D.E., 1999, The development and evaluation of a benthic index of biological integrity for the Cedar River watershed, Washington: U.S. Geological Survey Water-Resources Investigations Report 00-4203, 92 p.

Blob, R.W., Rai, R., Julius, M.L., and Schoenfuss, H.L., 2006, Functional diversity in extreme environments; effects of locomotor style and substrate texture on the waterfall-climbing performance of Hawaiian gobiid fishes: Journal of Zoology, v. 268, p. 315–324.

Board of Water Supply, 2010, Punaluu Stream Kamehameha Schools irrigation system improvements project 2009: http://www.boardofwatersupply.com/cssweb/display.cfm?sid=2141 (accessed June 2011)

Brasher, Anne, 1991, Aquatic survey of Waikakalaua Stream, Oahu, Hawaii: Prepared for Dames and Moore, 16+ p.

Brasher, A.M., 1997, Life history characteristics of the native Hawaiian stream snail *Neritina granosa* (hīhīwai): Cooperative National Park Resources Studies Unit Hawaii Technical Report 114, 46 p.

Brasher, A.M.D., 2003, Impacts of human disturbances on biotic communities in Hawaiian streams: BioScience, v. 53, p. 1052–1060.

Brasher, A.M.D., and Wolff, R.H., 2004, Relations between land use and organochlorine pesticides, PCBs, and semi-volatile organic compounds in streambed sediment and fish on the island of Oahu, Hawaii: Archives of Environmental Contamination and Toxicology, v. 46, p. 385–398.

Brasher, A.M.D., Wolff, R.H., and Luton, C.D., 2004, Associations among land use, habitat characteristics, and invertebrate community structure in nine streams on the island of Oahu, Hawaii, 1999-2001: U.S. Geological Survey Water-Resources Investigations Report 03-4256, 47 p.

Brasher, A.M.D., Luton, C.D., Goodbred, S.L., and Wolff, R.H., 2006, Invasion patterns along elevation and urbanization gradients in Hawaiian streams: Transactions of the American Fisheries Society, v. 135, p. 1109–1129.

Brigham, W.T., 1911, Ka hana kapa; the making of bark-cloth in Hawaii: Memoirs of the Bernice Pauahi Bishop Museum of Polynesian Ethnology and Natural History, v. 3, 273+ p.

Brock, V.E., 1952, A history of the introduction of certain aquatic animals to Hawaii: Biennial Report of the Board of Commissioners of Agriculture and Forestry of the Territory of Hawaii, June 30, 1952, p. 114–123.

Brock, V.E., 1960, The introduction of aquatic animals into Hawaiian waters: Internationale Revue der gesamten Hydrobiologie, v. 45, p. 463–480.

Brusca, G.J., 1973, Pelagic Amphipoda from the waters near Oahu, Hawaii, excluding the family Scinidae: Pacific Science, v. 27, no. 1, p. 8–27.

Bryan, W.A., 1915, Natural History of Hawaii: The Hawaiian Gazette Co., Ltd., Honolulu, Hawaii, 596 p.

Burky, A.J., Way, C.M., Hau, Skippy, and Benbow, M.E., 2000, The occurrence of the freshwater clams, *Musculium partumeium* (Say) and *Pisidium casertanum* (Poli) (Bivalvia: Sphaeriidae), in the Hawaiian Islands: Micronesica, v. 33, p. 161–164.

Carlton, J.T., 1982, A global framework of introduced species (abs.): 63rd Annual Meeting of the Western Society of Naturalists, p. 19.

Carlton, J.T., 1996, Biological invasions and cryptogenic species: Ecology, v. 77, no. 6, p. 1653–1655.

Carlquist, Sherwin, 1980, Hawaii—a natural history: Pacific Tropical Botanical Garden, 468 p.

Clarke, K.R., 1993, Non-parametric multivariate analyses of changes in community structure: Australian Journal of Ecology, v. 18, p. 117–143.

Clarke, KR, and Gorley, RN., 2006, PRIMER v6: User Manual/Tutorial; PRIMER-E, Plymouth Marine Laboratory, Plymouth, U.K.

Commission on Water Resource Management, 2006, In the matter of water use permit applications, petitions for interim instream flow standard amendments, and petitions for water reservations for the Waiahole Ditch combined contested case hearing (CCH-OA95-1): Findings of Fact, Conclusions of Law, and Decision and Order in the second remand proceedings, 8 p.

Commission on Water Resource Management, 2010, ‘lao ground water management area high-level source water-use permit applications and petition to amend interim instream flow standards of Waihe‘e River and Waiehu, ‘lao, & Waikapu Streams, contested case hearing: Findings of Fact, Conclusions of Law, and Decision and Order, 227+ p.

Couret, C.L., Jr., 1976, The biology and taxonomy of a freshwater shrimp, *Atya bisulcata*, Randall, endemic to the Hawaiian islands: Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 168 p.

Cowie, R.H., 1997, Catalog and bibliography of the nonindigenous nonmarine snails and slugs of the Hawaiian Islands: Bishop Museum Occasional Papers, v. 50, p. 1–66.

Cowie, R.H., 1998, Patterns of introduction of non-indigenous non-marine snails and slugs of the Hawaiian Islands: Biodiversity and Conservation, v. 7, p. 349–368.

Cowie, R.H., 2001, Invertebrate invasions on Pacific Islands and the replacement of unique native faunas; a synthesis of the land and freshwater snails: Biological Invasions, v. 3, p. 119–136.

Cox, T.R., 1991, The birth of Hawaiian forestry; the web of influences: Prepared for the XVII Pacific Science Congress, 13 p.

Cuffney, T.F., Gurtz, M.E., and Meador, M.R., 1993, Methods for collecting benthic invertebrate samples as part of the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 93-406, 66 p.

Davis, C.J., and Krauss, N.L.H., 1962, Recent introductions for biological control in Hawaii - VII: Proceedings of the Hawaiian Entomological Society, v. 18, no. 1, p. 125–129.

Denning, D.G., and Beardsley, J.W., 1967, The collection of *Cheumatopsyche analis* in Hawaii (Hydropsychidae: Trichoptera): Proceedings of the Entomological Society of Washington, v. 69, no. 1, p. 56–57.

Denning, D.G., and Blickle, R.L., 1971, A new Trichoptera from the Hawaiian Islands: The Pan-Pacific Entomologist, v. 47, no. 2, p. 164.

Derrickson, S.A.K., Robotham, M.P., Olive, S.G., and Evensen, C.I., 2002, Watershed management and policy in Hawaii—coming full circle: Journal of the American Water Resources Association, v. 38, p. 563–576.

DeShon, J.E., 1995, Development and application of the invertebrate community index (ICI), *in* Davis, W.S., and Simon, T.P., eds., Biological assessment and criteria; tools for water resource planning and decision making: Lewis Publishers, Boca Raton. Florida, p. 217–243.

Devaney, D.M., Kelly, Marion, Lee, P.J., and Motteler, L.S., 1982, Kāneʻohe; a history of change: The Bess Press, Honolulu, Hawaii, 271 p.

Devick, W.S., 1991, Patterns of introductions of aquatic organisms to Hawaiian freshwater habitats, *in* Devick, W.S., ed., New directions in research, management and conservation of Hawaiian freshwater stream ecosystems: Proceedings of the 1990 Symposium on Freshwater Stream Biology and Fisheries Management: Department of Land and Natural Resources, Division of Aquatic Resources, Honolulu, Hawaiʻi, p. 189–213.

Devick, W.S., Fitzsimons, J.M., and Nishimoto, R.T., 1992, Conservation of Hawaiian freshwater fishes: Division of Aquatic Resources, Department of Land and Natural Resources, State of Hawaii, 26 p.

DiSalvo, Carol, Orr, Richard, and Foote, David, 2003, Dragonflies and damselflies; invertebrate indicators of ecological health: U.S. National Park Service, Natural Resource Year in Review, 2003, p. 86–87.

Edmondson, C.H., 1929, Hawaiian Atyidae: Bulletin of the Bernice P. Bishop Museum, v. 66, p. 1–37.

Edmondson, C.H., 1933, Reef and shore fauna of Hawaii: Bernice P. Bishop Museum Special Publication 22, 381 p.

Edmondson, C.H., and Wilson, I.H., 1940, The shellfish resources of Hawaii: Proceedings of the Sixth Pacific Science Congress of the Pacific Science Association, v. 3, p. 241–243.

Ego, K., 1956, Life history of freshwater gobies: State of Hawaiʻi, Department of Land and Natural Resources, Freshwater Game Fish Management Research, Project no. F–4–R, 24 p.

Eldredge, L. G., 1992, Unwanted strangers; an overview of animals introduced to Pacific Islands: Pacific Science, no. 46, p. 384–386.

Englund, R.A., 1999, The impacts of introduced poeciliid fish and Odonata on the endemic *Megalagrion* (Odonata) damselflies of Oahu Island, Hawaii: Journal of Insect Conservation, v. 3, p. 225–243.

Englund, R.A., 2000, Report on aquatic insect monitoring of 17 September 2000 in Kaipapaʻu Stream, Oʻahu, Hawaiʻi: Contribution No. 2000-020 to the Hawaiʻi Biological Survey, 6 p.

Englund, R.A., and Cai, Yixiong, 1999, The occurrence and description of *Neocaridina denticulata sinensis* (Kemp, 1918) (Crustacea: Decapoda: Atyidae), a new introduction to the Hawaiian Islands: Bishop Museum Occasional Papers, v. 58, p. 58–65.

Englund, R.A., Polhemus, D.A., and Preston, D.J., 2000a, Assessment of the impacts of rainbow trout predation on native aquatic invertebrate species within Kōkeʻe State Park streams, Kauaʻi, Hawaiʻi: Bishop Museum Technical Report, v. 18, 126 p.

Englund, R.A., Preston, D.J., Wolff, R.H., Coles, S.L., Eldredge, L.G., and Arakaki, K., 2000b, Biodiversity of freshwater and estuarine communities in lower Pearl Harbor, Oʻahu, Hawaiʻi with observations on introduced species: Final Report prepared for the U.S. Navy: Bishop Museum Technical Report, v. 16, 167 p.

Englund, R.A., Wright, M.G., and Polhemus, D.A., 2007, Aquatic insect taxa as indicators of aquatic species richness, habitat disturbance, and invasive species impacts in Hawaiian streams, *in* Evenhuis, N.L. and Fitzsimons, J.M., eds., Biology of Hawaiian Streams and Estuaries: Bishop Museum Bulletin in Cultural and Environmental Studies, Honolulu, p. 207–232.

Engott, J.A., and Vana, T.T., 2007, Effects of agricultural land-use changes and rainfall on ground-water recharge in central and west Maui, Hawaiʻi: U.S. Geological Survey Scientific Investigations Report 2007-5103, 56 p.

Evenhuis, N.L., and Cowie, R.H., 1994, A survey of the snails, insects and related arthropods in the grounds of the Tripler Army Medical Center, Honolulu, Hawaii: Bishop Museum Technical Report, no. 3, 23 p.

Eydoux, F., and Souleyet, F.A., 1850, Poissons, *in* Voyage autour du monde exécuté pendant les années 1836 et 1837 sur la corvette “La Bonite”, commandée par M. Vaillant, Zoologie: Arthus Bertrand, Paris, v. 1, no. 2, p. 157–216.

Fitzpatrick, F.A., Waite, I.R., D’Arconte, P.J., Meador, M.R., Maupin, M.A., and Gurtz, M.E., 1998, Revised methods for characterizing stream habitat in the National Water-Quality Assessment program: U.S. Geological Survey Water-Resources Investigations Report 98-4052, 67 p.

Fitzsimmons, J.M., Zink, R.M., and Nishimoto, R.T., 1990, Genetic variation in the Hawaiian stream goby, *Lentipes concolor*: Biochemical Systematics and Ecology, v. 18, no. 1, p. 81–83.

Flint, O.S., Jr., Englund, R.A., and Kumashiro, B.R., 2003, A reassessment and new state records of Trichoptera occurring in Hawai‘i with discussion on origins and potential ecological impacts: Bishop Museum Occasional Papers, v. 73, p. 31–40.

Font, W.F., and Tate, D.C., 1994, Helminth parasites of native Hawaiian freshwater fishes; an example of extreme ecological isolation: The Journal of Parasitology, v. 80, no. 5, p. 682–688.

Ford, J.I., 1979, Biology of a Hawaiian fluvial gastropod *Neritina granosa* Sowerby (Prosobranchia: Neritidae): Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 92 p.

Ford, J.I., 1982, Final coordination act report, Wailua River hydroelectric power study (phase 3 pre-authorization survey report): Final Environmental Impact Statement, Wailua River Hydropower, Kauai, Hawaii Prepared by Bingham Engineering, 23 p.

Ford, J.I., and Kinzie, R.A., III, 1982, Life crawls upstream: Natural History, v. 91, p. 61–66.

Fore, L.S., Karr, J.R., and Wisseman, R.W., 1996, Assessing invertebrate responses to human activities; evaluating alternative approaches: Journal of the North American Benthological Society, v. 15, p. 212–231.

Fullaway, D.T., 1913, Report of the entomologist; mosquitoes: Annual Report of the Hawaii Agricultural Experiment Station for 1912, p. 16–23.

Fullaway, D.T., 1941, Crayfish control: Report of the Board of Commissioners of Agriculture and Forestry of the Territory of Hawaii for the Biennial Period ended December 31, 1940, p. 21

Gagne, W.C., 1988, Conservation priorities in Hawaiian natural systems: BioScience, v. 38, p. 264–271.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall atlas of Hawai‘i: State of Hawaii Department of Land and Natural Resources, Report R76, 267 p.

Gingerich, S.B., 2005, Median and low-flow characteristics for streams under natural and diverted conditions, Northeast Maui, Hawaii: U.S. Geological Survey Scientific Investigations Report 2004-5262, 72 p.

Gingerich, S.B., and Wolff, R.H., 2005, Effects of surface-water diversions on habitat availability for native macrofauna, northeast Maui, Hawaii: U.S. Geological Survey Scientific Investigations Report 2005-5213, 93 p.

Groombridge, J., 2008, Hawaii—extinction capital of the world: National Environmental Research Council, PlanetEarth online [http://planetearth.nerc.ac.uk/features/story.aspx?id=129, accessed March 2011],

Hall, W.L., 1904, The forests of the Hawaiian Islands: U.S. Department of Agriculture, Bureau of Forestry, Bulletin no. 48, 29 p.

Harding, J.S., Benfield, E.F., Bolstad, P.V., Helfman, G.S., and Jones, E.B.D., 1998, Stream biodiversity; the ghost of land use past: Proceedings of the National Academy of Sciences of the United States of America, v. 95, p. 14843–14847.

Hardy, D.E., 1956, Notes and exhibitions; *Cricotopus bicinctus*: Proceedings of the Hawaiian Entomological Society, v. 16, no. 1, p. 15.

Hardy, D.E., 1960, Insects of Hawaii; Volume 10; Diptera, Nematocera-Brachycera: University of Hawaii Press, Honolulu, Hawaii, 368 p.

Hardy, D.E., 1985, Notes and exhibitions; *Hemerodromia* sp.: Proceedings of the Hawaiian Entomological Society, v. 25, p. 20.

Hawaii Board of Commissioners, 1939, Spread of the Wi: Report of the Board of Commissioners of Agriculture and Forestry of the Territory of Hawaii for the Biennial Period ended December 31, 1938, p. 46.

Hawaiian Gazette, 1905, Little fish here to kill mosquitoes: Hawaiian Gazette, September 19, 1905, p. 2.

Heacock, D.E., Berg, Kristina, and Kido, M.H., 1994, Diet of the introduced smallmouth bass *Micropterus dolomieui*. in the Wailua and Huleia rivers, Kauai, Hawai‘i; impact on native Hawaiian stream fauna, *in* Way, C.M., ed., Proceedings of the international symposium on Hawaiian stream ecology, preservation, and management: Miscellaneous Paper EL-94-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, p. 9.

Henderson, Katina, and Harrigan-Lum, June, 2002, 2002 list of impaired waters prepared under Clean Water Act §303(d): Hawaii State Department of Health, 61 p.

Holt, Alan, 1988, Protection of natural habitats, *in* Stone, C.P., and Stone, D.B., eds., Conservation biology in Hawaii: University of Hawaii Press, Honolulu, p. 168–174.

Homer, Collin, Huang, Chengquan, Yang, Limin, Wylie, Bruce, and Coan, Michael, 2004, Development of a 2001 National Landcover Database for the United States: Photogrammetric Engineering and Remote Sensing, v. 70, no. 7, p. 829–840.

Hosmer, R.S., 1908, Forestry in Hawaii; why the practice of forestry is an economic necessity in the Hawaiian Islands: Territory of Hawaii, 8 p.

Howard, L.O., 1900, Notes on the mosquitoes of the United States; giving some account of their structure and biology, with remarks on remedies: Bulletin of the U.S. Department of Agriculture, Division of Entomology, v. 25, 70 p.

Howard, L.O., 1901, Mosquitoes; how they live; how they carry disease; how they are classified; how they may be destroyed: McClure, Phillips and Co., New York, 241 p.

Howarth, F.G., 1990, Hawaiian terrestrial arthropods: an overview: Bishop Museum Occasional Papers, v. 30, p. 4–26.

Howarth, F.G., and Mull, W.P., 1992, Hawaiian insects and their kin: University of Hawaii Press, Honolulu, Hawaii, 160 p.

Howarth, F.G., and Polhemus, D.A., 1991, A review of the Hawaiian stream insect fauna, *in* Devick, W.S., ed., New directions in research, management and conservation of Hawaiian freshwater stream ecosystems, Proceedings of the 1990 Symposium on Freshwater Stream Biology and Fisheries Management: Department of Land and Natural Resources, Division of Aquatic Resources, Honolulu, Hawaii, p. 40–50.

Hubbell, T.H., 1968, The biology of islands: Proceedings of the National Academy of Sciences of the United States of America, v. 60, p. 22–32.

Hughes, R.M., Kaufmann, P.R., Herlihy, A.T., Kinkaid, T.M., Reynolds, Lou, and Larsen, D.P., 1998, A process for developing and evaluating indices of fish assemblages integrity: Canadian Journal of Fisheries and Aquatic Sciences, v. 55, p. 1618–1631.

Hung, Ming-Shih, Chan, Tin-Yam, and Yu, Hsiang-Ping, 1993, Atyid shrimps (Decapoda: Caridea) of Taiwan, with descriptions of three new species: Journal of Crustacean Biology, v. 13, p. 481–503.

Ibara, Wayne, and Conant, Patrick, 1972, Aquatic fauna of the streams of Waihoi Valley, *in* Kjargaard, J., ed., Scientific Report of the Waihoi Valley Project: University of Hawaii, Honolulu, Hawaii, p. 202–214.

Iguchi, K., 2007, Limitations of early seaward migration success in amphidromous fishes, *in* Evenhuis, N.L., and Fitzsimons, J.M., eds., Biology of Hawaiian streams and estuaries: Bishop Museum Bulletin in Cultural and Environmental Studies, Honolulu, p. 75–85.

Iguchi, K., and Mizuno, N., 1999, Early starvation limits survival in amphidromous fishes: Journal of Fish Biology, v. 54, p. 705–712.

Iizuka, R.K., 1979, The use of larvivorous fish for mosquito control in Oahu, Hawaii: Long Beach, California State University, M.S. thesis, 42 p.

Illingworth, J.F., 1930, The use of arsenic in mosquito control: Proceedings of the Hawaiian Entomological Society, p. 414.

Illingworth, J.F., 1931, Insects in the Waiahole Ditch: Proceedings of the Hawaiian Entomological Society, p. 408-409.

Jarves, J.J., 1843, History of the Hawaiian or Sandwich Islands: Tappan and Dennet, Boston, 407 p.

Johnson, C.G., 2001, Conservation biology of the orangeblack Hawaiian damselfly, *Megalagrion xanthomelas*, (Odonata: Coenagrionidae) on Oʻahu: Honolulu, University of Hawaiʻi at Mānoa, M.S. thesis, 92 p.

Jordan, D.S., 1905, The origin of species through isolation: Science, v. 22, p. 545–562.

Joyce, C.R., 1961, Potentialities for accidental establishment of exotic mosquitoes in Hawaii: Proceedings of the Hawaiian Entomological Society, v. 17, no. 3, p. 403–413.

Joyce, C.R., 1969, Notes and exhibitions; *Hydroptila* sp.: Proceedings of the Hawaiian Entomological Society, v. 20, no. 2, p. 275.

Joyce, C.R., 1970, Notes and exhibitions; *Cheumatopsyche analis*: Proceedings of the Hawaiian Entomological Society, v. 20, no. 3, p. 485.

Judd, C.S., 1919, Forestry in Hawaii: The Hawaiian Forester and Agriculturist, v. 16, no. 11, p. 271–297.

Juvik, S.O., and Juvik, J.O., 1998, Atlas of Hawaiʻi (3rd ed.): University of Hawaiʻi Press, Honolulu, 333 p.

Kanayama, R.K., 1967, Hawaii's aquatic animal introductions: Presented at the 47th annual conference of the Western Association of State Game and Fish Commissioners, 8 p.

Karr, J.R., Fausch, K.D., Angermeier, P.L., Yant, P.R., and Schlosser, I.J., 1986, Assessing biological integrity in running waters; a method and its rationale: Illinois Natural History Survey, Special Publication 5, 28 p.

Kawamura, K., 1974, Notes and exhibitions; *Cheumatopsyche analis*: Proceedings of the Hawaiian Entomological Society, v. 21, no. 3, p. 303.

Kawate, David, 1969, An ecological comparison of two Hawaiian streams: Honolulu, University of Hawaiʻi at Mānoa, M.S. thesis, 29 p.

Kerans, B.L., and Karr, J.R., 1994, A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley: Ecological Applications, v. 4, p. 768–785.

Kido, M.H., 1996, Diet and food selection in the endemic Hawaiian amphidromous goby, *Sicyopterus stimpsoni* (Pisces: Gobiidae): Environmental Biology of Fishes, v. 45, p. 199–209.

Kido, M.H., 1997, Food relations between coexisting native Hawaiian stream fishes: Environmental Biology of Fishes, v. 49, p. 481–494.

Kido, M.H., 2002, Hawaii stream bioassessment protocol version 3.01: Hawaii Stream Research Center, Center for Conservation Research and Training, University of Hawaii, 47 p.

Kido, M.H., 2007, A biological and habitat assessment of Lower Lawai Stream, Kauai: Final technical Report to the National Tropical Botanical Garden, 17 p.

Kido, M.H., and Smith, G.C., 1997, Biocriteria for assessing the biological integrity of Hawaii's streams: Paper presented at the 1997 Conservation Conference, July 24-25, Maui, Hawaii, 5 p.

Kido, M.H., Ha, Phyllis, and Kinzie, R.A., III, 1993, Insect introductions and diet changes in an endemic Hawaiian amphidromous goby, *Awaous stamineus* (Pisces: Gobiidae): Pacific Science, v. 47, p. 43–50.

Kido, M.H., Heacock, D.E., and Asquith, Adam, 1999a, Alien rainbow trout (*Oncorhynchus mykiss*) (Salmoniformes: Salmoniae) diet in Hawaiian streams: Pacific Science, v. 53, p. 242–251.

Kido, M.H., Smith, G.C., and Heacock, D.E., 1999b, The Hawaii stream bioassessment protocol; a manual for biological monitoring and assessment of Hawaiian streams: Hawaii Stream Research Center, 44 p.

Kinzie, R.A., III, 1988, Habitat utilization by Hawaiian stream fishes with reference to community structure in oceanic island streams: Environmental Biology of Fishes, v. 22, p. 179–192.

Kinzie, R.A., III, 1990, Species profiles; life histories and environmental requirements of coastal vertebrates and invertebrates, Pacific Ocean Region; Report 3, Amphidromous macrofauna of island streams: Technical Report EL-89-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 28 p.

Kinzie, R.A., III, and Ford, J.I., 1977, A limnological survey of Lower Palikea and Pīpīwai Streams, Kipahulu, Maui: Cooperative National Park Resources Studies Unit, University of Hawaii, Technical Report 17, 44 p.

Kinzie, R.A., III, Chong, C., Devrell, J., Lindstrom, D., and Wolff, R., 2006, Effects of water removal on a Hawaiian stream ecosystem: Pacific Science, v. 60, p. 1–47.

Kirch, P.V., 1982, The impact of prehistoric Polynesians on the Hawaiian ecosystem: Pacific Science, v. 36 no. 1, p. 1–14.

Klemm, D.J., Blockson, K.A., Fulk, F.A., Herlihy, A.T., Hughes, R.M., Kaufmann, P.R., Peck, D.V., Stoddard, J.L., Thoeny, W.T., and Griffith, M.B., 2003, Development and evaluation of a macroinvertebrate biotic integrity index (MBII) for regionally assessing Mid-Atlantic Highlands streams: Environmental Management, v. 31, p. 656–669.

Koch, Linda, Harrigan-Lum, June, and Henderson, Katina, 2004, Final 2004 list of impaired waters in Hawaii: Prepared Under Clean Water Act 303(d): Hawaii State Department of Health, Environmental Planning Office, 67 p.

Kondratieff, B.C., Bishop, R.J., and Brasher, A.M., 1997, The life cycle of an introduced caddisfly, *Cheumatopsyche pettiti* (Banks) (Trichoptera: Hydropsychidae) in Waikolu Stream, Molokai, Hawaii: Hydrobiologia, v. 350, p. 81–85.

Krumholz, L.A., 1948, Reproduction in the western mosquitofish, *Gambusia affinis affinis* (Baird and Girard), and its use in mosquito control: Ecological Monographs, v. 18, p. 1–43.

Kubota, W.T., 1972, The biology of an introduced prawn *Macrobrachium lar* (Fabricius) in Kahana Stream: Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 185 p.

Kuykendall, R.S., and Gregory, H.E., 1926, A history of Hawaii: The Macmillan Company, New York, 375 p.

Lea, Isaac, 1856, Description of fifteen new species of exotic Melaniana: Proceedings of the Academy of Natural Sciences of Philadelphia, v. 8, p. 144–145.

Lee, W.L., 1851, Proceedings of the Royal Agricultural Society: The Transactions of the Royal Hawaiian Agricultural Society, v. 1, no. 2, p. 4–9.

Lenat, D.R., and Barbour, M.T. 1994, Using benthic macroinvertebrate community structure for rapid, cost-effective, water quality monitoring; rapid bioassessment, *in* Loeb, S.L. and Spacie, A., eds., Biological monitoring of aquatic systems: Boca Raton, Lewis Publishers, CRC Press, Inc., p. 187–215.

Liebherr, J.K., and Polhemus, D.A., 1997, Comparisons to the century before; the legacy of R. C. L. Perkins and Fauna Hawaiiensis as the basis for a long-term ecological monitoring program: Pacific Science, v. 51, p. 490–504.

Lindstrom, D.P., and Brown, C.L., 1996, Captive breeding and rearing of native amphidromous Hawaiian gobioids; ramifications for ecosystem management, *in* Devick, W.S., ed., Will stream restoration benefit freshwater, estuarine, and marine fisheries? Proceedings of the Hawaii Stream Restoration Symposium: Hawai‘i Department of Land and Natural Resources, Technical Report 96–01, Honolulu, Hawai‘i, p. 112–131.

Loope, L.L., and Mueller-Dombois, Dieter, 1989, Characteristics of invaded islands, with special reference to Hawaii, *in* Drake, J.A., Mooney, H.A., di Castri, F., Groves, R.H., Kruger, E.J., Rejmánek, M., and Williamson, M, eds., Biological invasions; a global perspective: John Wiley and Sons, New York, p. 257–280.

Lyon, H.L., 1922, Hawaiian Forests: The Hawaiian Forester and Agriculturist, v. 19, no. 7, p. 159–162.

Maciolek, J.A., 1972, Diadromous macrofauna and the Kahana stream-estuary ecosystem: Report to Division of State Parks, Department of Land and Natural Resources, State of Hawai‘i, Honolulu, 22 p.

Maciolek, J.A., 1975, Limnological ecosystems and Hawaii's preservational planning: Verhandlungen Internationale Vereinigung fūr Theoretische und Angewandte Limnologie, v. 19, p. 1461–1467.

Maciolek, J.A., 1976, Fauna of streams and other inlands waters (Draft): Contribution to the Encyclopedia of Hawaii, 13 p.

Maciolek, J.A., 1984, Exotic fishes in Hawaii and other islands of Oceania, *in* Courtenay, W.R. Jr., and Stauffer, J.R. Jr., eds., Distribution, biology, and management of exotic fishes: The Johns Hopkins University Press, Baltimore, Md., p. 131–161.

Mainland, G.B., 1939, Gobioidea and fresh water fish on the island of Oahu: Honolulu, University of Hawai'i at Mānoa, M.S. thesis, 101 p.

Marsden, Joseph, 1894, Conservation of forests: Biennial Report of the Board of the Minister of the Interior, p. 92–96.

McCune, Bruce, and Grace, J.B., 2002, Analysis of ecological communities: MJM Software Design, Gleneden Beach, Oregon, 300 p.

McDowall, R.M., 1988, Diadromy in fishes: Portland, Oregon, Timber Press, 308 p.

McDowall, R.M., 1993, A recent marine ancestry for diadromous fishes? Sometimes yes, but mostly no!: Environmental Biology of Fishes, v. 37, p. 329–335.

McDowall, R.M., 2003, Hawaiian biogeography and the islands' freshwater fish fauna: Journal of Biogeography, v. 30, p. 703–710.

McIntosh, M.D., Benbow, M.E., and Burky, A.J., 2002, Effects of stream diversion on riffle macroinvertebrate communities in a Maui, Hawaii, stream: River Research and Applications, v. 18, p. 569–581.

McIntosh, M.D., Benbow, M.E., and Burky, A.J., 2003, Effect of water removal on introduced caddisflies from a tropical mountain stream: Annales de Limnologie – International Journal of Limnology, v. 39, p. 297–306.

McIntosh, M.D., Schmitz, J.A., Benbow, M.E., and Burky, A.J., 2008, Structural and functional changes of tropical riffle macroinvertebrate communities associated with stream flow withdrawal: River Research and Applications, v. 24, p. 1045–1055.

McLachlan, Robert, 1883, Neuroptera of the Hawaiian Islands. Part I. Pseudo-Neuroptera: The Annals and Magazine of Natural History (Fifth Series), v. 12, no. 70, p. 226–240.

McRae, M.G., 2007a, Watershed-scale patterns of seaward migration in *Lentipes concolor*, a Hawaiian stream goby: Baton Rouge, Louisiana State University, Ph.D. dissertation, 71 p.

McRae, M.G., 2007b, The potential for source-sink population dynamics in Hawaii's amphidromous fishes, *in* Evenhuis, N.L., and Fitzsimons, J.M., eds., Biology of Hawaiian streams and estuaries: Honolulu, Bishop Museum Bulletin in Cultural and Environmental Studies, p. 87–98.

Meador, M.R., Hupp, C.R., Cuffney, T.F., and Gurtz, M.E., 1993, Methods for characterizing stream habitat as part of the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 93–408, 48 p.

Moulton, S.R., II, Kennen, J.G., Goldstein, R.M., and Hambrook, J.A., 2002, Revised protocols for sampling algal, invertebrate, and fish communities as part of the National Water-Quality Assessment program: U.S. Geological Survey Open-File Report 02-150, 75 p.

Nakagawa, P.Y., 1964, Mosquito control in Hawaii: Pest Control Magazine (Reprint), v. 32, no. 4, 3 p.

Nakagawa, P.Y., and Hirst, J.M., 1959, Current efforts in mosquito control in Hawaii: Mosquito News, v. 19, no. 2, p. 64–67.

Needham, P.R., and Usinger, R.L., 1961, Combined report on the mayfly project for the months January - March and April - June: Hawaii Division of Fish and Game, Freshwater Game Fish Management Research, Introduction of Aquatic Insects and Other Invertebrates, 2 p.

Newman, L.J., 1975, Cytogenetics of the Hawaiian *Telmatogeton* (Diptera): Island Ecosystems Integrated Research Program, U.S. International Biological Program, Technical Report No. 56, 23 p.

Newman, L.J., 1977, Chromosomal evolution of the Hawaiian *Telmatogeton* (Chironomidae, Diptera): Chromosoma, v. 64, p. 349–369.

Newman, L.J., 1988, Evolutionary relationships of the Hawaiian and North American *Telmatogeton* (Insecta; Diptera; Chironomidae): Pacific Science, v. 42, p. 56–64.

Nielsen, Anker, 1950, The torrential invertebrate fauna: Oikos, v. 2, no. 2, p. 176–196.

Nishida, G.M., 1992, Hawaiian Terrestrial Arthropod Checklist: Bishop Museum Press, Honolulu, Hawaii, 262 p.

Nordhoff, Charles, 1874, Northern California, Oregon, and the Sandwich Islands: Harper and Brothers, New York, 256 p.

Oki, D.S., and Brasher, A.M.D., 2003, Environmental setting and the effects of natural and human-related factors on water quality and aquatic biota, Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report

03-4156, 98 p.

Oki, D.S., Wolff, R.H., and Perreault, J.A., 2006, Effects of surface-water diversion and ground-water withdrawal on streamflow and habitat, Punalu‘u Stream, Oahu, Hawaii: U.S. Geological Survey Scientific Investigations Report 06-5153, 104 p.

Oki, D.S., Wolff, R.H., and Perreault, J.A., 2010, Effects of surface-water diversion on streamflow, recharge, physical habitat, and temperature, Nā Wai ‘Ehā, Maui, Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2010-5011, 154 p.

Osten-Sacken, C.R., 1884, Facts concerning the importation or non-importation of Diptera into distant countries: The Transactions of the Entomological Society of London for the Year 1884, p. 489–496.

Pease, W.H., 1870, Remarks on the species of *Melania* and *Limnaea* inhabiting the Hawaiian Islands, with descriptions of new species: American Journal of Conchology, v. 6, no. 1, p. 4–7.

Peck, J.E., 2010, Multivariate analysis for ommunity ecologists; step-by-step using PC-ORD: MjM Software Design, Gleneden Beach, Oregon, 162 p.

Penn, G.H., 1954, Introductions of American crawfishes into foreign lands: Ecology, v. 35, 296 p.

Perkins, R.C.L., 1913, Introduction; being a review of the land-fauna of Hawaii, *in* Sharp, D., ed., Fauna Hawaiiensis or the zoology of the Sandwich (Hawaiian) Isles: Cambridge University Press, v. 1, part 6, p. xv–ccxxviii.

Polhemus, D.A., 1992, A survey of the aquatic insect fauna of Hanawi Stream, East Maui, Hawaii: Prepared for the Natural Area Reserves System, Hawaii State Department of Land and Natural Resources, 16 p.

Polhemus, D.A., 1993, Damsels in distress; a review of the conservation status of Hawaiian *Megalagrion* damselflies (Odonata: Coenagrionidae): Aquatic Conservation, Marine and Freshwater Ecosystems, v. 3, p. 343–349.

Polhemus, D.A., 1995, A survey of the aquatic insect faunas of selected Hawaiian streams: Prepared for the Commission on Water Resource Management, Hawai‘i State Department of Land and Natural Resources, 128 p.

Polhemus, D.A., 2008, Integrating aquatic insect data into Hawaiian stream assessments: Presented at the Workshop on Ecology, Restoration, and Management of Hawaiian Stream and Riparian Systems, Windward Community College, Kāne‘ohe, Hawai‘i, 20–22 May 2008, 30 p.

Polhemus, D.A., and Asquith, Adam, 1996, Hawaiian damselflies; a field identification guide: Bishop Museum Press, Honolulu, Hawaii, 122 p.

Polhemus, D.A., Maciolek, John, and Ford, John, 1992, An ecosystem classification of inland waters for the tropical Pacific Islands: Micronesica, v. 25, p. 155–173.

Radtke, R.L., Kinzie, R.A., III, and Folsom, S.D., 1988, Age at recruitment of Hawaiian freshwater gobies: Environmental Biology of Fishes, v. 23, p. 205–213.

Radtke, R.L., Kinzie, R.A., III, and Shafer, D.J., 2001, Temporal and spatial variation in length of larval life and size at settlement of the Hawaiian amphidromous goby *Lentipes concolor*: Journal of Fish Biology, v. 59, p. 928–938.

Resh, V.H., and Jackson, J.K., 1993, Rapid assessment approaches to biomonitoring using benthic macroinvertebrates, *in* Rosenberg, D.M., and Resh, V.H., eds., Freshwater biomonitoring and benthic macroinvertebrates: New York, Chapman and Hall, p. 195–233.

Reynolds, S.R., 1850, Reminiscences of Hawaiian agriculture: The Transactions of the Royal Hawaiian Agricultural Society, v. 1, no. 1, p. 49–53.

Rosenberg, D.M., and Resh, V.H., 1993, Introduction to freshwater biomonitoring and benthic macroinvertebrates, *in* Rosenberg, D.M., and Resh, V.H., eds., Freshwater biomonitoring and benthic macroinvertebrates: New York, Chapman and Hall, p. 1–9.

Rowe, B.L., Landrigan, S.J., and Lopes, T.J., 1997, Summary of published aquatic toxicity information and water-quality criteria for selected volatile organic compounds: U.S. Geological Survey Open-File Report 97-563, 60 p.

Russel, C.H., 1891, The best mosquito remedy: U.S. Department of Agriculture, Division of Entomology, Insect Life, v. 4, nos. 5 and 6, p. 223.

S.A.M., 1891, The destruction of mosquitoes (Letters to the editor): Nature, v. 44, October 22, p. 591.

Schoenfuss, H.L., and Blob, R.W., 2003, Kinematics of waterfall climbing in Hawaiian freshwater fishes (Gobiidae); vertical propulsion at the aquatic-terrestrial interface: Journal of Zoology, London, v. 261, p. 191–205.

Seale, Alvin, 1905, Report of Mr. Alvin Seale of the United States Fish Commission, on the introduction of top-minnows to Hawaii from Galveston, Texas: The Hawaiian Forester and Agriculturist, v. 2, p. 364–367.

Shima, S.I., 1968, Introduction of aquatic insects and other invertebrates: Hawaii Division of Fish and Game, Job

Completion Report, Research Project Segment, Freshwater Game Fish Management Research, Project no. F-4-R-16, Job no. 2, 2 p.

Shima, S.I., 1969, Introduction of aquatic insects and other invertebrates: Hawaii Division of Fish and Game, Job Completion Report, Research Project Segment, Freshwater Game Fish Management Research, Project no. F-4-R-17, Job no. 2, 2 p.

Shima, S.I., 1970, Limnological survey for introduction of exotic species of fish: Hawaii Division of Fish and Game, Job Completion Report, Research Project Segment, Freshwater Game Fish Management Research, Project no. F-4-R-18, Job no. 3, 4+ p.

Shiroma, E., 1972, Notes and exhibitions; *Cheumatopsyche analis*: Proceedings of the Hawaiian Entomological Society, v. 21, no. 2, p. 161.

Shoda, M.E., 2009, Cascade macroinvertebrate assemblages for in-stream flow criteria and biomonitoring of high gradient tropical streams: Dayton, Ohio, University of Dayton, M.S. thesis, 117 p.

Shoda, M.E., Gorbach, K.R., Benbow, M.E., and Burky, A.J., 2011, Cascade macroinvertebrate assemblages for in-stream flow criteria and biomonitoring of tropical mountain streams: River Research and Applications, doi: 10.1002/rra.1458, 12 p.

Smith, G.C., 2000, Rediscovery of the introduced mayfly *Caenis nigropuncata* (Ephemeroptera: Caenidae) in Waimanalo Stream, Oahu: Bishop Museum Occasional Papers, v. 64, p. 30–31.

St. John, Harold, 1947, The history, present distribution, and abundance of sandalwood on Oahu, Hawaiian Islands: Hawaiian plant studies 14: Pacific Science, v. 1, p. 5–20.

State of Hawaii, 2009, The State of Hawaii data book 2009, a statistical abstract: State of Hawaii, Department of Business, Economic Development, and Tourism, accessed May 13, 2011 at http://hawaii.gov/dbedt/info/economic/databook/db2009/.

Stearns, H.T., and MacDonald, G.A., 1942, Geology and ground-water resources of the island of Maui, Hawaii: Hawai‘i Division of Hydrography Bulletin 7, 344 p.

Stubbs, W.C., 1901, Forestry: Paradise of the Pacific, v. 14, no. 11, p. 17.

Svihla, Arthur, 1941, The occurrence of freshwater sponges in the Hawaiian Islands: Science, v. 94, no. 2438, p. 278–279.

Sykes, E.R., 1900, Mollusca: Fauna Hawaiiensis, v. 2, part 4, p. 271–412.

Tate, D.C., Fitzsimons, J.M., and Cody, R.P., 1992, Hawaiian freshwater fishes (Osteichthyes, Gobioidei); a field key to the species of larvae and postlarvae during recruitment into fresh waters: Baton Rouge, Louisiana State University, Occasional Papers of the Museum of Natural Science, v. 65, p. 1–10.

Terry, F.W., 1913, On a new genus of Hawaiian chironomids: Proceedings of the Hawaiian Entomological Society, v. 2, no. 5, p. 291–294.

Tester, A.L., and Trefz, S.M., 1954, The food of the aholehole, *Kuhlia sandvicensis* (Steindachner), in Hawaiian waters: Pacific Science, v. 8, p. 3–10.

Thrum, T.G., 1904, The sandalwood trade of early Hawaii: Thrum’s Hawaiian Almanac and Annual for 1905, p. 43–74.

Timbol, A.S., 1977, A report on the aquatic survey of stream macrofauna for the hydroelectric power study for Hawaii: Prepared for Department of the Army Corps of Engineers, Pacific Ocean Division, 48+ p.

Timbol, A.S., 1984a, Biological reconnaissance of Kaluanui Stream, Oahu: Revised Environmental Impact Statement for the Kaluanui Wells, p. B1–B17.

Timbol, A.S., 1984b, Biological reconnaissance of Kaneohe Stream and two of its tributaries; Luluku and Kamooalii, Oahu: Revised Environmental Impact Statement for Kamooalii Watershed Wells, Board of Water Supply, City and County of Honolulu, p. B1–B11.

Timbol, A.S., and Maciolek, J.A., 1978, Stream channel modification in Hawaii. Part A; statewide inventory of streams; habitat factors and associated biota: U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-78/16, 158 p.

Tomihama, M.T., 1972, The biology of *Sicydium stimpsoni*; freshwater goby endemic to Hawaii: Honolulu, University of Hawai‘i at Mānoa, B.S. Honors thesis, 123 p.

U.S. Army, 1945, Army activities resulting in benefits to the Territory of Hawaii; series 8 disease prevention; subject 2 mosquito control: Prepared By Control Division, Headquarters AFMIDPAC, 12 p.

USEPA, 2004, Wadeable streams assessment; field operations manual: U.S. Environmental Protection Agency (USEPA), Office of Water and Office of Research and Development, Washington, D.C., EPA 841–B–04–004, 152 p.

USFWS, 1978, The biological resources of the Hilo study area, Hawaii, Hawaii; An Overview: U.S. Department of the Interior, Fish and Wildlife Service, Hilo Area Comprehensive Study, 143+ p.

USFWS, 1996, Endangered and threatened species, plant and animal taxa; proposed rule: Federal Register, v. 61, no. 40, p. 7595–7613.

USFWS, 2009, Endangered and threatened wildlife and plants; proposed endangered status for flying earwig Hawaiian damselfly (*Megalagrion nesiotes*) and Pacific Hawaiian damselfly (*M. pacificum*) throughout their ranges: Federal Register, v. 74, no. 129, p. 32490–32510.

USFWS, 2010, Endangered and threatened wildlife and plants; listing the flying earwig Hawaiian damselfly and Pacific Hawaiian damselfly as endangered throughout their ranges: Federal Register, v. 75, no. 121, p. 35990–36012.

Usinger, R.L., 1941, Problems of insect speciation in the Hawaiian Islands: The American Naturalist, v. 75, no. 758, p. 251–263.

Van Dine, D.L., 1903, Mosquitoes: Public Informational Poster for Mosquitoe Extermination (Printed in five languages: English, Hawaiian, Portuguese, Japanese, and Chinese), U.S. Department of Agriculture, Hawaii Experiment Station.

Van Dine, D.L., 1904, Mosquitoes in Hawaii: Hawaii Agricultural Experiment Station, Bulletin no. 6, 30 p.

Van Dine, B.L., 1907, The introduction of top-minnows into the Hawaiian Islands: Hawaii Agricultural Experiment Station, Press Bulletin No. 20, 10 p.

Van Zwaluwenburg, R.H., 1945, Notes and exhibitions; new or rare insect records for Hawaii: Proceedings of the Hawaiian Entomological Society, v. 12, no. 2, p. 228.

Vincent, A.G., and Font, W.F., 2003a, Host specificity and population structure of two exotic helminthes, *Camallanus cotti* (Nematoda) and *Bothriocephalus acheilognathi* (Cestoda), parasitizing exotic fishes in Waianu Stream, Oahu, Hawaii: Journal of Parasitology, v. 89, no. 3, p. 540–544.

Vincent, A.G., and Font, W.F., 2003b, Seasonal and yearly population dynamics of two exotic helminthes, *Camallanus cotti* (Nematoda) and *Bothriocephalus acheilognathi* (Cestoda), parasitizing exotic fishes in Waianu Stream, Oahu, Hawaii: Journal of Parasitology, v. 89, no. 4, p. 756–760.

Walther, A.C., 2008, A systematic study of North American freshwater limpets (Gastropoda: Hygrophila: Ancylidae): Michigan, University of Michigan, Ph.D. dissertation, 122 p.

Way, C.M., and Burky, A.J., 1991, A preliminary survey of macroinvertebrates and a preliminary assessment of the diet of the endemic Hawaiian goby (‘o‘opu ‘alamo‘o), *Lentipes concolor* (Gill), *in* Devick, W.S., ed., New directions in research, management and conservation of Hawaiian freshwater stream ecosystems, Proceedings of the 1990 Symposium on Freshwater Stream Biology and Fisheries Management: Department of Land and Natural Resources, Division of Aquatic Resources, Honolulu, Hawaii, p. 158–164.

Weigel, B.M., 2003, Development of stream macroinvertebrate models that predict watershed and local stressors in Wisconsin: Journal of the North American Benthological Society, v. 22, p. 123–142.

Weigel, B.M., Henne, L.J., and Martinez-Rivera, L.M., 2002, Macroinvertebrate-based index of biotic integrity for protection of streams in west-central Mexico: Journal of the North American Benthological Society, v. 21, p. 686–700.

Wiederholm, T., 1984. Responses of aquatic insects to environmental pollution, *in* Resh, V.H., and Rosenberg, D.M., eds., The ecology of aquatic insects: Praeger, New York, p. 508–557.

Wilcox, Carol, 1996, Sugar water; Hawaii’s plantation ditches: University of Hawai‘i Press, Honolulu, 191 p.

Williams, F.X., 1936, Biological studies in Hawaiian water-loving insects; Part I. Coleoptera or beetles; Part II. Odonata or dragonflies: Proceedings of the Hawaiian Entomological Society, v. 9, no. 2, p. 235–349.

Wirth, W.W., 1947, A review of the genus *Telmatogeton* Schiner, with descriptions of three new Hawaiian species (Diptera: Tendipedidae): Proceedings of the Hawaiian Entomological Society, v. 13, no. 1, p. 143–195.

Wolff, R.H., 2000, Seasonal recovery patterns of Hawaiian stream flora and fauna, Wainiha River, Kauai, Hawaii: Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 74 p.

Wolff, R.H., 2005, Feasibility of using benthic invertebrates as indicators of stream quality in Hawaii: U.S. Geological Survey Scientific Investigations Report 2005-5079; 78 p.

Wolff, R.H., and Koch, L.A., 2009, Ecological assessment of wadeable streams on O‘ahu, Hawai‘i, 2006–2007: a pilot study: U.S. Geological Survey Scientific Investigations Report 2009-5229, 83 p.

Wolff, R.H., Brasher, A.M., and Richards, A.B., 2002, New generic records of Hawaiian Chironomidae (Diptera): Bishop Museum Occasional Papers, v. 69, p. 31–33.

Yamamoto, M.N., 1992, Occurrence, distribution and abundance of accidentally introduced freshwater aquatic organisms in Hawaii; investigations of the impact of accidentally introduced freshwater aquatic organisms and of methods for control or eradication: Hawaii Department of Land and Natural Resources, Division of Aquatic Resources, Job Progress Report, Freshwater Fisheries Research and Surveys, Project no. F-14-R-16, Job nos. 1 and 2 (Study VIII), 6 p.

Yamamoto, M.N., 1993, Occurrence, distribution and abundance of accidentally introduced freshwater aquatic organisms in Hawaii: Hawaii Department of Land and Natural Resources, Division of Aquatic Resources, Annual Performance Report, Freshwater Fisheries Research and Surveys, Project no. F-14-R-17, Job no. 1 (study VIII), 5+ p.

Yamamoto, M.N., 1996, Accidental introductions of aquatic organisms into Hawaiian freshwater ecosystems: Hawaii Division of Aquatic Resources, Job Progress Report, Freshwater Fisheries Research and Surveys, Project no. F-14-R-20, Job nos. 1 and 2 (Study VIII), 4+ p.

Yamamoto, M.N., and Tagawa, A.W., 2000, Hawaii's native and exotic freshwater animals: Honolulu, Hawai‘i, Mutual Publishing, 200 p.

Yee, J.J.S., and Ewart, C.J., 1986, Biological, morphological, and chemical characteristics of Wailuku River, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 86-4043, 69 p.

Yoshida, R.N., 1961, Introduction of aquatic insects and other invertebrates: Hawaii Division of Fish and Game, Job Completion Report, Fresh Water Game Fish Management Research, Project no. F-4-R-9, Job no. 2, 2+ p.

Zimmerman, E.C., 1943, On the establishment of the order Trichoptera in Hawaii: Proceedings of the Hawaiian Entomological Society, v. 11, no. 3, p. 350–352.

Zimmerman, E.C., 1947, Insects of Hawaii; Volume 1. Introduction (reissued 2001): University of Hawaii Press, Honolulu, Hawaii, 206 p.

Zimmerman, E.C., 1948, Insects of Hawaii; Volume 2. Apterygota to Thysanoptera: University of Hawaii Press, Honolulu, Hawaii, 475 p.

Zimmerman, E.C., 1951, Notes and exhibitions; *Caenis nigropunctata*: Proceedings of the Hawaiian Entomological Society, v. 14, no. 2, p. 205.

Appendixes A–D

Appendix A. Evaluation of Replicate, Re-sort, and Repeat Samples of Macroinvertebrates Collected from Streams on Maui, Hawai‘i, 2009-2010

Multivariate statistical analyses were used to evaluate the results of the replicate, re-sort, and repeat samples collected on Maui (figs. A1–A2). Nonmetric multidimensional scaling (nMDS) was used to examine the relations among the samples (Clarke, 1993). These relations were assessed using the abundance (organisms/m^2) dataset and the relative abundance (proportional) dataset. Abundance data were log(x + 1) transformed before the analysis, and the proportional data were arcsine–square root transformed before the analysis. Hierarchical agglomerative clustering was performed on both datasets using Bray–Curtis similarity scores to compare the samples. Figure A3 displays the nMDS ordination of the results for (A) the proportional dataset and (B) the abundance dataset. Samples that plot near to each other are most similar. The results of the resemblance clustering were overlaid on the ordination plots to show the percent similarity between the samples.

Re-sorted Samples

The unsorted material remaining from four previously sorted quantitative samples was sorted by the contract laboratory, EcoAnalysts Inc., to assess some of the variability inherent in the subsampling process. These samples were from Kōlea, Kopili‘ula-B, Hanawī-A, and the replicate sample from Hanawī-A (fig. A1; tables A1–A3) The Kōlea re-sort and original sort grouped very closely on the nMDS ordination and clustered with a 90 percent similarity using the proportional data (fig. A3*A*). They were a little farther apart using the abundance data, with an 80 percent similarity (fig. A3*B*). This was because the original sort was calculated to have 23,137 organisms/m^2, with only 1.82 percent of the sample sorted to achieve the 500-organism count, whereas the re-sort contained 9,869/m^2, with 4.17 percent of the remaining material required to be sorted (table A1). The samples from Kopili‘ula-B showed a similar trend, grouping closely together in the ordination with a 90 percent similarity using the proportional data (fig. A3*A*) and an 85 percent similarity with the abundance data (fig. A3*B*). The original sort required 10.94 percent of the sample whereas the re-sort required 18.76 percent. The Hanawī-A samples all grouped closely together, the two replicates and one re-sort had an 85 percent similarity, and all four had an 80 percent similarity with the proportional data (fig. A3*A*), and they also grouped closely together, with both re-sorts having an 85 percent similarity, the two replicates having an 80 percent similarity, and all four having a 75 percent similarity with the abundance data (fig. A3*B*). These results show that there is some variability in the subsampling process, although there is an overall high degree of similarity between the samples.

Replicate Samples

Replicate quantitative samples were collected at eight sites, including Hanawī-A (as discussed in the previous section), Hanawī-B, Honolua, Olowalu-B, Waihe‘e-B, ‘Īao-C, North Waiehu-A, and South Waiehu-A (figs. A1–A2; tables A4–A10). These paired samples all tended to group closely together using either dataset (fig. A3*A* and *B*). The percent similarity ranged from 75 to 85 percent with a mean of 81.25 percent, using the proportional data (fig. A3*A*) and from 70 to 90 percent, with a mean of 80 percent similarity with the abundance data. These results show that there is some variability between the pairs of samples due to the heterogeneous nature of physical habitats in tropical streams, and that some macroinvertebrate assemblages from other similar streams grouped closely to these pairings, although there is an overall high degree of similarity between the paired replicate samples.

Repeat Samples

Three repeat quantitative samples were collected at the Waihe‘e-A site over the duration of the field work on Maui (fig. A2). The first sample was collected on September 22, 2009, the second on October 23, 2009, and the third on January 29, 2010 (table A11).The ordination of the proportional data revealed that the first and third samples had a higher degree of similarity, grouping closer together with an 85 percent similarity, than either sample had with the second sample, with a 70 percent similarity (fig. A3*A*). The ordination of the abundance data revealed a comparable trend, with the first and third samples grouping closer together and sharing an 80 percent similarity and the second sample having a 75 percent similarity with the others (fig. A3*B*). The second sample had a lower total abundance of macroinvertebrates than the other two samples, 57 percent less than the first and 61 percent less than the third sample. This was mainly due to much lower abundances of the chironomids *Cricotopus* (73 and 77 percent fewer, respectively) and *Eukiefferiella* (71 and 70 percent fewer, respectively) in the second sample (table A11). This reduction caused the relative abundances of other macroinvertebrates, especially the trichopterans *Cheumatopsyche* and Hydroptilidae to be greater in the second sample (table A11). The exact cause of the decline in chironomids in the second sample is uncertain. Some of this variability is accounted for in the spatial heterogeneity demonstrated in the replicate sample comparisons, but this does not account for the sharp decline and subsequent upturn in chironomid abundances. It is possible that the sampling locations of the second sample were disturbed by a series of four relatively small spates that occurred in the 32 days between sampling, or perhaps the sampling locations were inadvertently disturbed during the collection of the first sample and the chironomids were not able to recover in the short time between sampling.

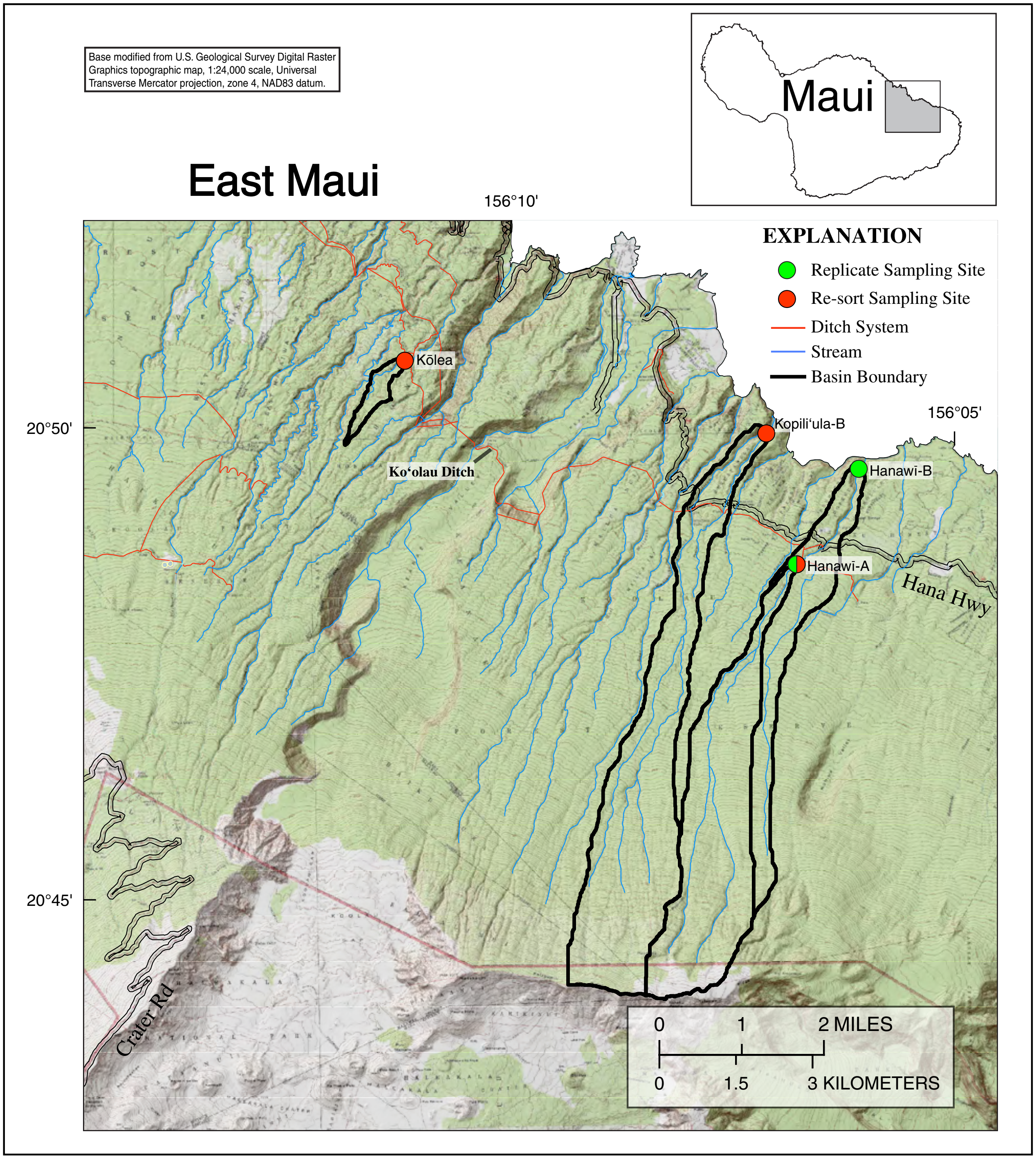


Figure A1. Locations of replicate and re-sort sampling sites on East Maui.

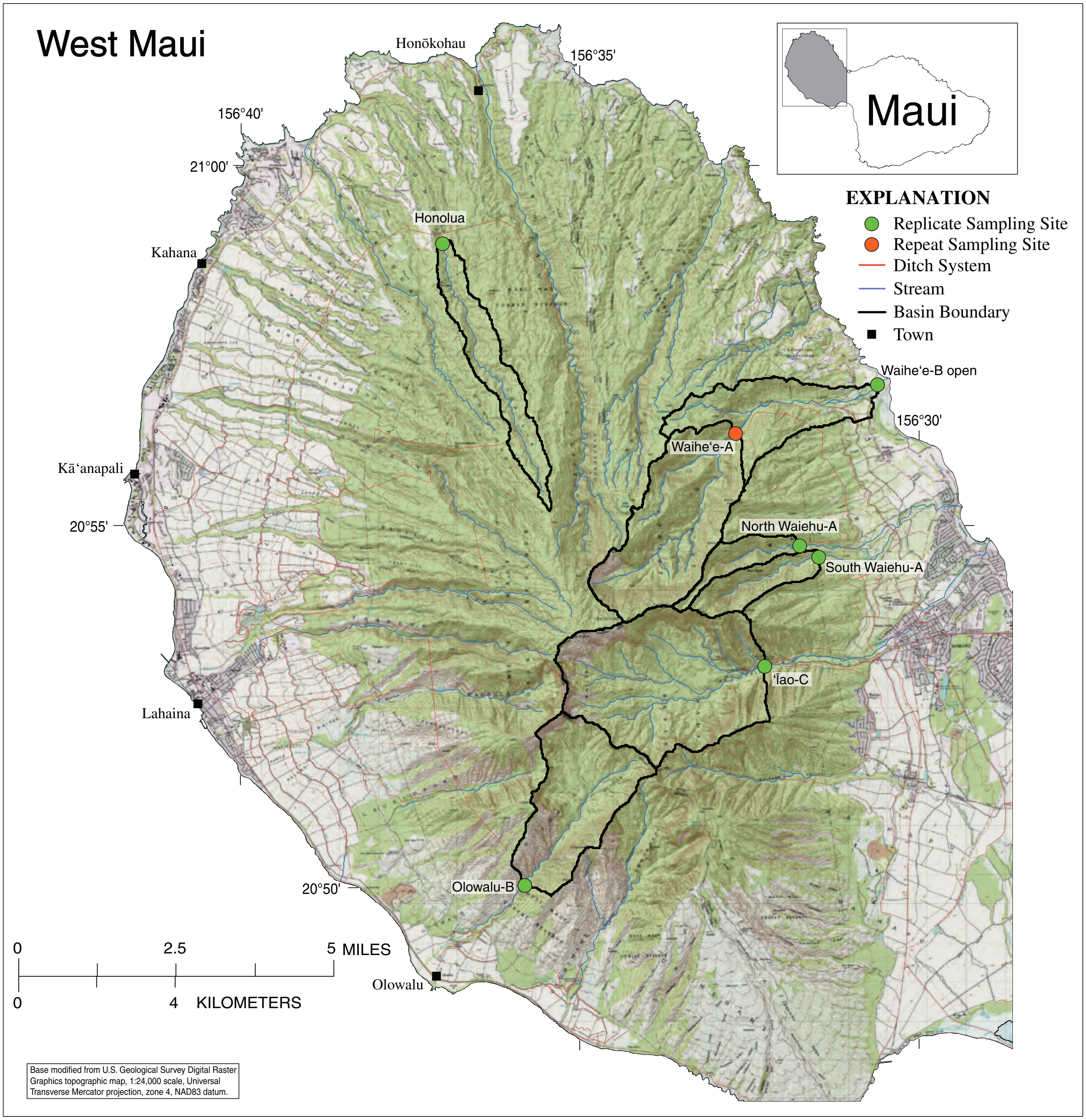


Figure A2. Locations of replicate and repeat sampling sites on West Maui.

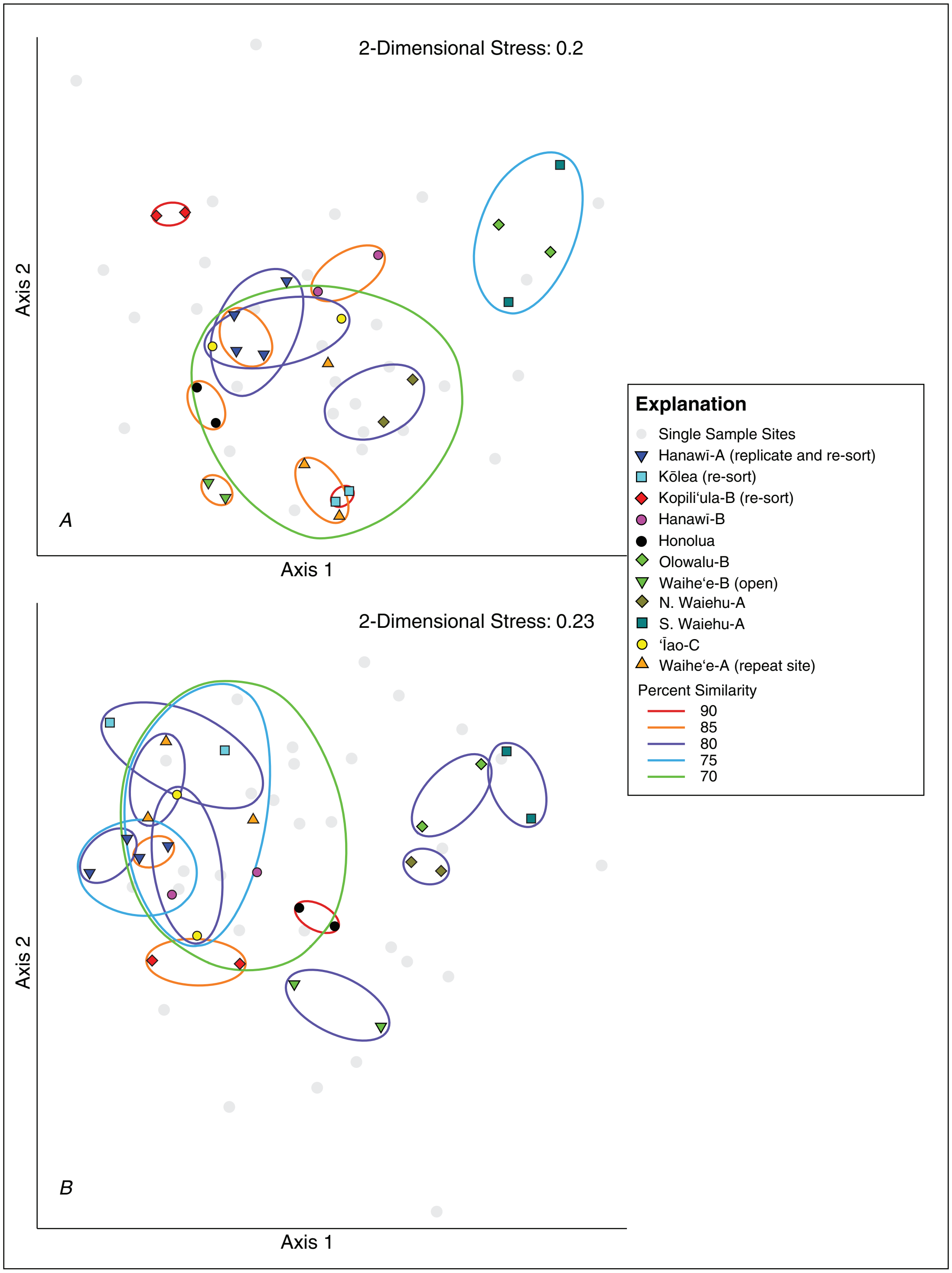


Figure A3. Nonmetric multidimensional scaling (nMDS) ordinations of the Maui quantitative macroinvertebrate samples displaying the relationships between the re-sorted, replicate, and repeat samples using (*A*) arcsine-square root transformed proportional data and (*B*) log(*x*+1) transformed abundance data (logarithm of the sum of the abundance plus one, with abundance in number of organisms per square meter). Colored lines are statistically derived overlay of cluster contours from a dendrogram plot determined using hierarchical agglomerative cluster analysis.

Table A1. Re-sorted quantitative sample from Kōlea (HI_MAUI_09-011).

[—, not observed in sample]

Taxon	Sample			
	A (first sort: 1.82 percent)		A (second sort: 4.17 percent)	
	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample
Nemertea	131.7	0.6	38.4	0.4
Oligochaeta	877.8	3.8	211.0	2.1
Ferrissia sp.	131.7	0.6	38.4	0.4
Lymnaeidae	131.7	0.6	19.2	0.2
Acari	43.9	0.2	38.4	0.4
Atyoida bisulcata	8.0	0.0	46.4	0.5
Cricotopus bicinctus gr.	8,470.4	36.6	4,086.3	41.4
Eukiefferiella sp.	9,699.3	41.9	3,760.2	38.1
Orthocladius Complex	43.9	0.2	—	—
Telmatogeton sp.	307.2	1.3	57.6	0.6
Megalagrion sp.	—	—	19.2	0.2
Cheumatopsyche sp.	2,721.1	11.8	1,381.3	14.0
Hydroptilidae	570.5	2.5	172.7	1.8
Total	23,137.2	100	9,869.1	100

Table A2. Re-sorted quantitative sample from Kopili‘ula-B (HI_MAUI_09-014).

[—, not observed in sample]

Taxon	Sample			
	A (first sort: 10.94 percent)		A (second sort: 18.76 percent)	
	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample
Nemertea	29.3	0.8	25.6	1.1
Oligochaeta	1,162.7	30.9	665.3	29.3
Ferrissia sp.	—	—	17.1	0.8
Lymnaeidae	7.3	0.2	12.8	0.6
Neritina granosa	34.4	0.9	34.4	1.5
Tanaidacea	14.6	0.4	—	—
Atyoida bisulcata	1.6	0.0	1.6	0.1
Apedilum sp.	95.1	2.5	38.4	1.7
Paratanytarsus sp.	—	—	4.3	0.2
Cricotopus bicinctus gr.	336.4	9.0	157.8	7.0
Eukiefferiella sp.	73.1	2.0	59.7	2.6
Orthocladius Complex	7.3	0.2	4.3	0.2
Cheumatopsyche sp.	1,053.0	28.0	733.5	32.3
Hydroptilidae	943.3	25.1	516.0	22.7
Total	3,758.1	100	2,270.8	100

Table A3. Replicate and re-sorted quantitative samples from Hanawī-A (HI_MAUI_09-004).

[—, not observed in sample]

Taxon	A (first sort: 5.21 percent)		A (second sort: 4.17 percent)		B (first sort: 6.25 percent)		B (second sort: 5.73 percent)	
	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample
Nemertea	—	—	19.2	0.2	—	—	14	0.2
Erpobdellidae	—	—	19.2	0.2	12.8	0.2	—	—
Oligochaeta	721.7	9.1	76.7	0.7	832.0	12.5	251.3	3.3
Acari	30.7	0.4	—	—	12.8	0.2	—	—
Atyoida bisulcata	80.0	1.0	80.0	0.8	56.0	0.8	56.0	0.7
Apedilum sp.	245.7	3.1	95.9	0.9	102.4	1.5	97.7	1.3
Paratanytarsus sp.	—	—	—	—	12.8	0.2	—	—
Pseudochironomus sp.	15.4	0.2	—	—	—	—	—	—
Cricotopus bicinctus gr.	2,011.5	25.4	2,647.5	25.3	2,291.2	34.4	2,890.1	38.4
Eukiefferiella sp.	460.7	5.8	326.1	3.1	486.4	7.3	432.8	5.8
Telmatogeton sp.	—	—	—	—	25.6	0.4	27.9	0.4
Limonia sp.	—	—	38.4	0.4	—	—	27.9	0.4
Coenagrionidae	15.4	0.2	—	—	—	—	—	—
Megalagrion sp.	—	—	38.4	0.4	1.6	0.02	—	—
Cheumatopsyche sp.	2,410.8	30.5	4,278.2	40.8	1,523.2	22.9	2,192.0	29.1
Hydroptilidae	1,919.4	24.3	2,858.5	27.3	1,305.6	19.6	1,535.8	20.4
Total	7,911.3	100	10,478.1	100	6,662.4	100	7,525.5	100

Table A4. Replicate quantitative samples from Hanawī-B (HI_MAUI_09-015).

[—, not observed in sample]

Taxon	Sample A: Absolute abundance, in number of organisms per square meter	Sample A: Relative abundance, in percentage of organisms in sample	Sample B: Absolute abundance, in number of organisms per square meter	Sample B: Relative abundance, in percentage of organisms in sample
Nemertea	38.4	0.6	23.0	0.5
Oligochaeta	153.6	2.3	23.0	0.5
Ferrissia sp.	—	—	7.7	0.2
Lymnaeidae	38.4	0.6	—	—
Neritina granosa	0.8	0.0	2.4	0.1
Atyoida bisulcata	40.0	0.6	8.8	0.2
Apedilum sp.	76.8	1.1	30.7	0.7
Cricotopus bicinctus gr.	1,638.4	24.1	583.5	13.8
Eukiefferiella sp.	371.2	5.5	215.0	5.1
Telmatogeton sp.	—	—	7.7	0.2
Ephydridae	51.2	0.8	15.4	0.4
Cheumatopsyche sp.	3,686.4	54.1	2,963.5	70.0
Hydroptilidae	716.8	10.5	353.2	8.3
Total	6,812	100	4,233.9	100

Table A5. Replicate quantitative samples from Honolua (HI_MAUI_09-020).

[—, not observed in sample]

Taxon	Sample A: Absolute abundance, in number of organisms per square meter	Sample A: Relative abundance, in percentage of organisms in sample	Sample B: Absolute abundance, in number of organisms per square meter	Sample B: Relative abundance, in percentage of organisms in sample
Nemertea	8.8	0.8	18.3	1.9
Oligochaeta	61.4	5.4	36.6	3.7
Ferrissia sp.	41.6	3.7	42.1	4.3
Lymnaeidae	188.5	16.7	263.8	26.8
Apedilum sp.	83.3	7.4	18.3	1.9
Cricotopus bicinctus gr.	309.0	27.4	225.3	22.9
Eukiefferiella sp.	184.1	16.3	111.8	11.4
Telmatogeton sp.	2.2	0.2	—	—
Cheumatopsyche sp.	190.7	16.9	208.8	21.2
Hydroptilidae	59.2	5.2	58.6	6.0
Total	1,128.8	100	983.6	100

Table A6. Replicate quantitative samples from Olowalu-B (HI_MAUI_09-022).

[—, not observed in sample]

Taxon	Sample			
	A		B	
	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample
Nemertea	—	—	2.9	0.2
Erpobdellidae	3.2	0.2	—	—
Oligochaeta	9.6	0.6	5.7	0.4
Ferrissia sp.	48.0	2.8	22.8	1.5
Physidae	364.8	21.6	42.7	2.8
Acari	6.4	0.4	2.9	0.2
Atyoida bisulcata	—	—	7.7	0.5
Apedilum sp.	3.2	0.2	2.9	0.2
Cricotopus bicinctus gr.	137.6	8.1	94.0	6.2
Eukiefferiella sp.	102.4	6.1	96.8	6.4
Ephydridae	—	—	2.9	0.2
Megalagrion sp.	—	—	5.7	0.4
Cheumatopsyche sp.	1,008.0	59.7	1,216.1	79.9
Hydroptilidae	6.4	0.4	19.9	1.3
Total	1,689.6	100	1,523.0	100

Table A7. Replicate quantitative samples from Waihe‘e-B open (HI_MAUI_09-023).

[—, not observed in sample; abundance in number per square meter]

Taxon	Sample A: Absolute abundance, in number of organisms per square meter	Sample A: Relative abundance, in percentage of organisms in sample	Sample B: Absolute abundance, in number of organisms per square meter	Sample B: Relative abundance, in percentage of organisms in sample
Oligochaeta	15.9	2.2	64.0	4.9
Ferrissia sp.	1.5	0.2	2.6	0.2
Acari	1.5	0.2	—	—
Ostracoda	4.3	0.6	—	—
Atyoida bisulcata	—	—	2.6	0.2
Apedilum sp.	140.5	19.0	189.4	14.4
Paratanytarsus sp.	2.9	0.4	5.1	0.4
Tanytarsus sp.	1.5	0.2	—	—
Cricotopus bicinctus gr.	324.3	43.8	657.9	50.1
Eukiefferiella sp.	23.2	3.1	41.0	3.1
Gymnometriocnemus sp.	—	—	2.6	0.2
Ephydridae	1.5	0.2	12.8	1.0
Megalagrion sp.	1.5	0.2	—	—
Cheumatopsyche sp.	204.2	27.6	322.6	24.6
Hydroptilidae	17.4	2.4	12.8	1.0
Total	740.2	100	1,313.4	100

Table A8. Replicate quantitative samples from ʻĪao-C (HI_MAUI_09-031).

[—, not observed in sample]

Taxon	Sample A: Absolute abundance, in number of organisms per square meter	Sample A: Relative abundance, in percentage of organisms in sample	Sample B: Absolute abundance, in number of organisms per square meter	Sample B: Relative abundance, in percentage of organisms in sample
Turbellaria	30.7	1.5	69.1	1.7
Oligochaeta	61.5	3.0	145.9	3.5
Apedilum sp.	11.5	0.6	7.7	0.2
Cricotopus bicinctus gr.	334.1	16.5	675.6	16.2
Eukiefferiella sp.	372.5	18.4	829.2	19.9
Orthocladius Complex	7.7	0.4	—	—
Telmatogeton sp.	—	—	7.7	0.2
Ephydridae	7.7	0.4	23.0	0.6
Limonia sp.	—	—	7.7	0.2
Cheumatopsyche sp.	395.6	19.5	1,804.2	43.4
Hydroptilidae	806.5	39.8	591.2	14.2
Total	2,027.8	100	4,161.3	100

Table A9. Replicate quantitative samples from North Waiehu-A (HI_MAUI_09-028).

[—, not observed in sample]

Taxon	Sample A: Absolute abundance, in number of organisms per square meter	Sample A: Relative abundance, in percentage of organisms in sample	Sample B: Absolute abundance, in number of organisms per square meter	Sample B: Relative abundance, in percentage of organisms in sample
Nemertea	2.3	0.2	—	—
Oligochaeta	15.8	1.3	188.0	13.1
Ferrissia sp.	2.3	0.2	17.1	1.2
Acari	2.3	0.2	—	—
Atyoida bisulcata	4.0	0.3	1.6	0.1
Paratanytarsus sp.	—	—	2.9	0.2
Cricotopus bicinctus gr.	419.6	35.1	373.1	26.1
Eukiefferiella sp.	198.5	16.6	381.6	26.7
Ephydridae	—	—	2.9	0.2
Limonia sp.	2.3	0.2	—	—
Megalagrion sp.	54.2	4.5	42.7	3.0
Cheumatopsyche sp.	489.6	41.0	418.7	29.3
Hydroptilidae	4.5	0.4	2.9	0.2
Total	1,195.4	100	1,443.5	100

Table A10. Replicate quantitative samples from South Waiehu-A (HI_MAUI_09-030).

[—, not observed in sample]

Taxon	Sample A: Absolute abundance, in number of organisms per square meter	Sample A: Relative abundance, in percentage of organisms in sample	Sample B: Absolute abundance, in number of organisms per square meter	Sample B: Relative abundance, in percentage of organisms in sample
Nemertea	3.1	0.2	—	—
Erpobdellidae	3.1	0.2	3.2	0.2
Oligochaeta	31.4	1.9	6.3	0.4
Ferrissia sp.	9.4	0.6	9.5	0.6
Physidae	18.8	1.2	6.3	0.4
Cricotopus bicinctus gr.	62.7	3.8	217.5	13.6
Eukiefferiella sp.	59.6	3.6	252.2	15.8
Megalagrion sp.	—	—	6.3	0.4
Cheumatopsyche sp.	1,452.0	88.5	1,096.9	68.6
Total	1,640.1	100	1,598.2	100

Table A11. Repeat quantitative sampling results from Waihe‘e-A (HI_MAUI_09-026).

[—, not observed in sample; richness, total number of taxa]

Taxon	Sample Date					
	9/22/2009		10/23/2009		1/29/2010	
	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance, in percentage of organisms in sample	Absolute abundance, in number of organisms per square meter	Relative abundance,in percentage of organisms in sample
Nemertea	—	—	7.7	0.2	—	—
Oligochaeta	68.2	0.7	15.4	0.4	95.9	0.9
Ferrissia sp.	—	—	7.7	0.2	—	—
Atyoida bisulcata	3.2	0.03	—	—	0.8	0.0
Apedilum sp.	—	—	7.7	0.2	115.1	1.1
Cricotopus bicinctus gr.	4,230.3	44.8	1,136.3	28.0	4,892.1	46.7
Eukiefferiella sp.	2,933.9	31.0	836.9	20.6	2,820.1	26.9
Orthocladius Complex	—	—	—	—	95.9	0.9
Telmatogeton sp.	187.6	2.0	69.1	1.7	—	—
Ephydridae	170.6	1.8	46.1	1.1	19.2	0.2
Cheumatopsyche sp.	1,518.1	16.1	1,335.9	32.9	2,033.6	19.4
Hydroptilidae	341.2	3.6	598.9	14.7	402.9	3.9
Total	9,453.1	100	4,061.7	100	10,475.6	100
Richness	8		10		9	

Appendix B. Maui Faunal Distribution Maps

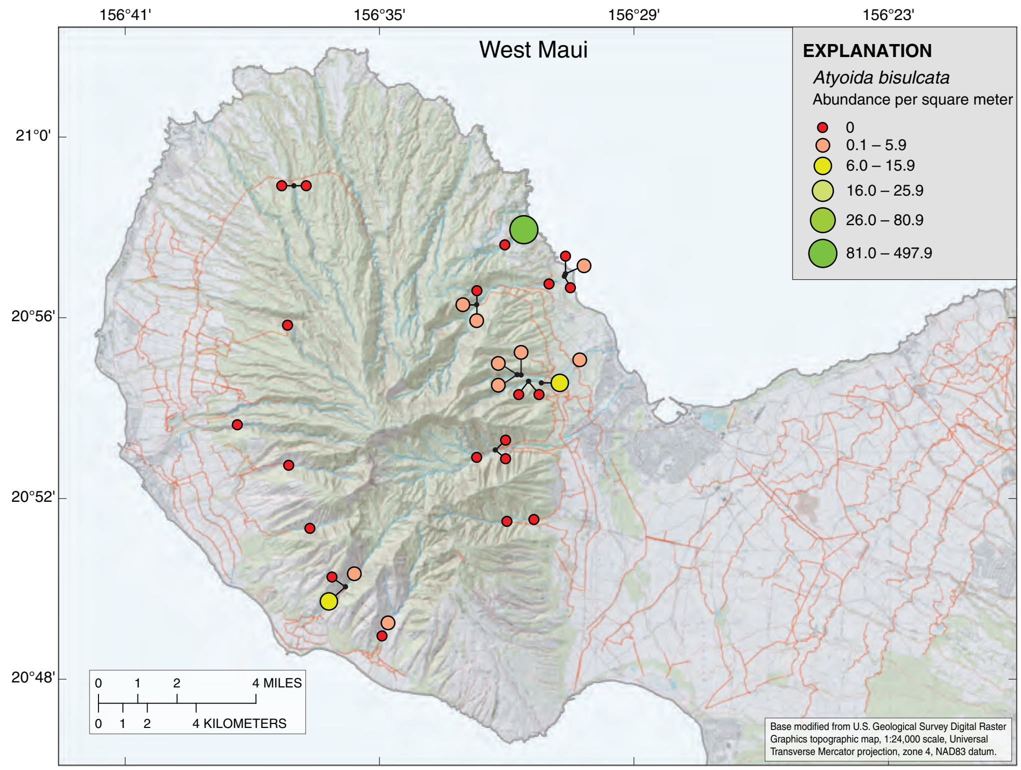


Figure B1. West Maui abundance of *Atyoida bisulcata* in quantitative samples.

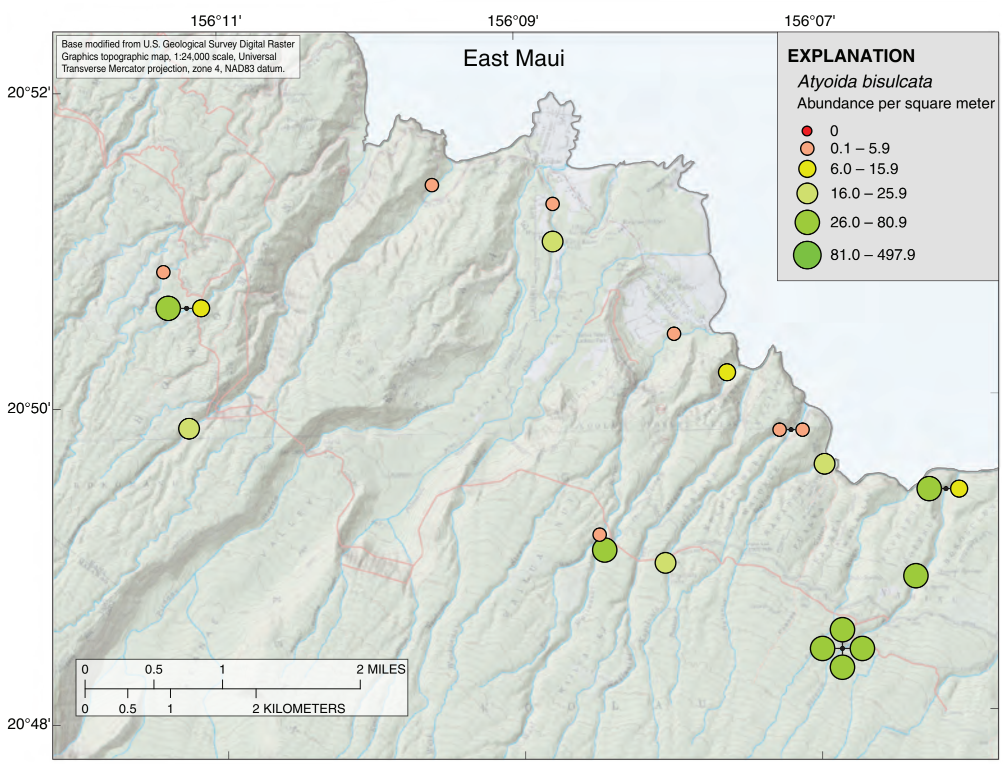


Figure B2. East Maui abundance of *Atyoida bisulcata* in quantitative samples.

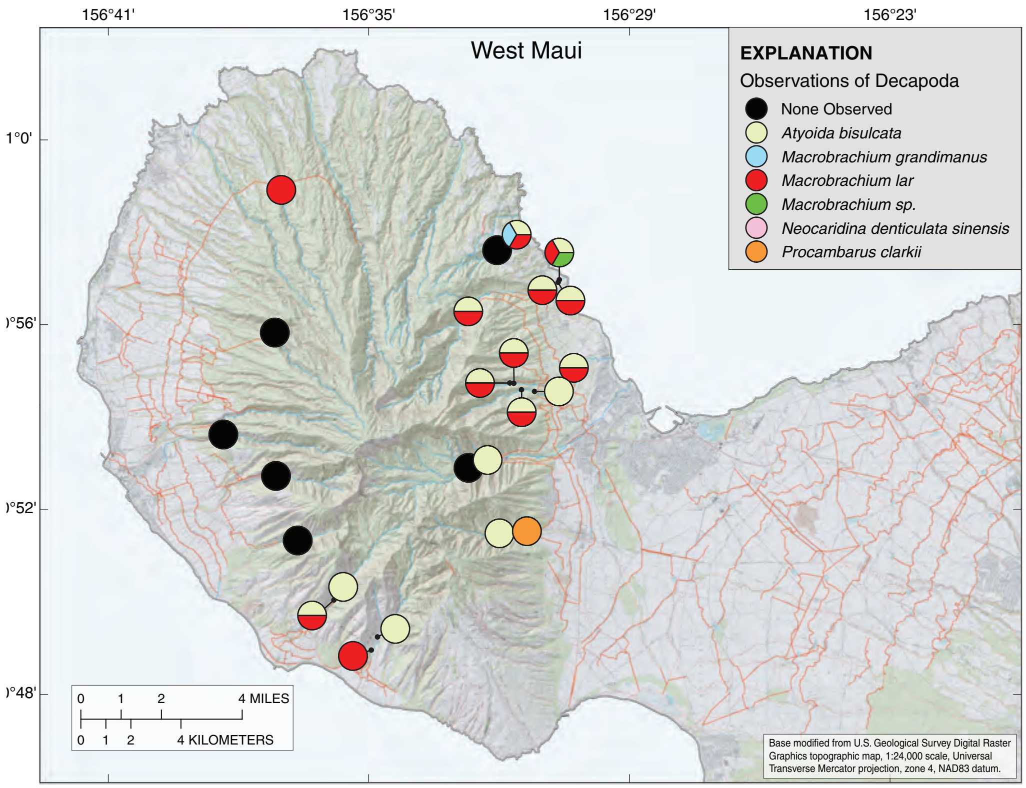


Figure B3. West Maui observations of Decapoda.

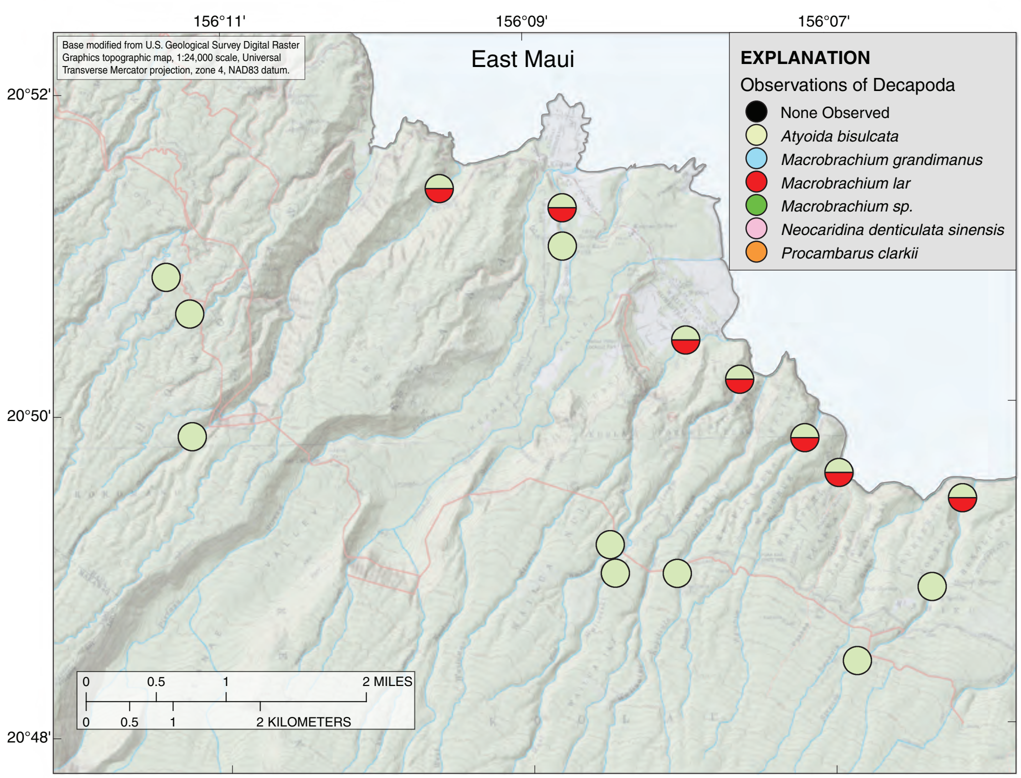


Figure B4. East Maui observations of Decapoda.

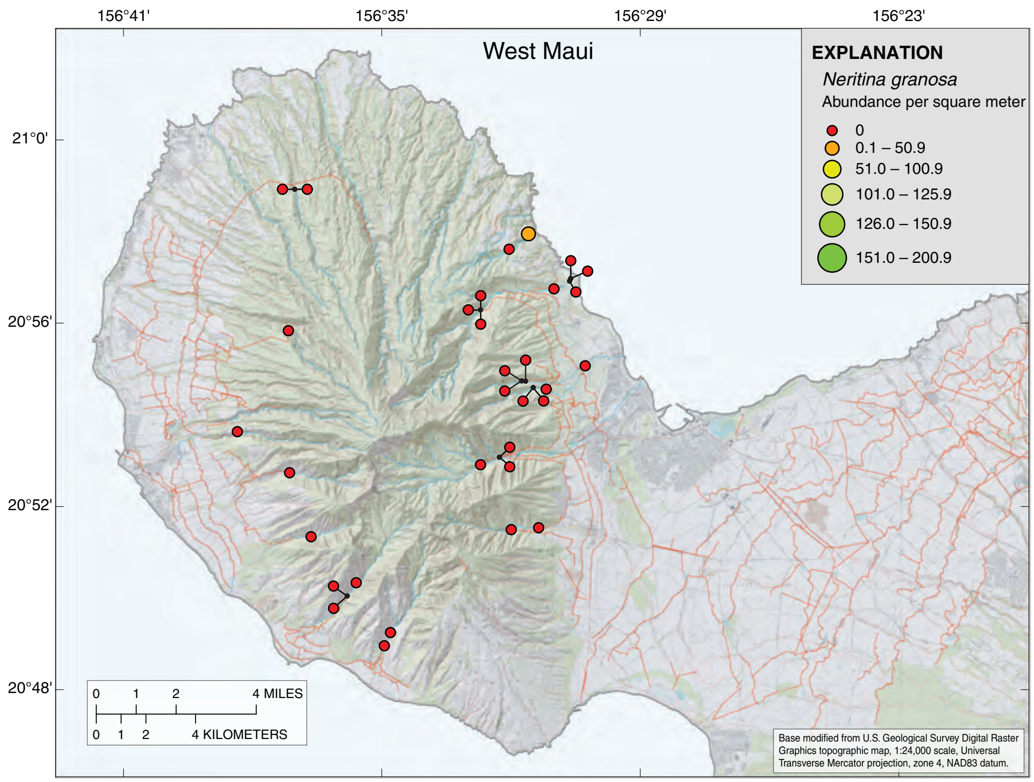


Figure B5. West Maui abundance of *Neritina granosa* in quantitative samples.

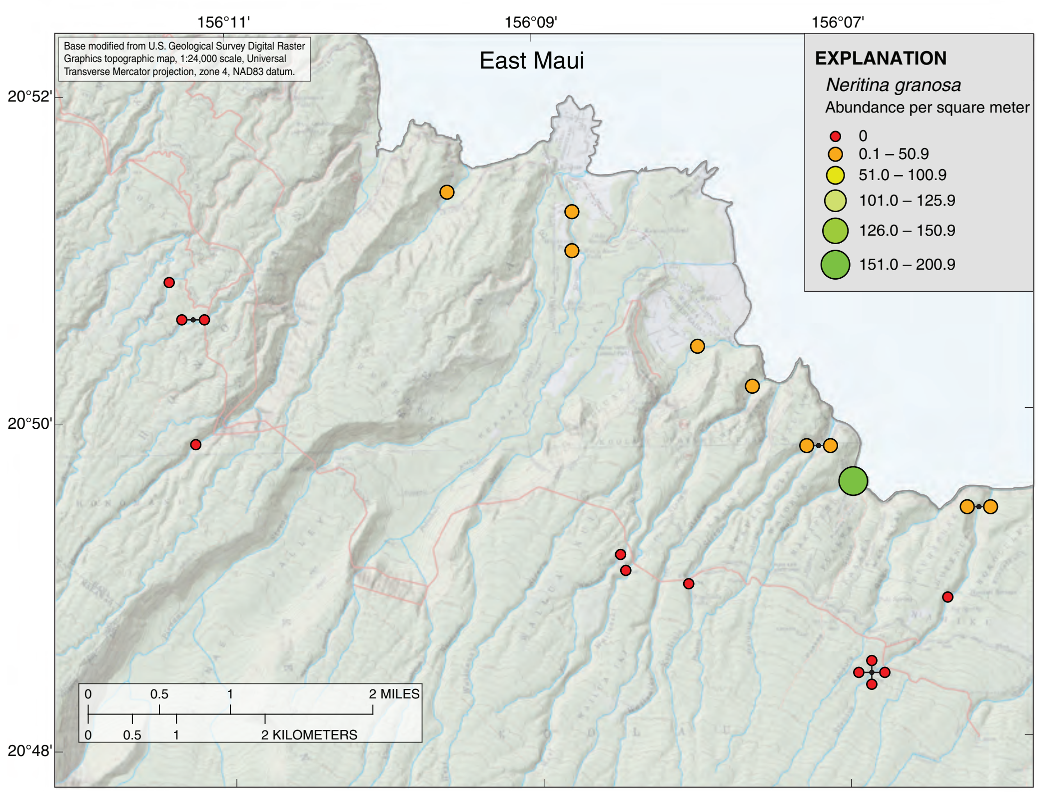


Figure B6. East Maui abundance of *Neritina granosa* in quantitative samples.

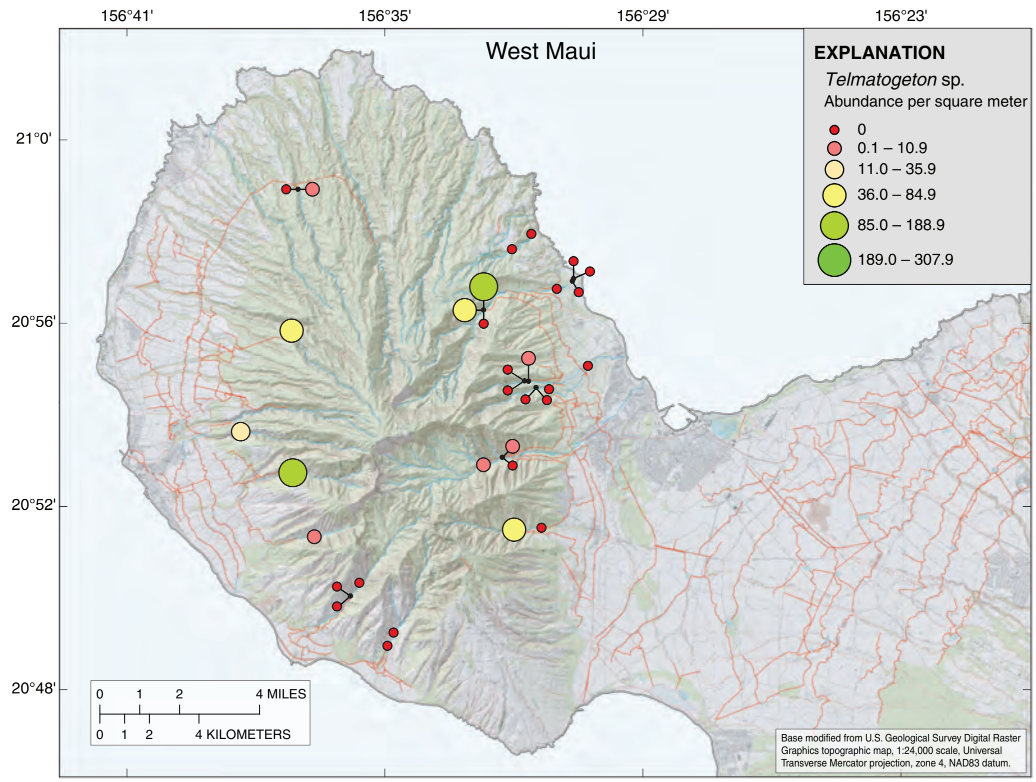


Figure B7. West Maui abundance of *Telmatogeton* in quantitative samples.

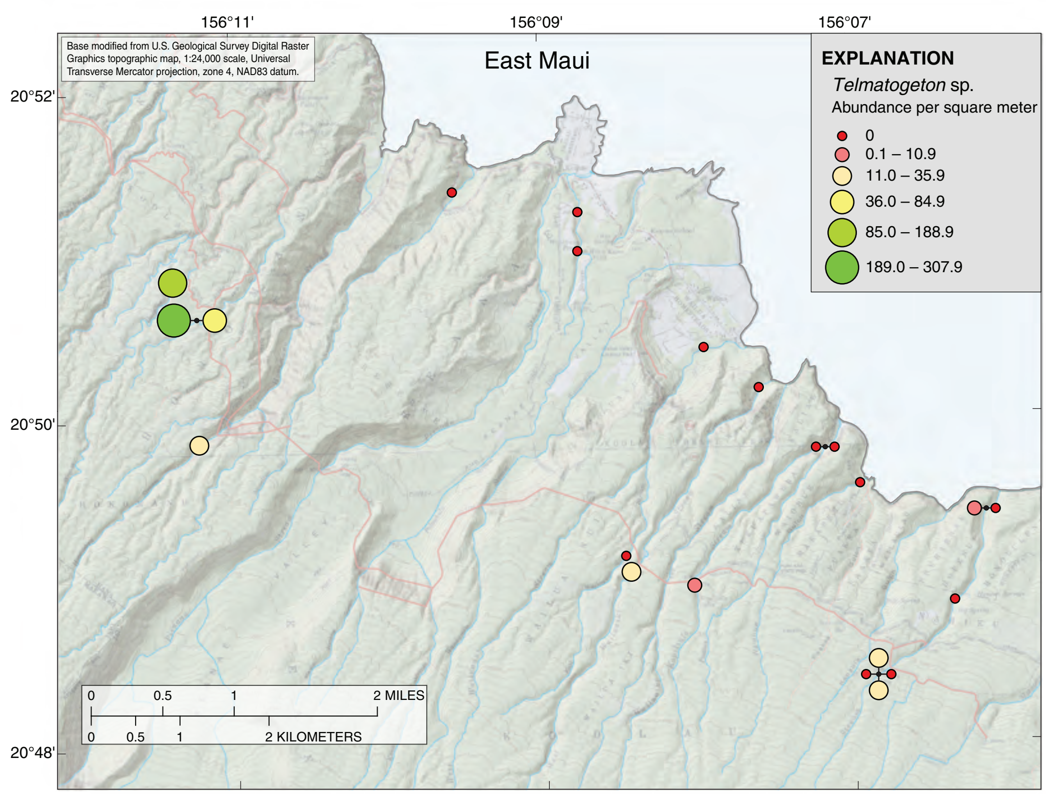


Figure B8. East Maui abundance of *Telmatogeton* in quantitative samples.

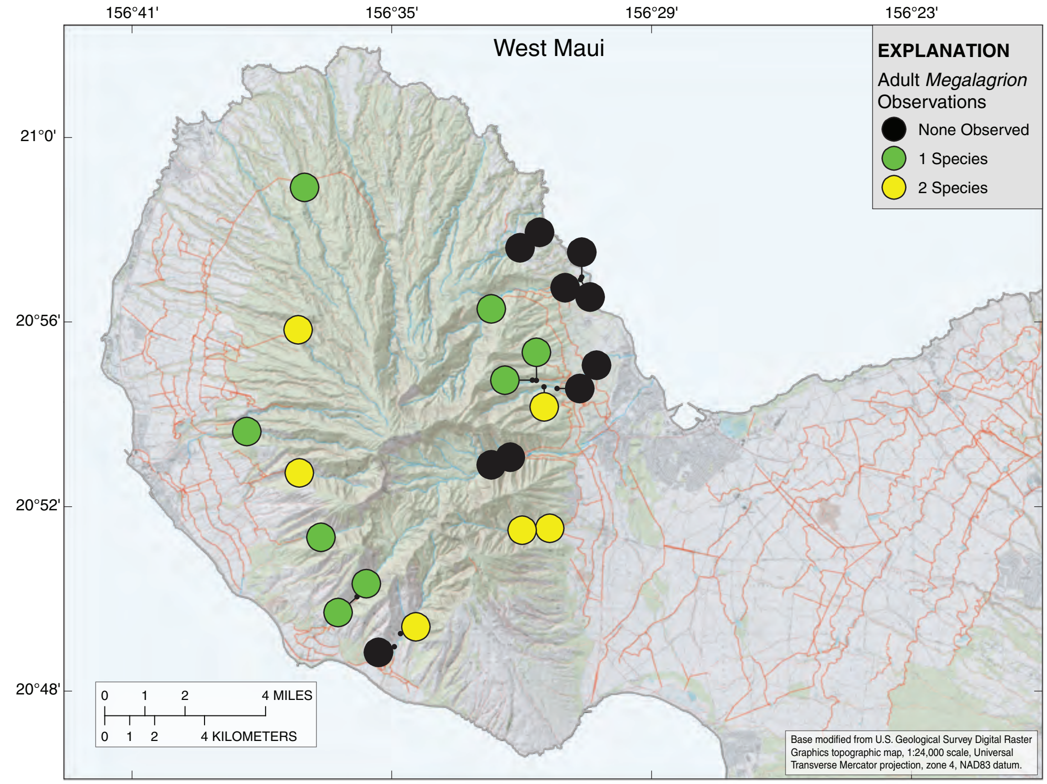


Figure B9. West Maui observations of adult *Megalagrion*.

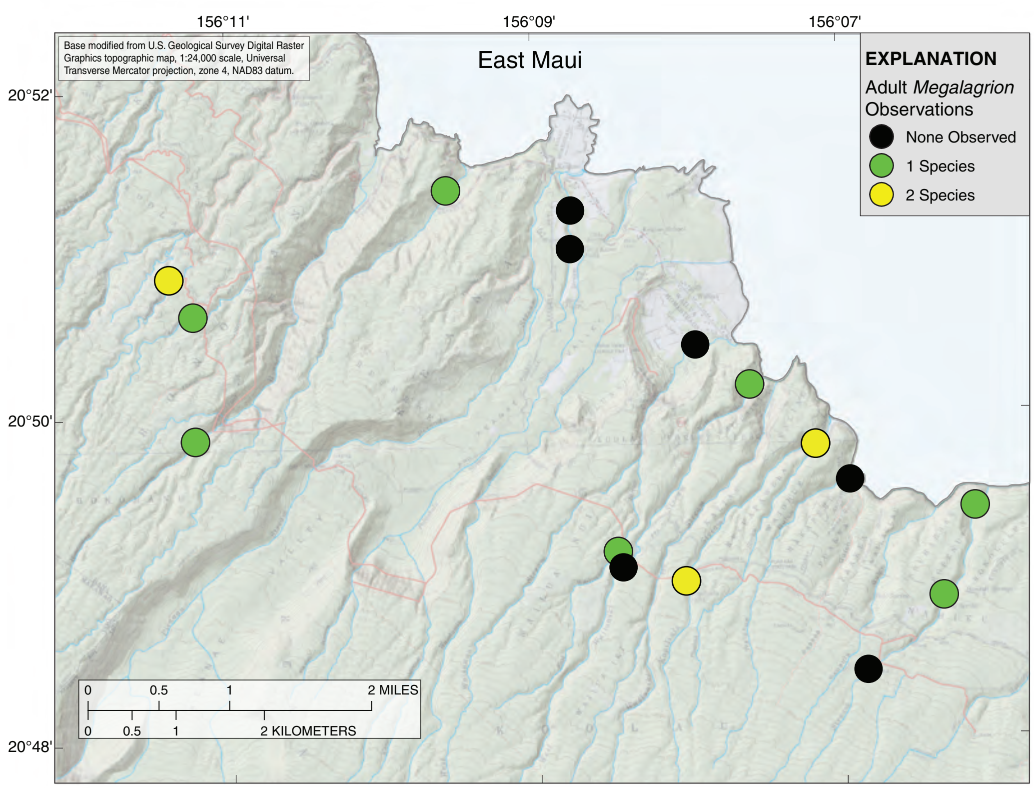


Figure B10. East Maui observations of adult *Megalagrion*.

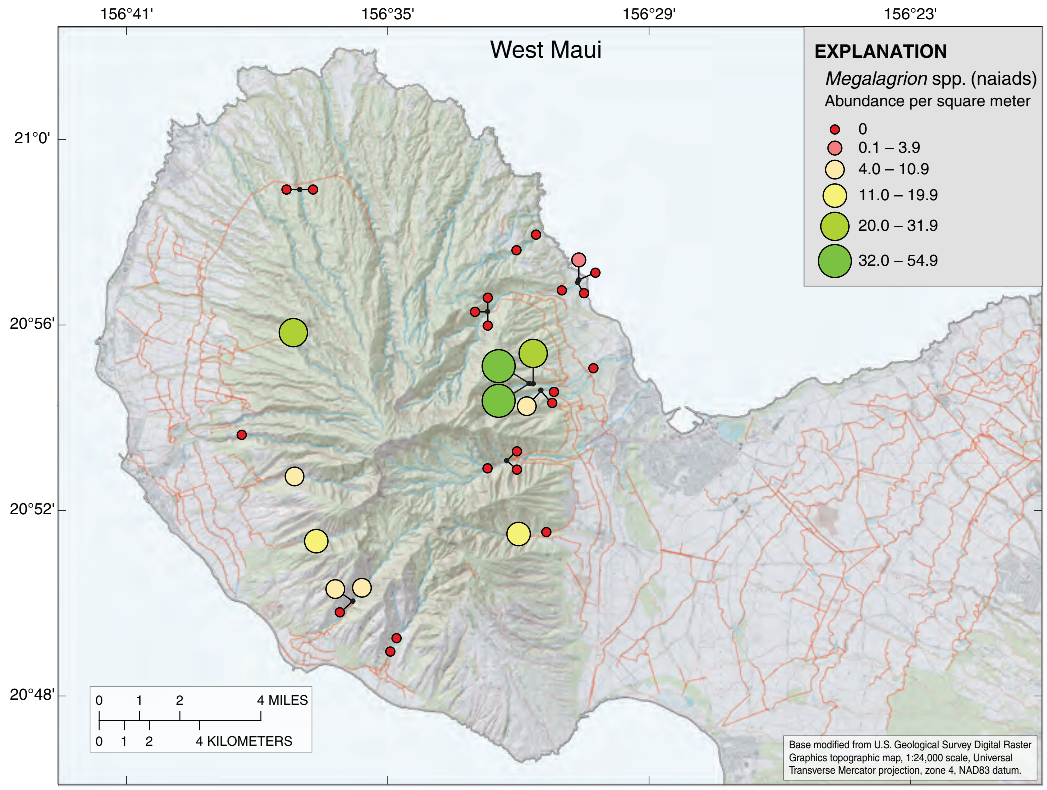


Figure B11. West Maui abundance of *Megalagrion* naiads in quantitative samples.

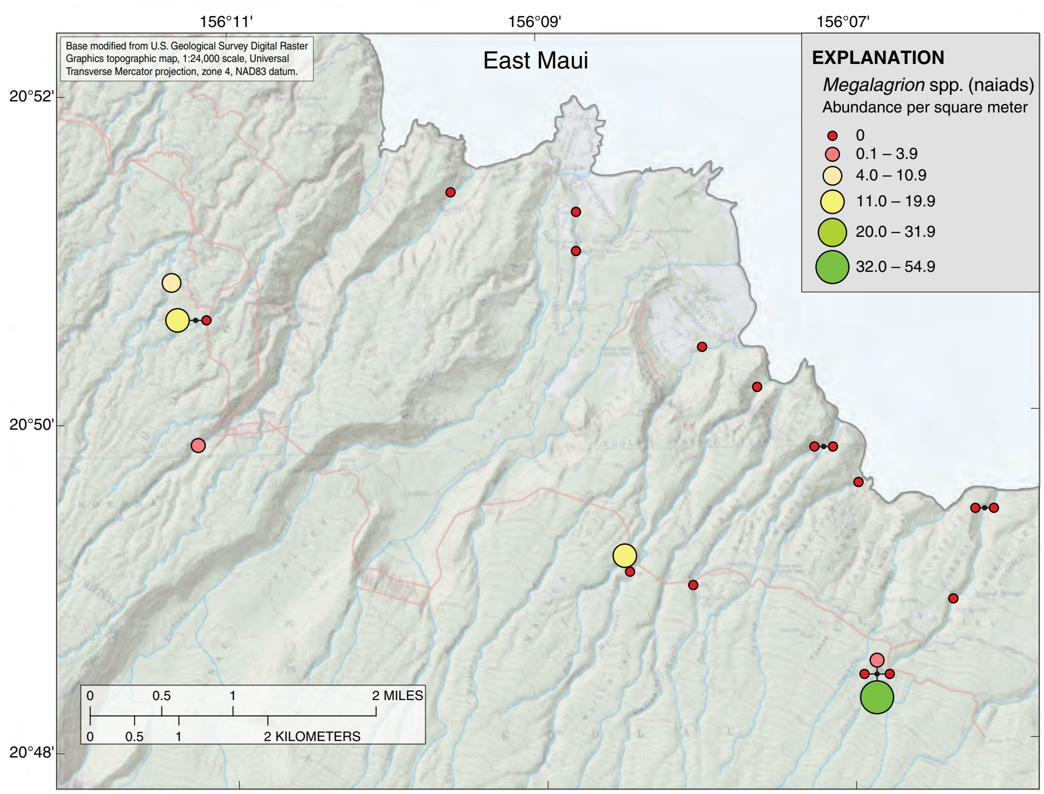


Figure B12. East Maui abundance of *Megalagrion* naiads in quantitative samples.

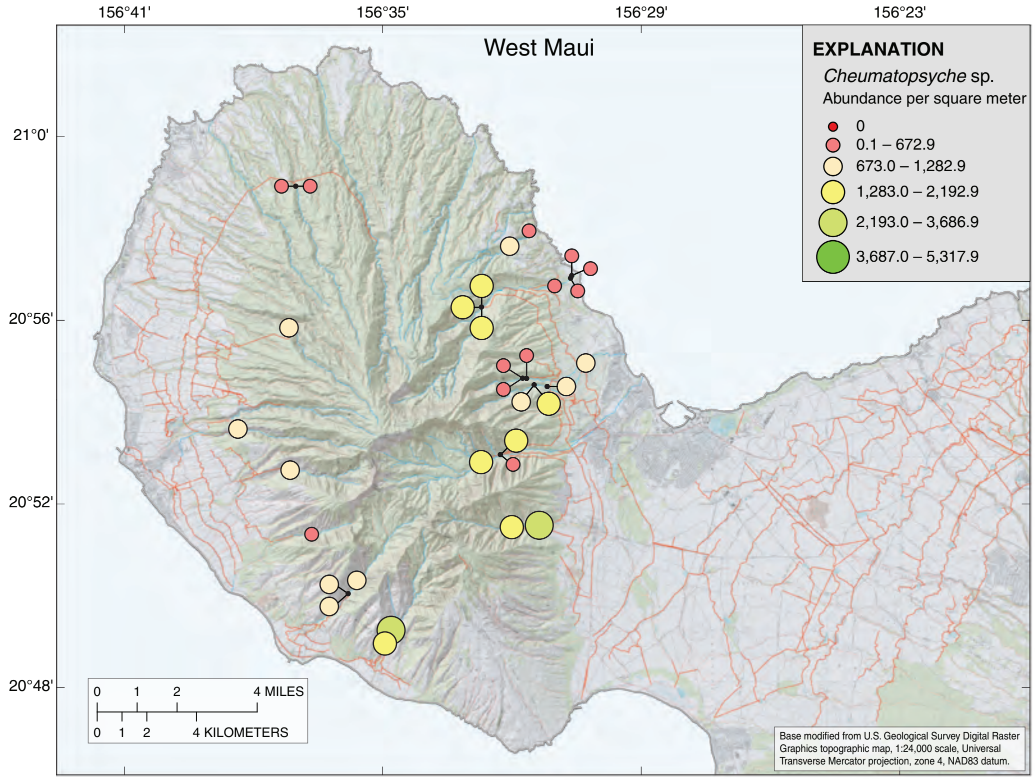


Figure B13. West Maui abundance of *Cheumatopsyche* in quantitative samples.

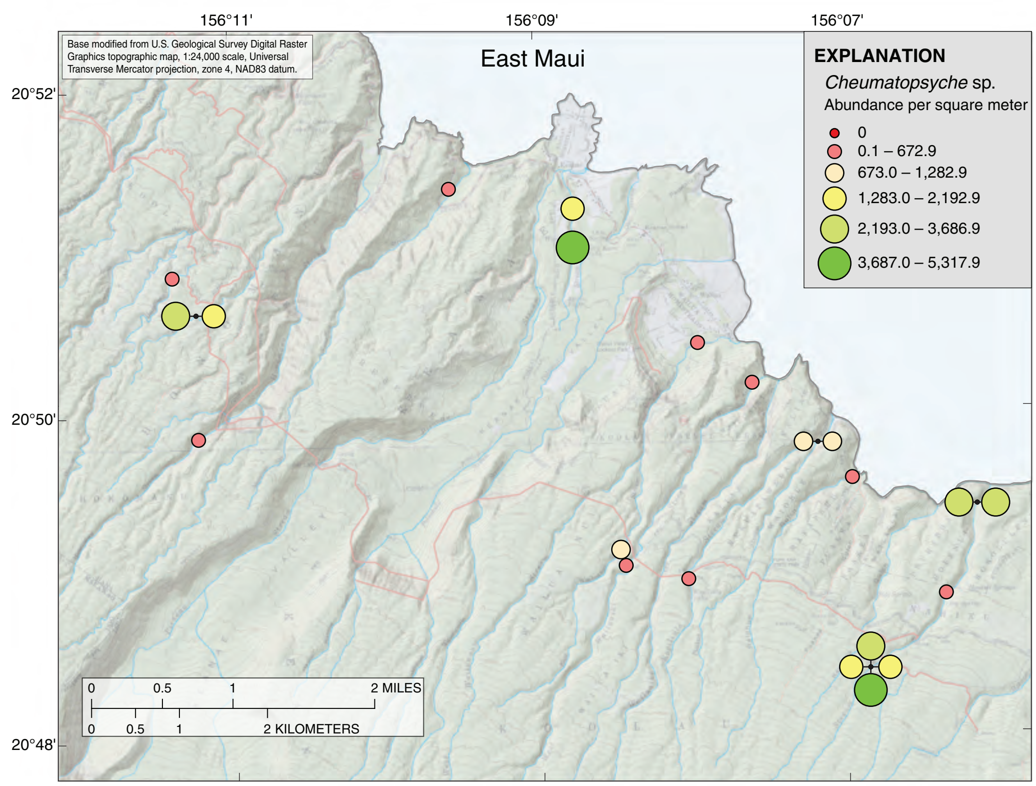


Figure B14. East Maui abundance of *Cheumatopsyche* in quantitative samples.

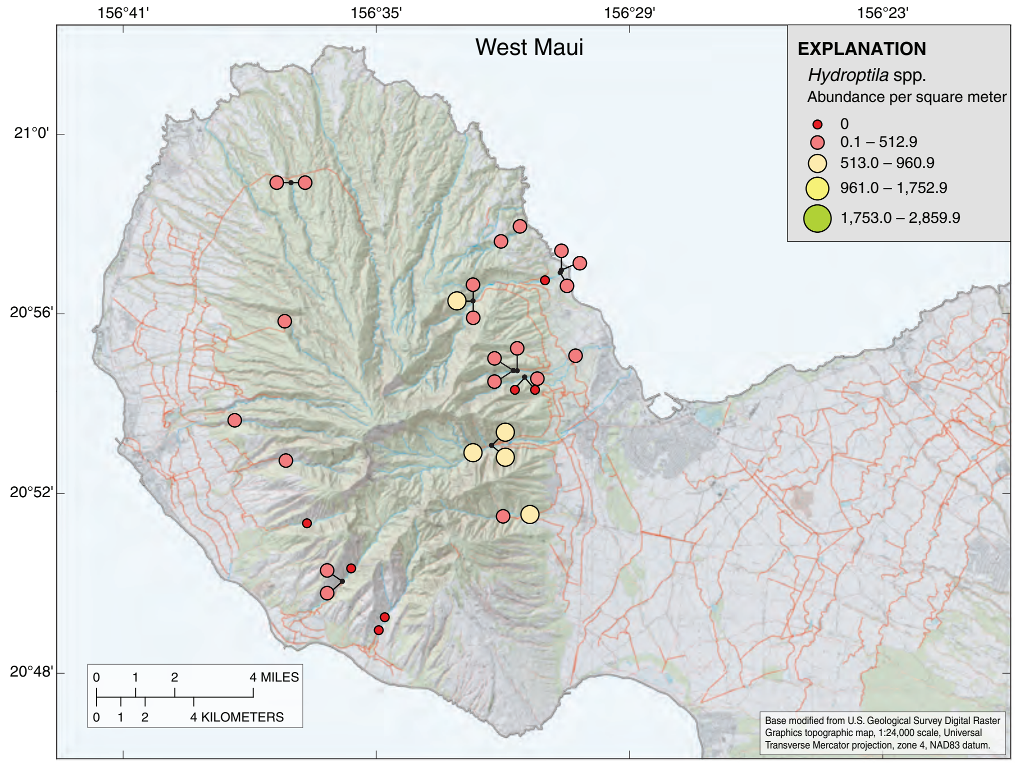


Figure B15. West Maui abundance of *Hydroptila* in quantitative samples.

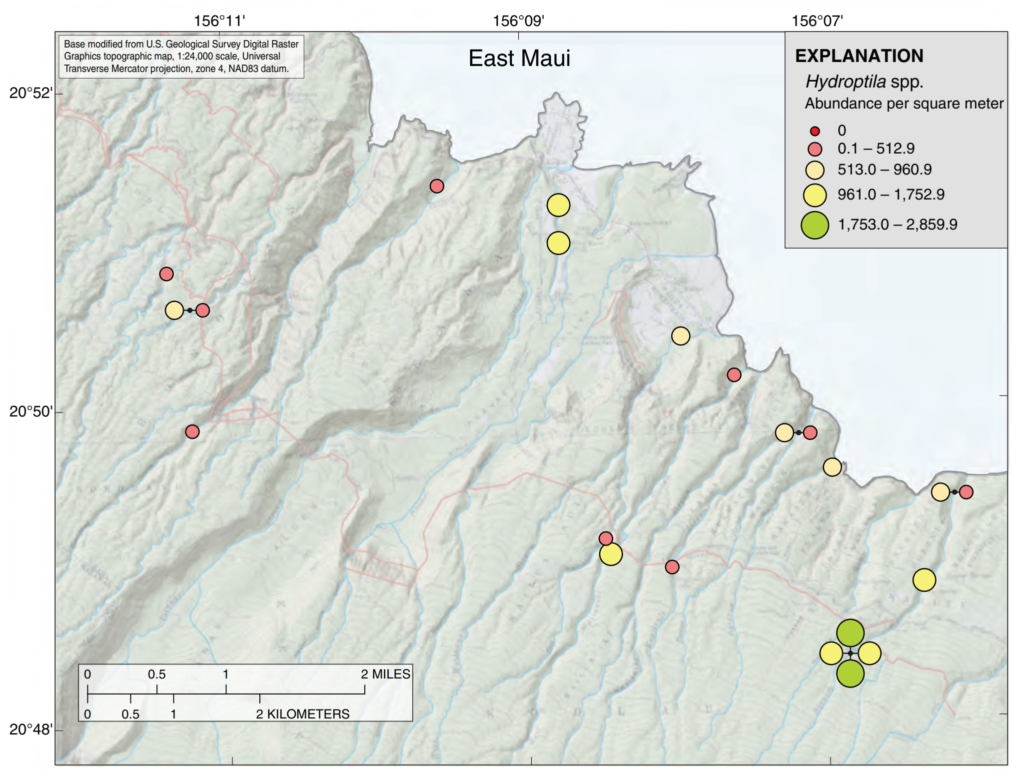


Figure B16. East Maui abundance of *Hydroptila* in quantitative samples.

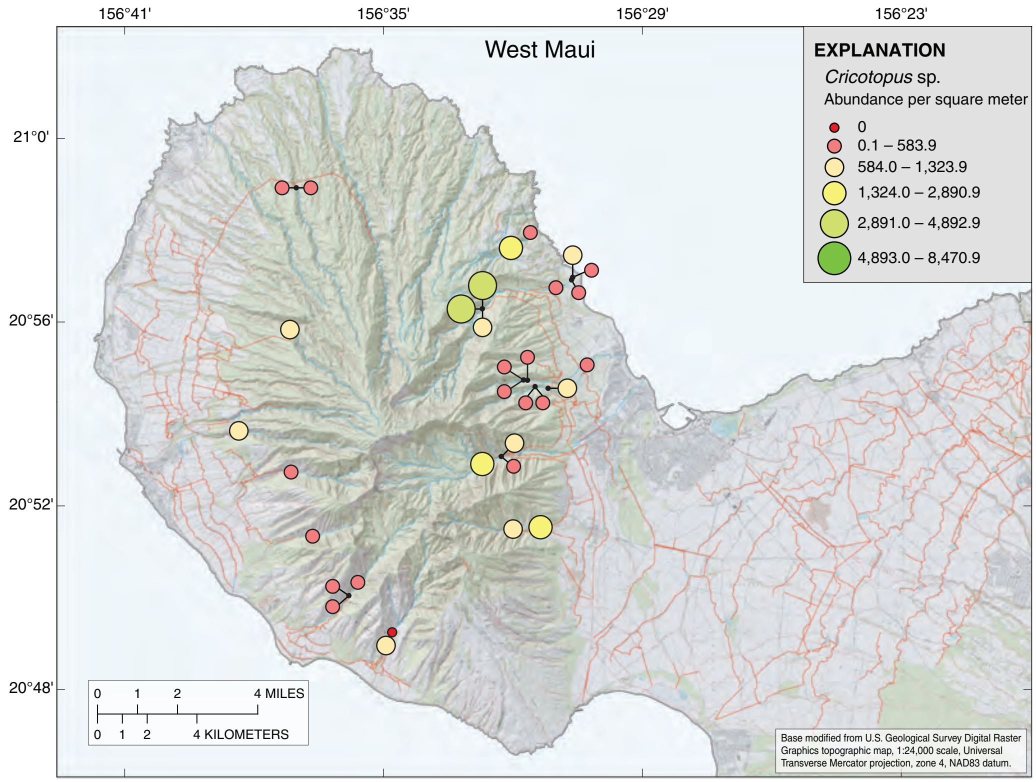


Figure B17. West Maui abundance of *Cricotopus* in quantitative samples.

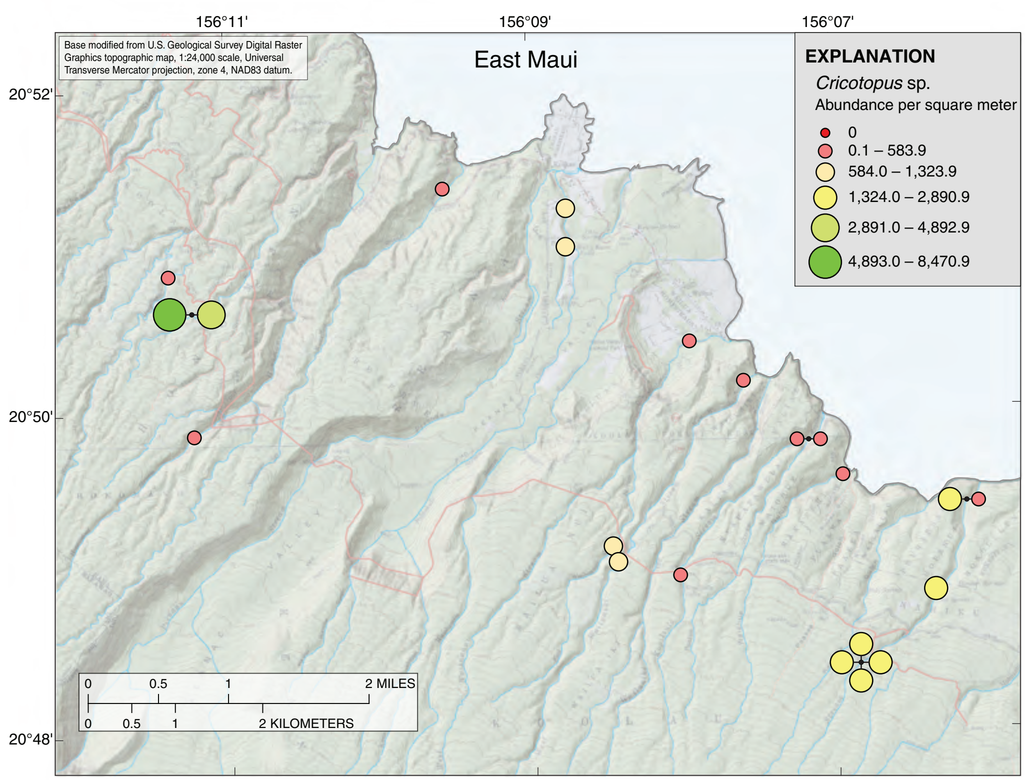


Figure B18. East Maui abundance of *Cricotopus* in quantitative samples.

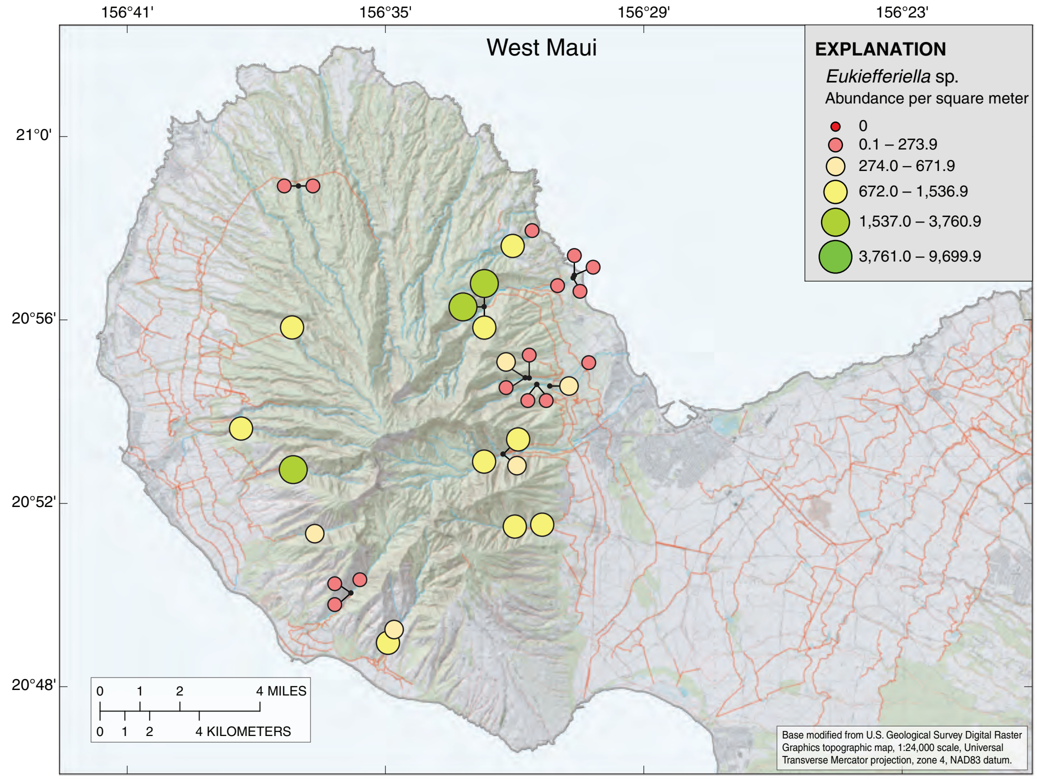


Figure B19. West Maui abundance of *Eukiefferiella* in quantitative samples.

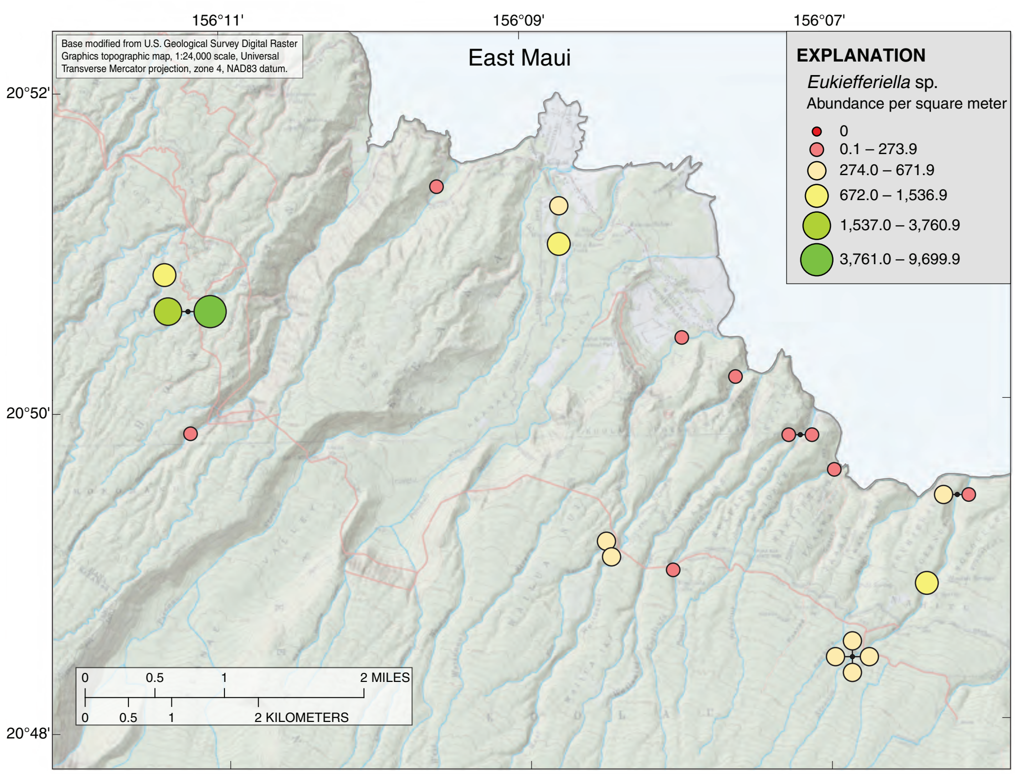


Figure B20. East Maui abundance of *Eukiefferiella* in quantitative samples.

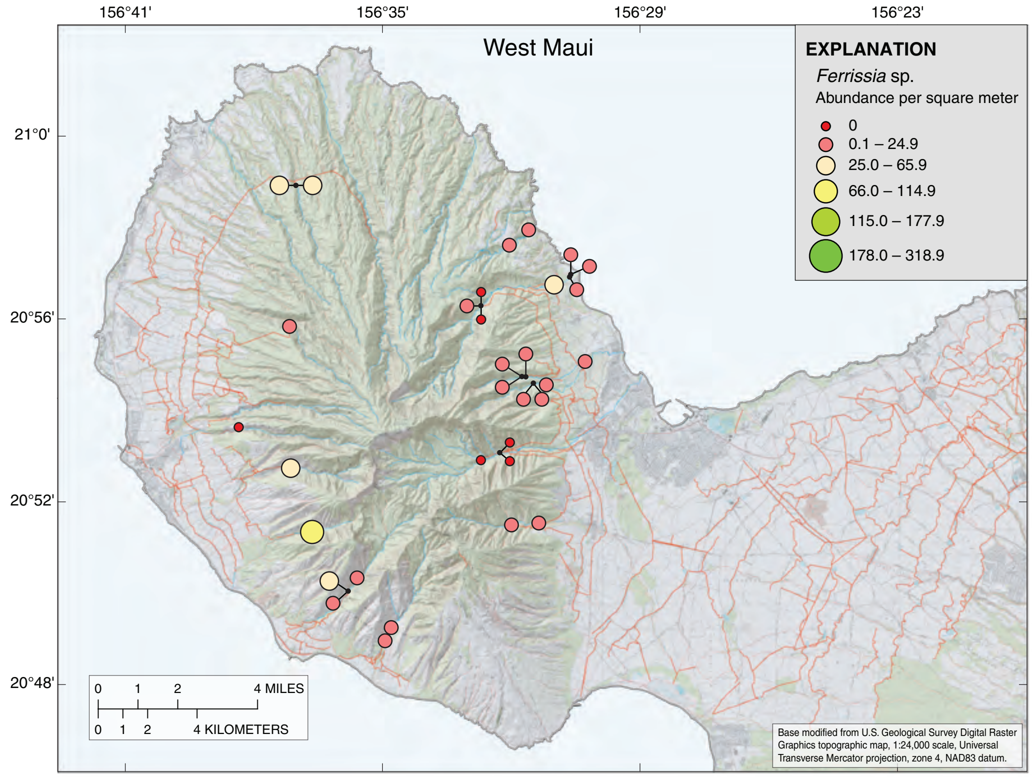


Figure B21. West Maui abundance of *Ferrissia* in quantitative samples.

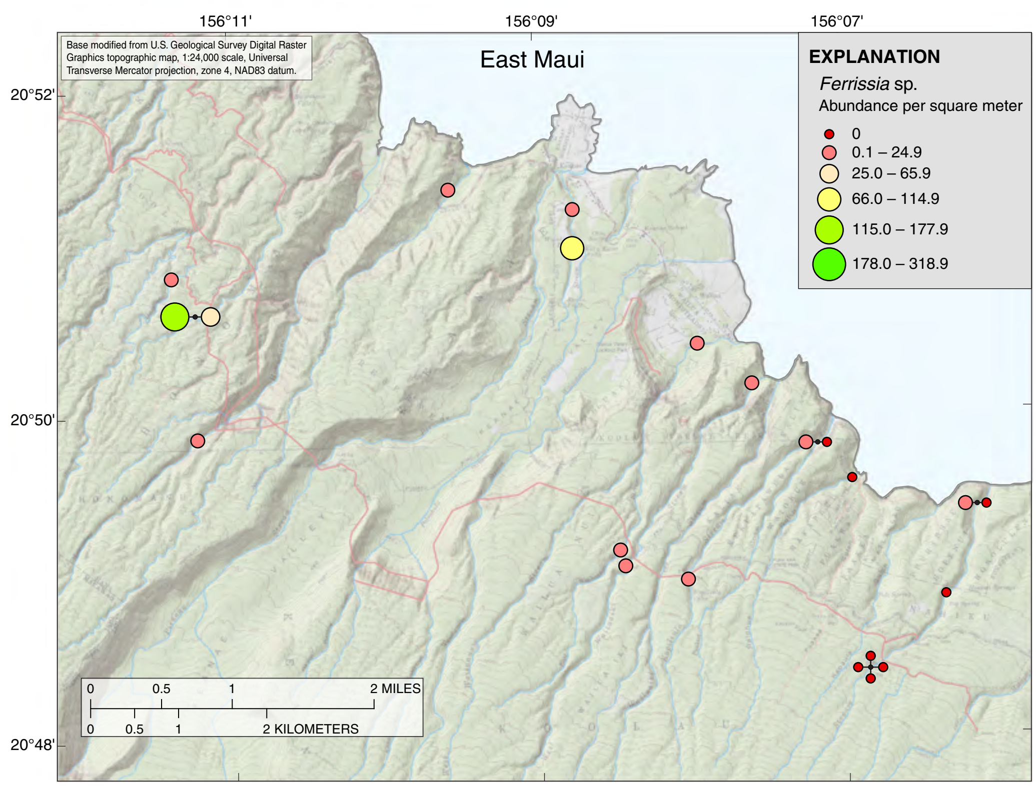


Figure B22. East Maui abundance of *Ferrissia* in quantitative samples.

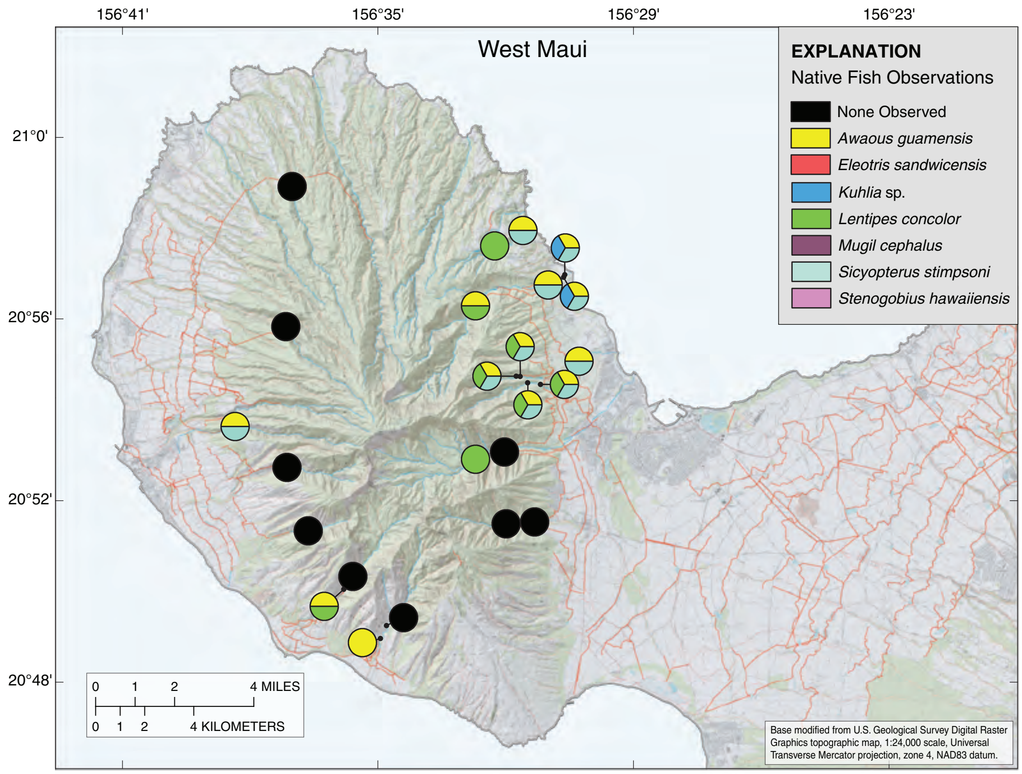


Figure B23. West Maui observations of native fish.

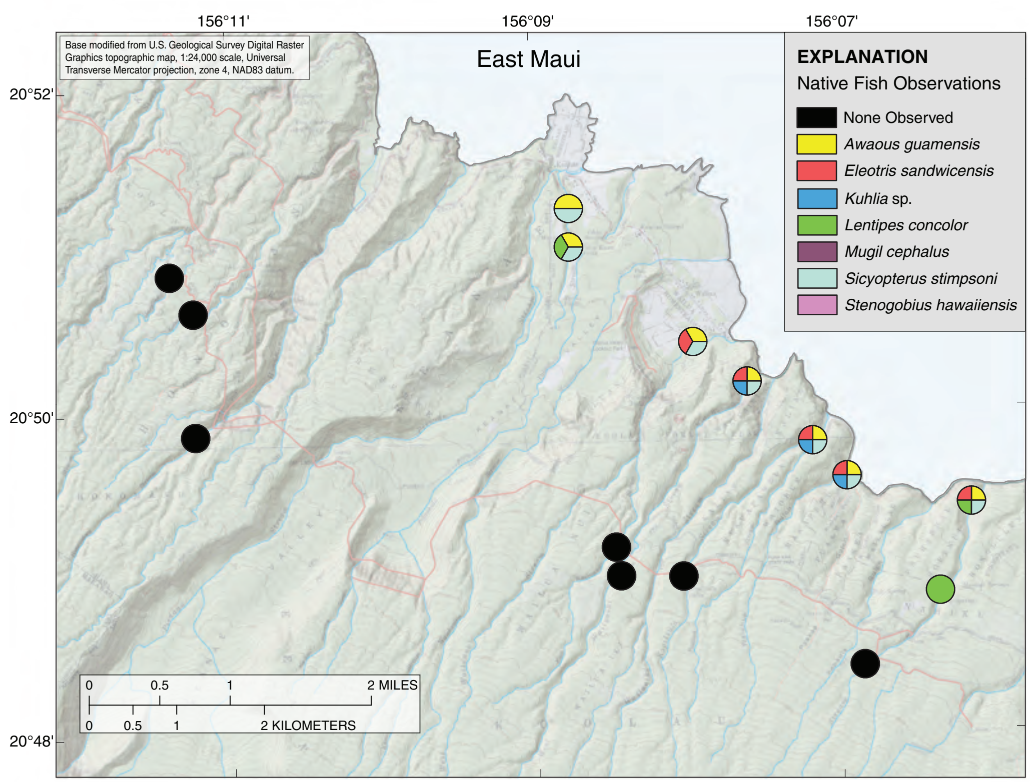


Figure B24. East Maui observations of native fish.

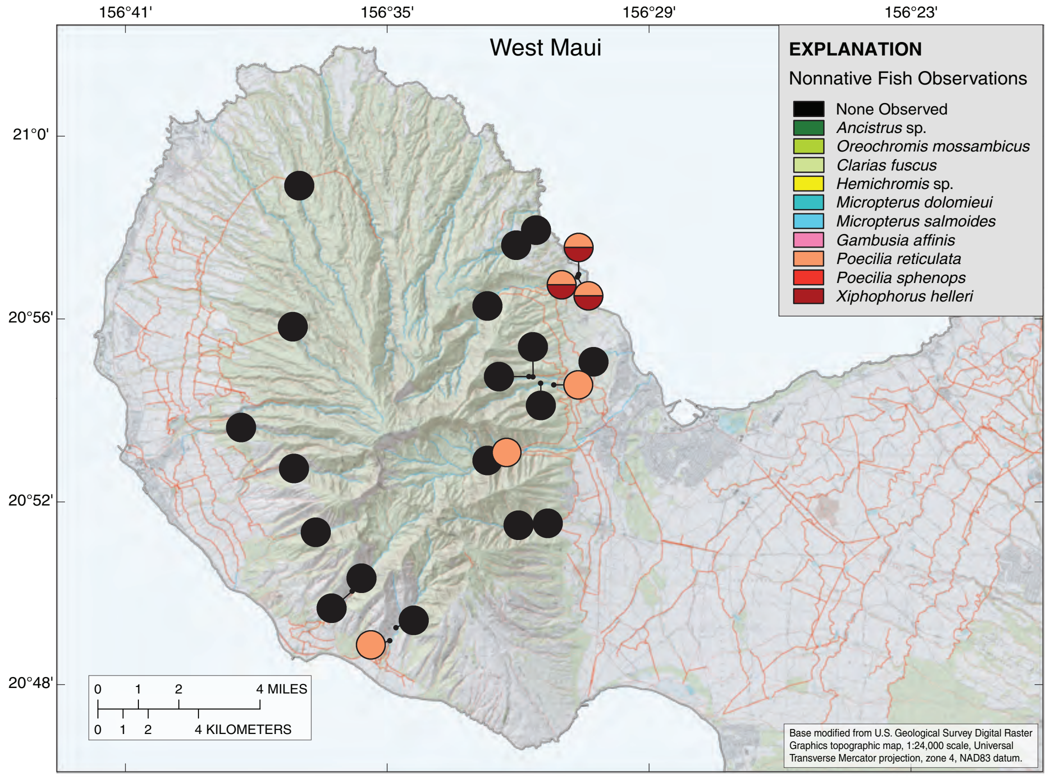


Figure B25. West Maui observations of nonnative fish.

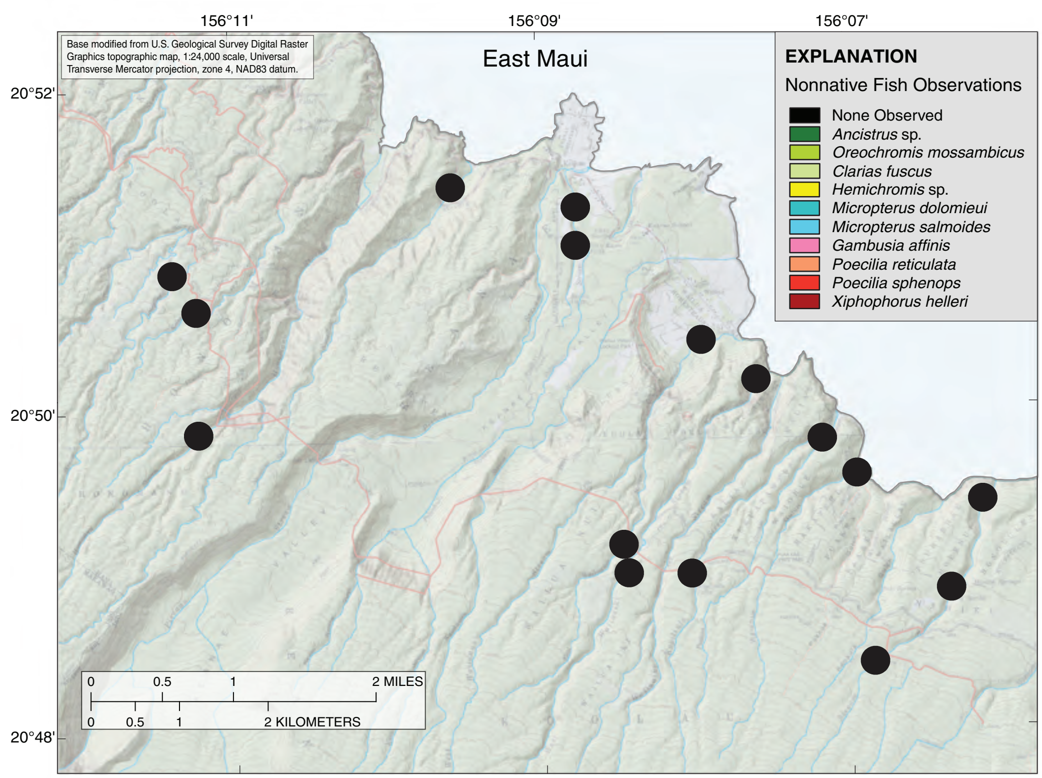


Figure B26. East Maui observations of nonnative fish.

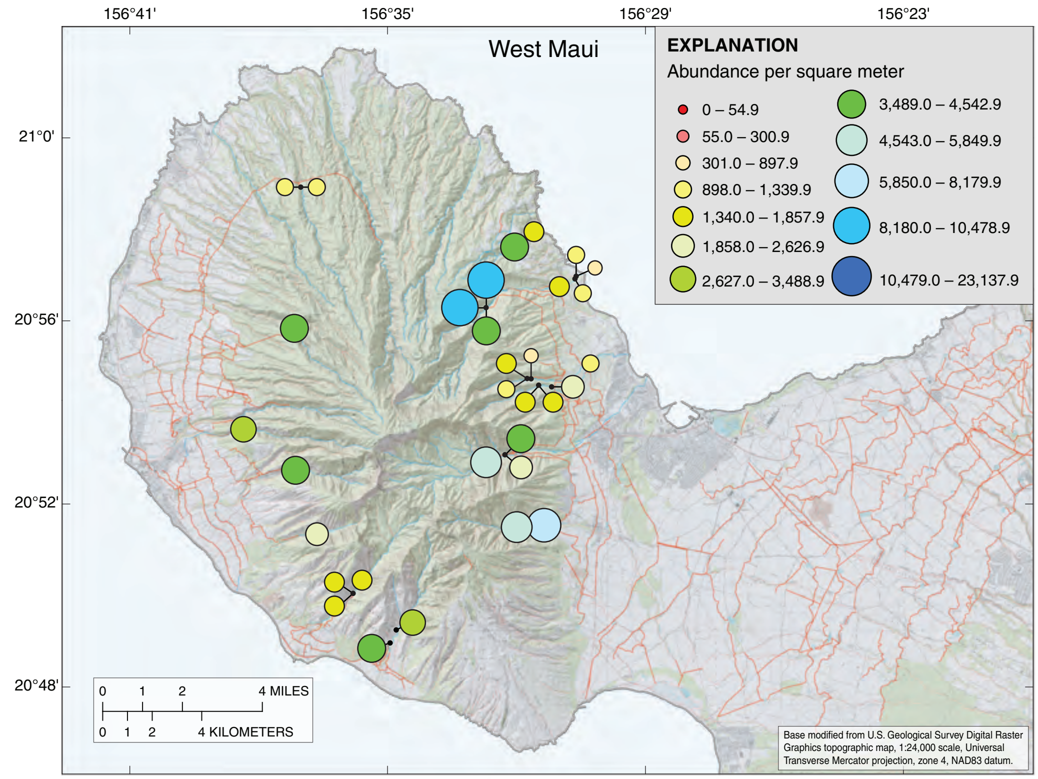


Figure B27. West Maui total quantitative macroinvertebrate abundances.

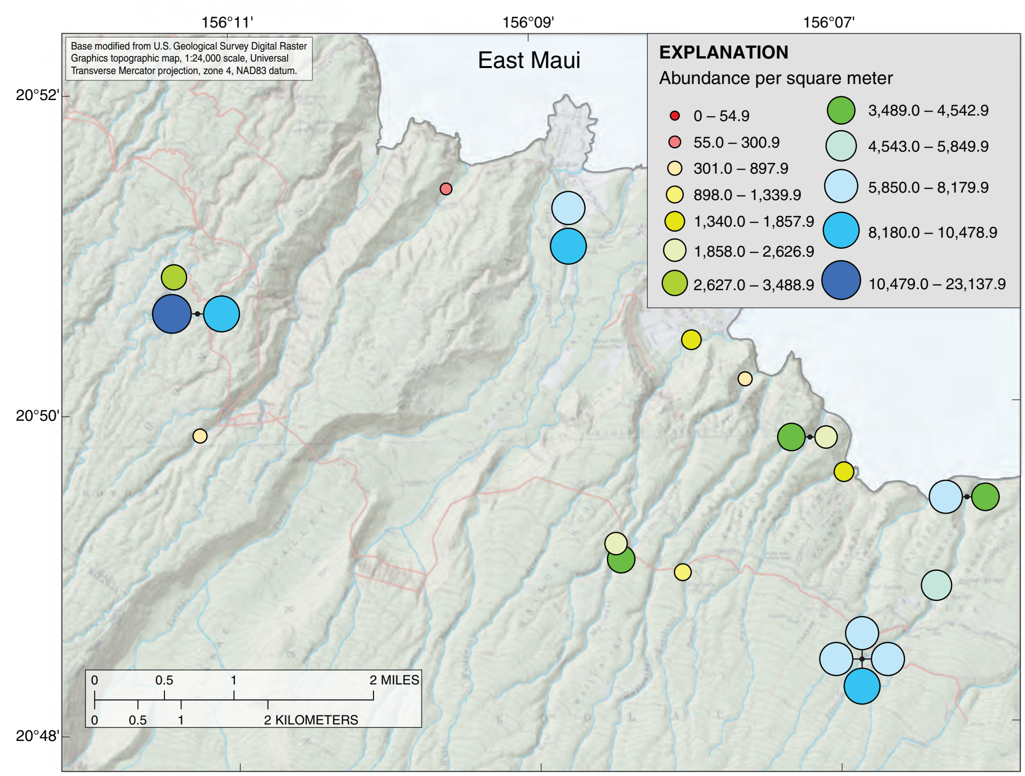


Figure B28. East Maui total quantitative macroinvertebrate abundances.

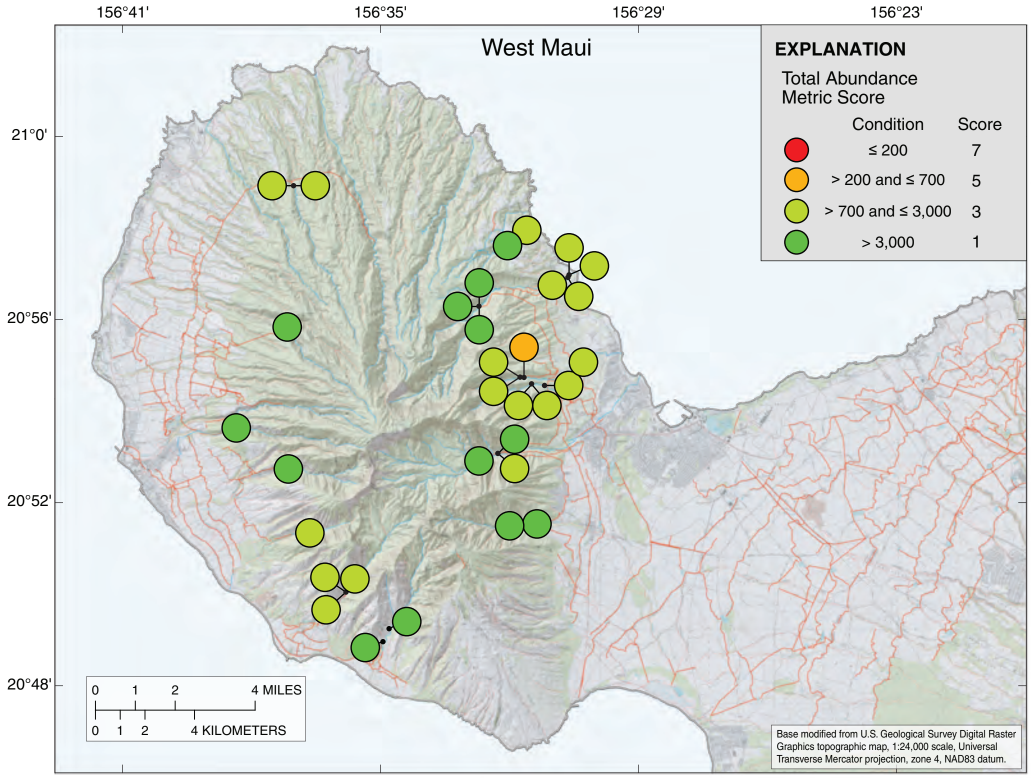


Figure B29. West Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) abundance metric scores.

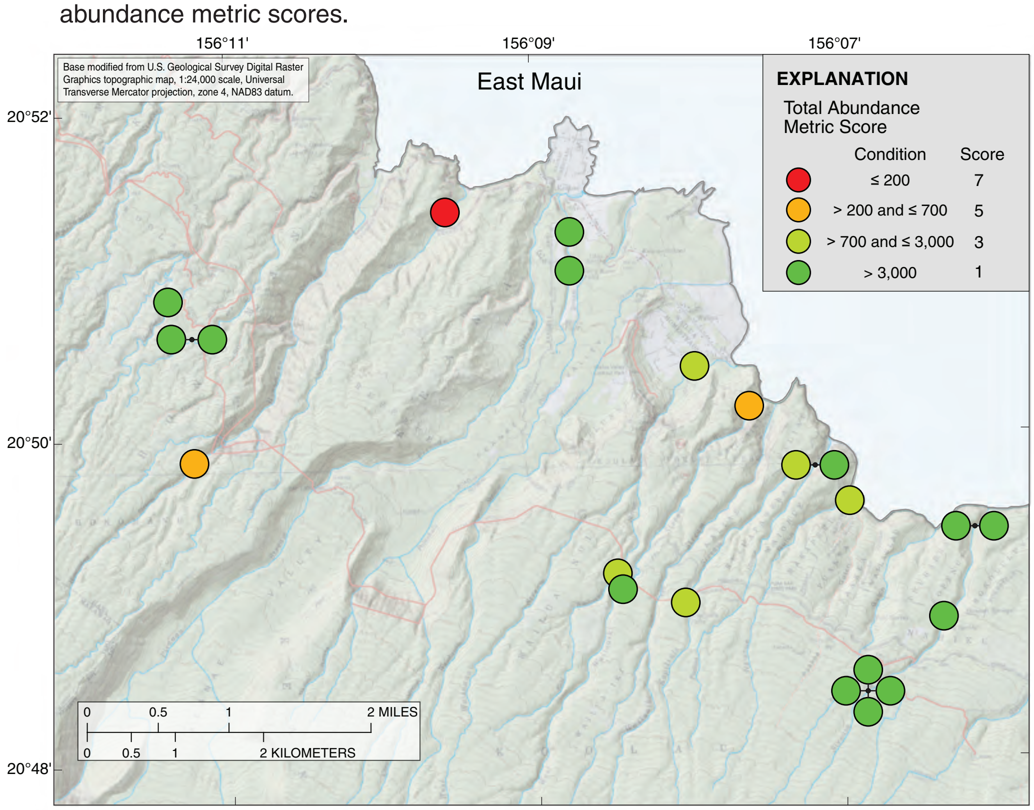


Figure B30. East Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) abundance metric scores.

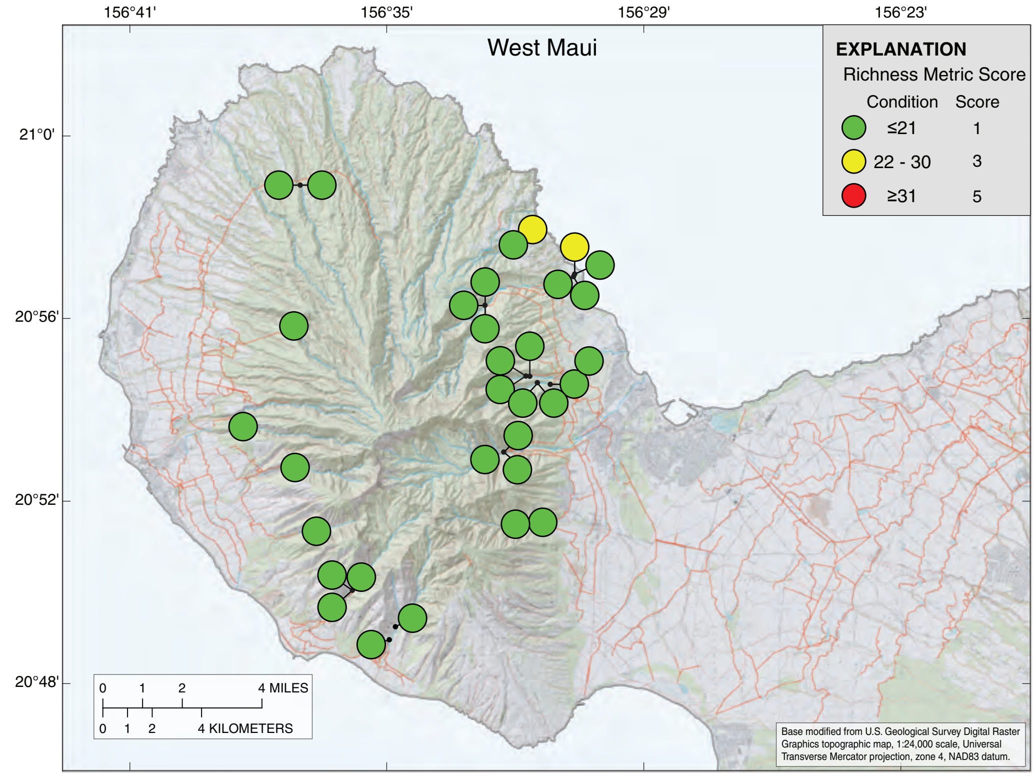


Figure B31. West Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) richness metric scores.

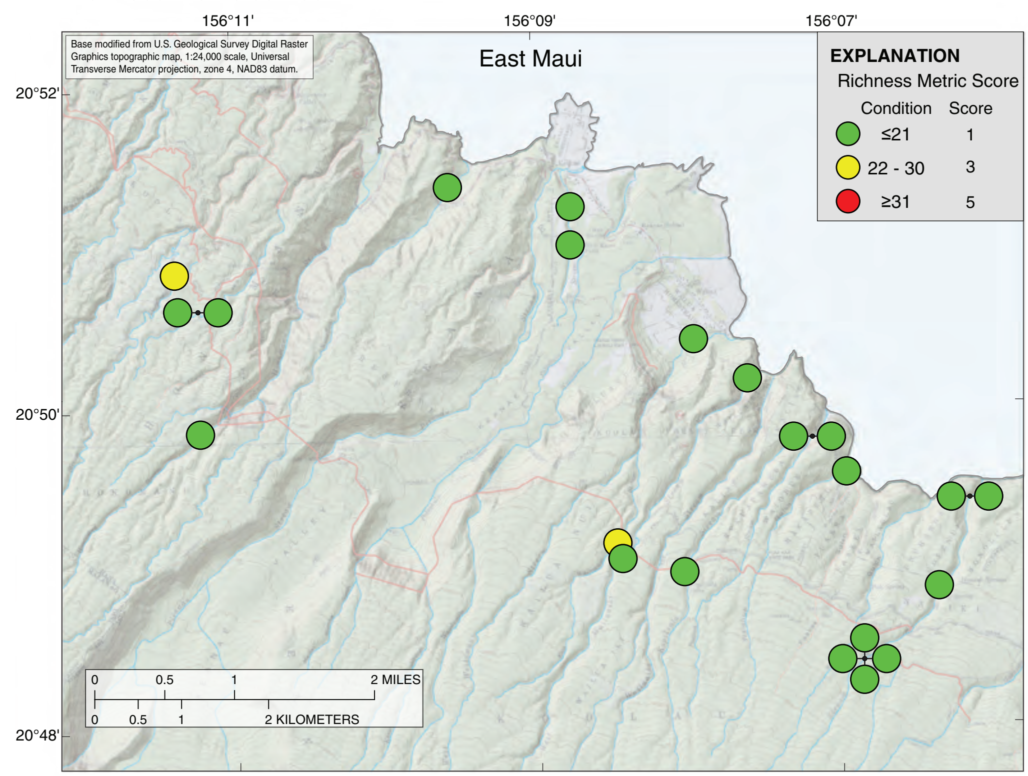


Figure B32. East Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) richness metric scores.

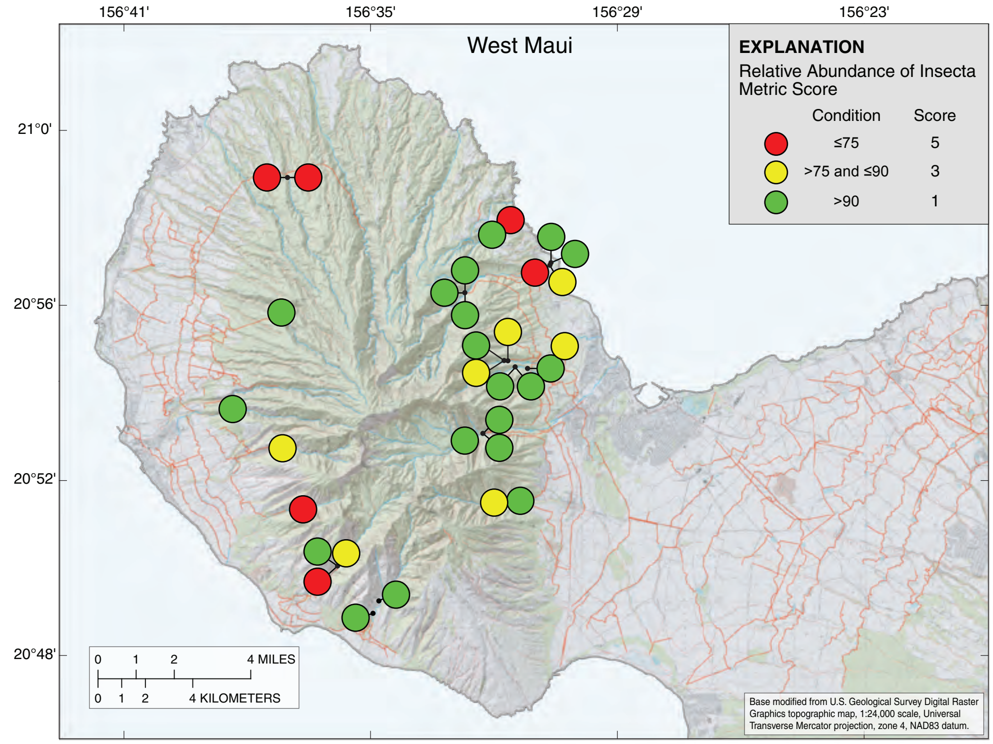


Figure B33. West Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) percentage of Insecta metric scores.

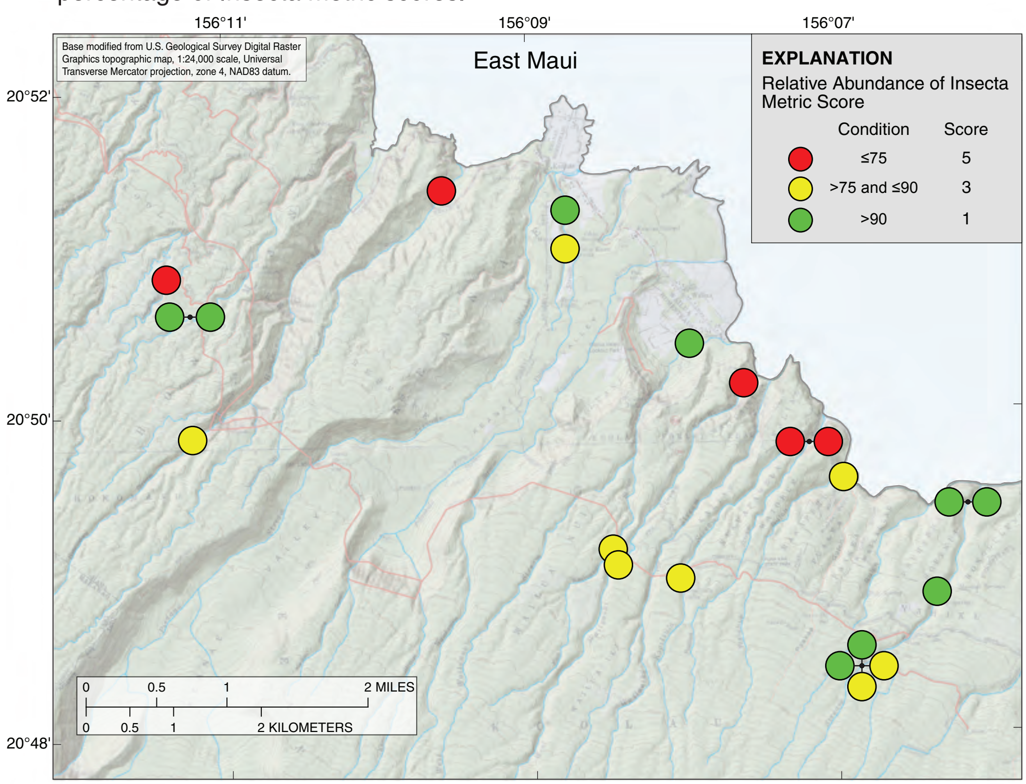


Figure B34. East Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) percentage of Insecta metric scores.

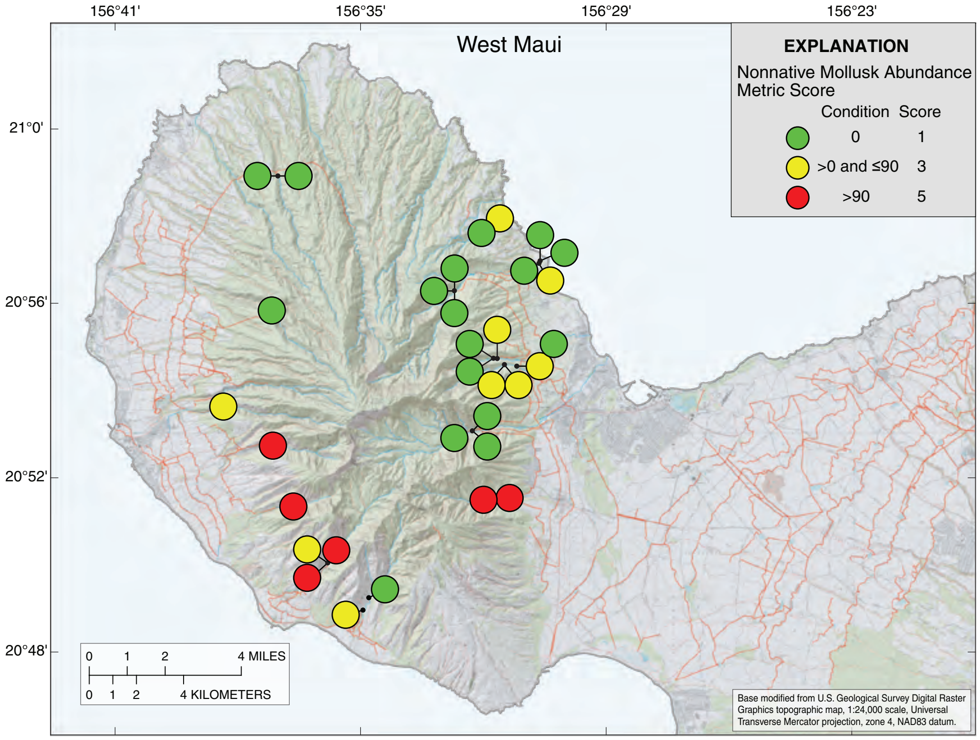


Figure B35. West Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) nonnative/cryptogenic mollusk metric scores.

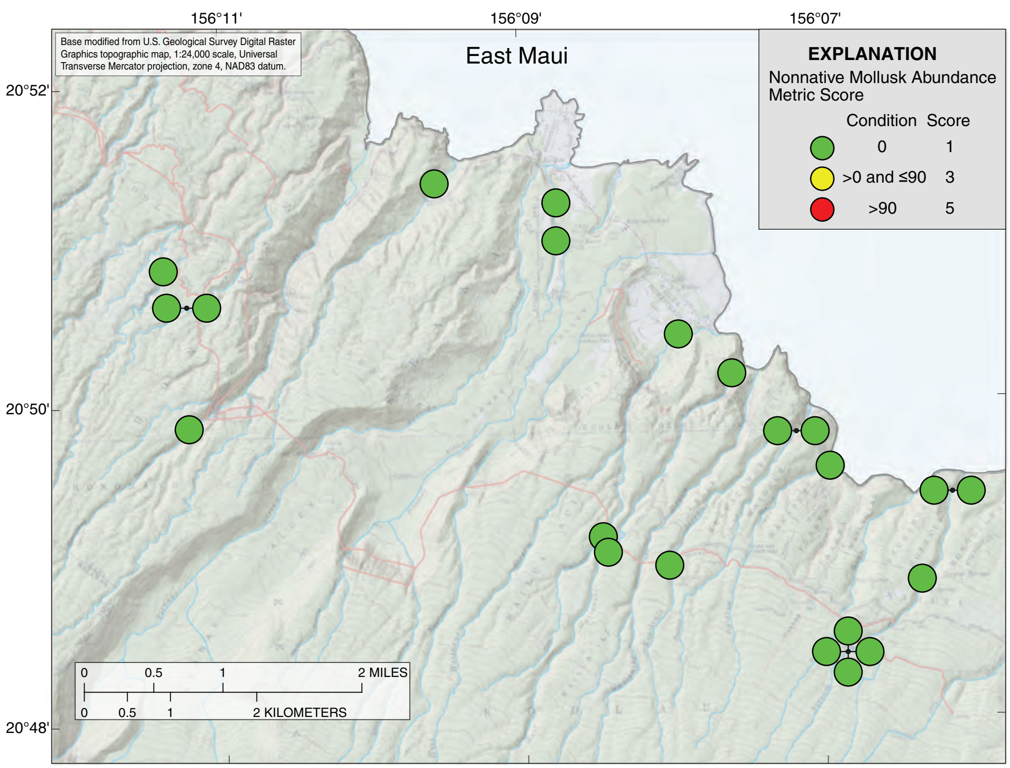


Figure B36. East Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) nonnative/cryptogenic mollusk metric scores.

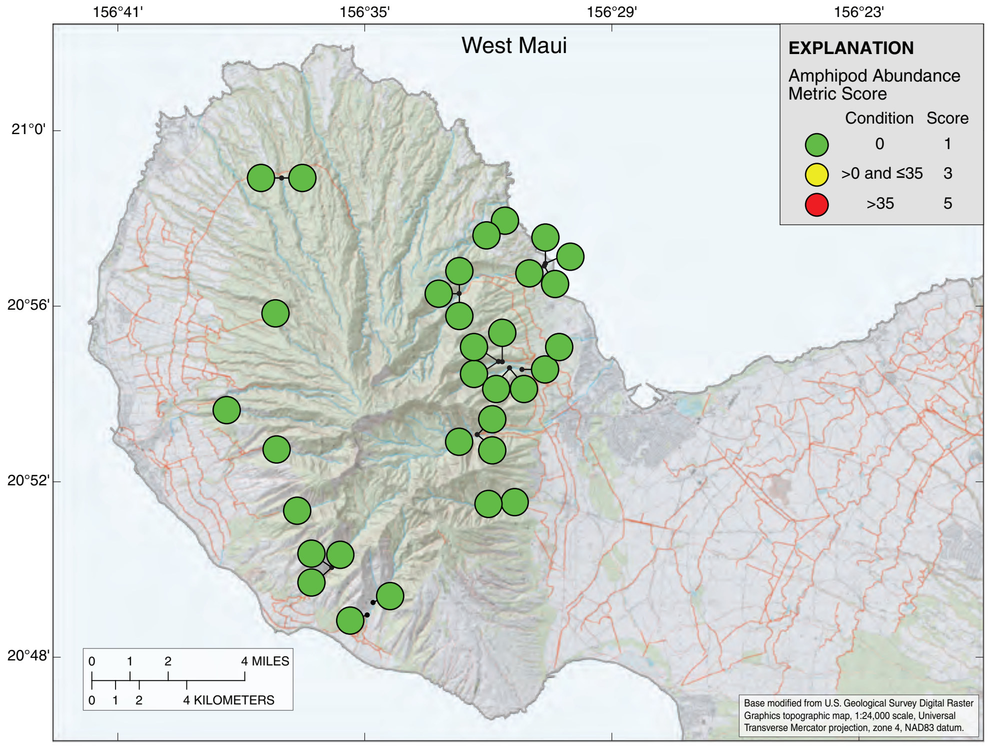


Figure B37. West Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) Amphipoda metric scores.

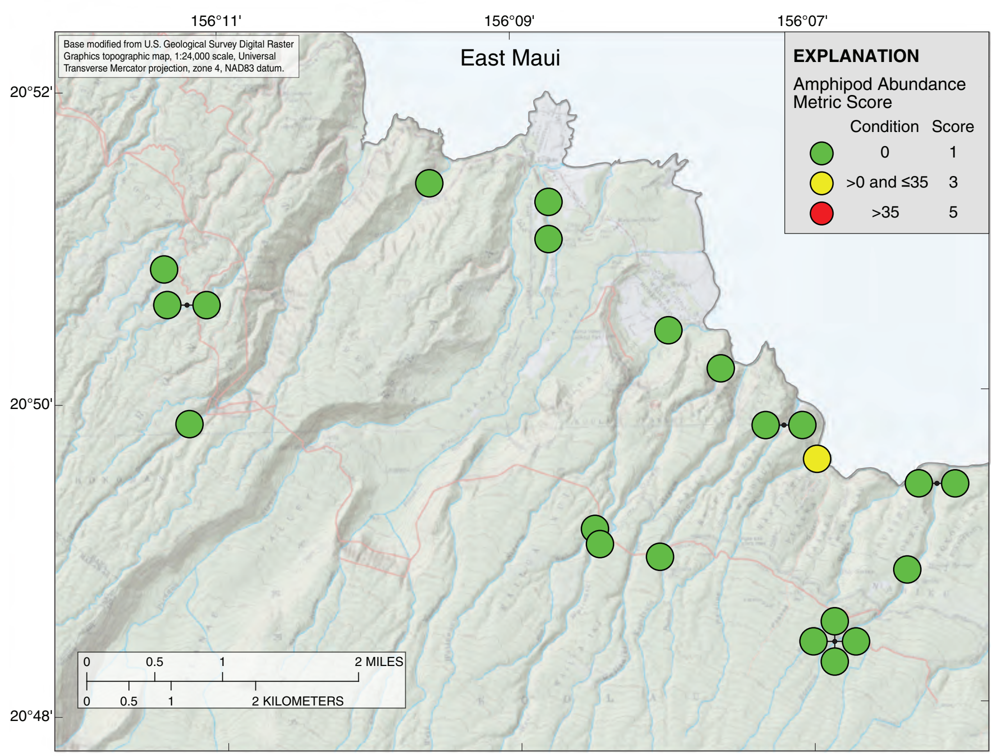


Figure B38. East Maui Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) Amphipoda metric scores.

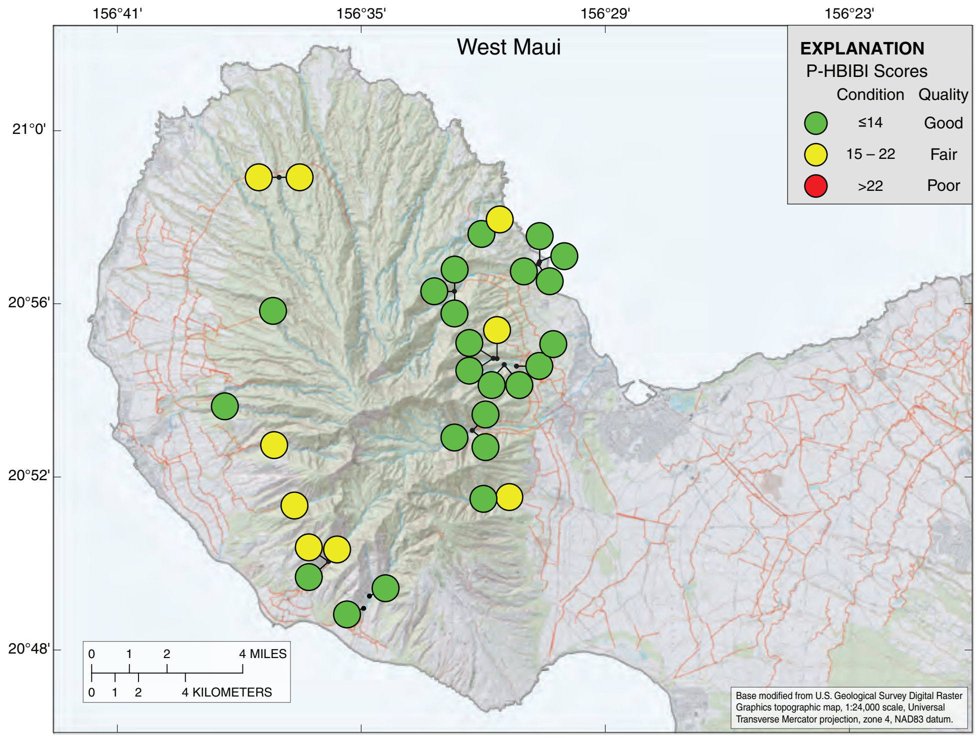


Figure B39. West Maui final Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) scores.

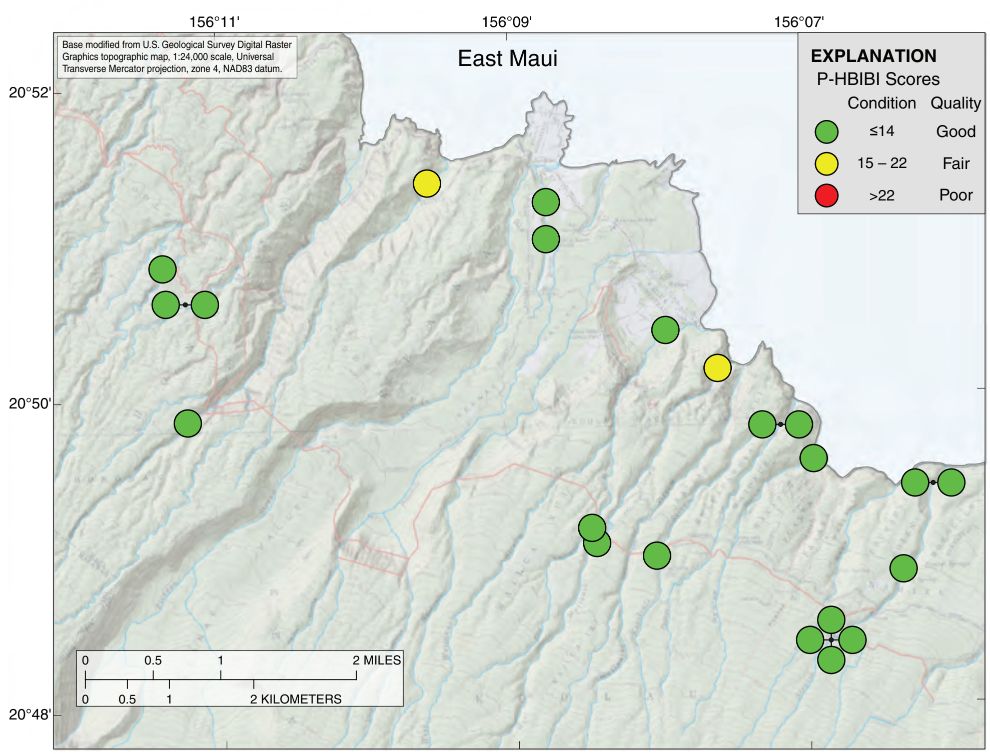


Figure B40. East Maui final Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) scores.

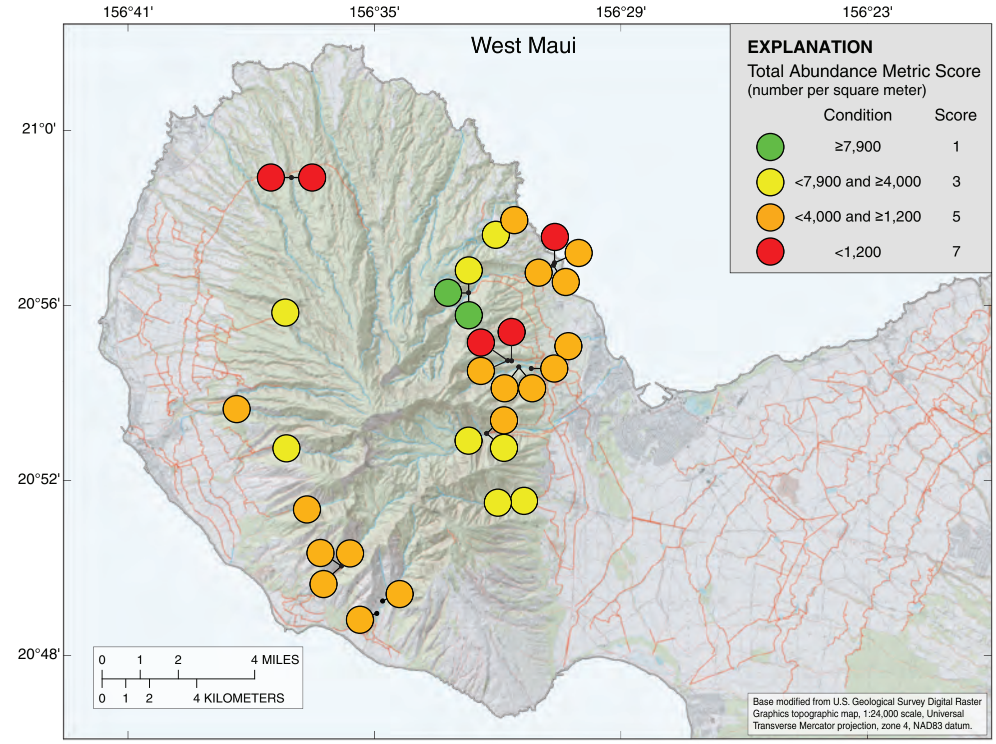


Figure B41. West Maui Invertebrate Community Index (ICI) Total Abundance metric scores.

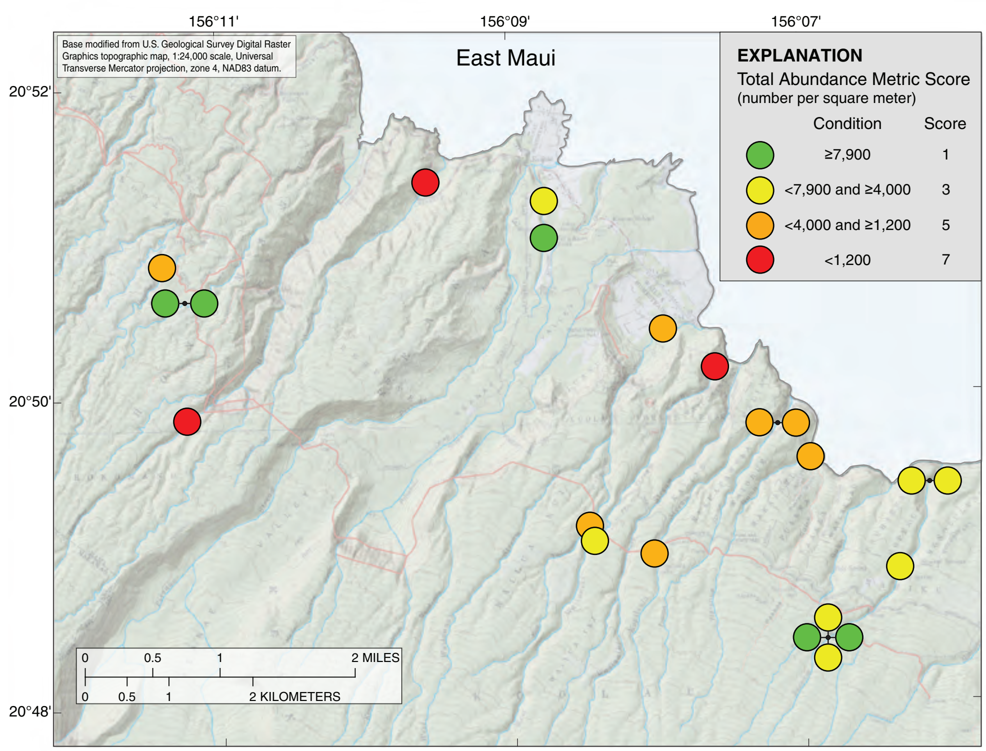


Figure B42. East Maui Invertebrate Community Index (ICI) Total Abundance metric scores.

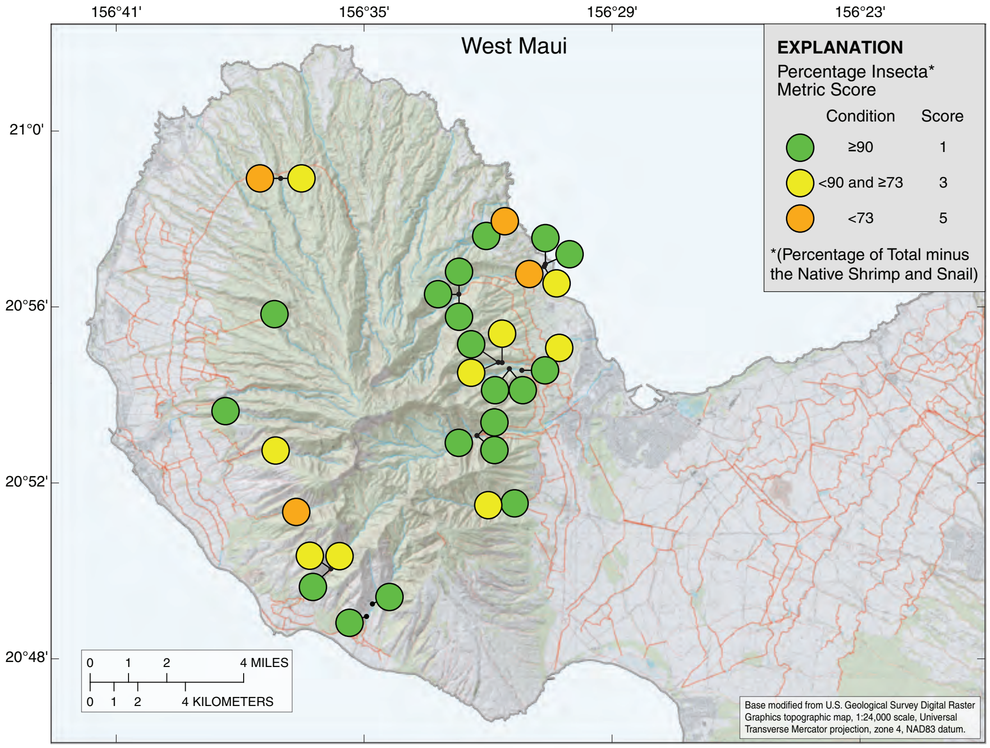


Figure B43. West Maui Invertebrate Community Index (ICI) Percentage of Insecta metric scores.

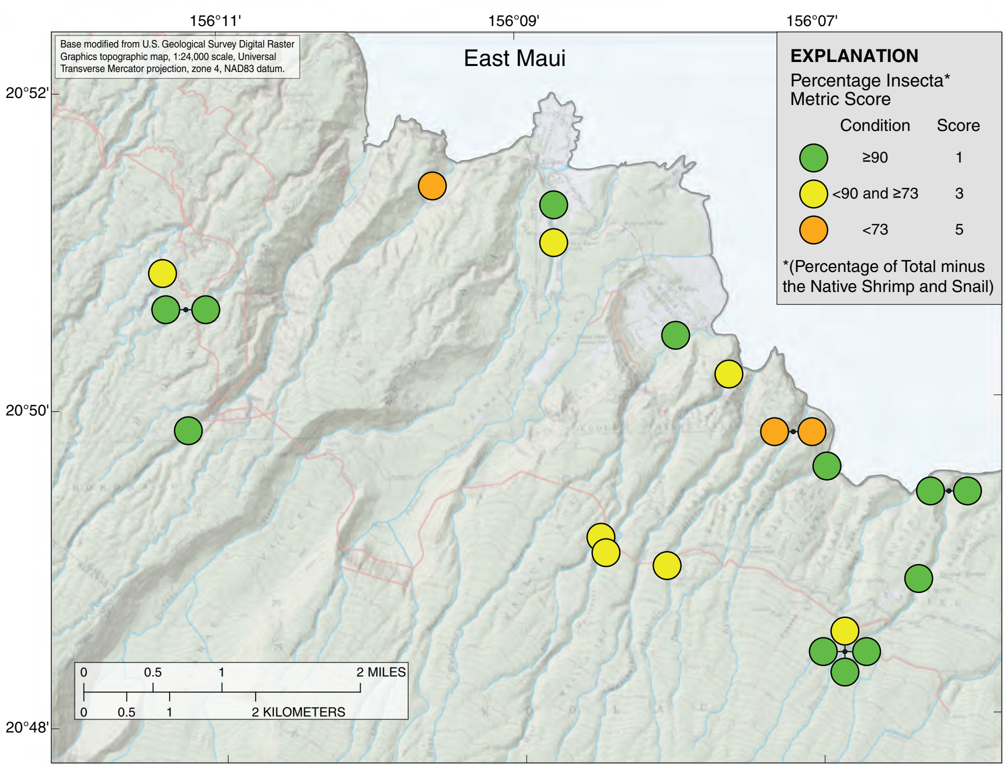


Figure B44. East Maui Invertebrate Community Index (ICI) Percentage of Insecta metric scores.

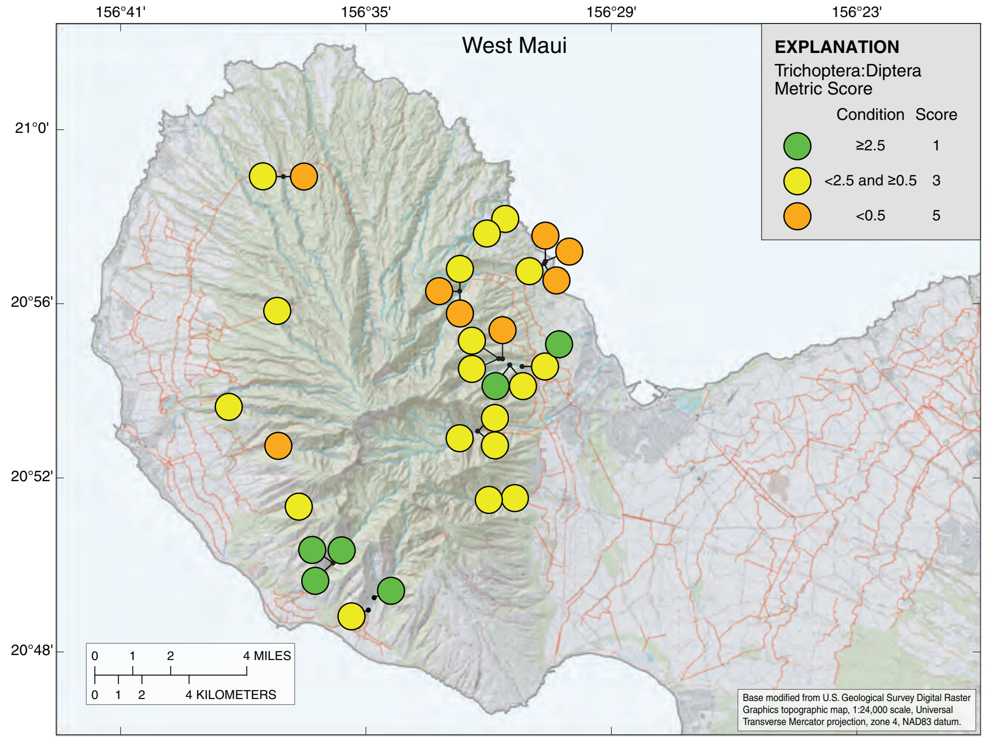


Figure B45. West Maui Invertebrate Community Index (ICI) Trichoptera:Diptera ratio metric scores.

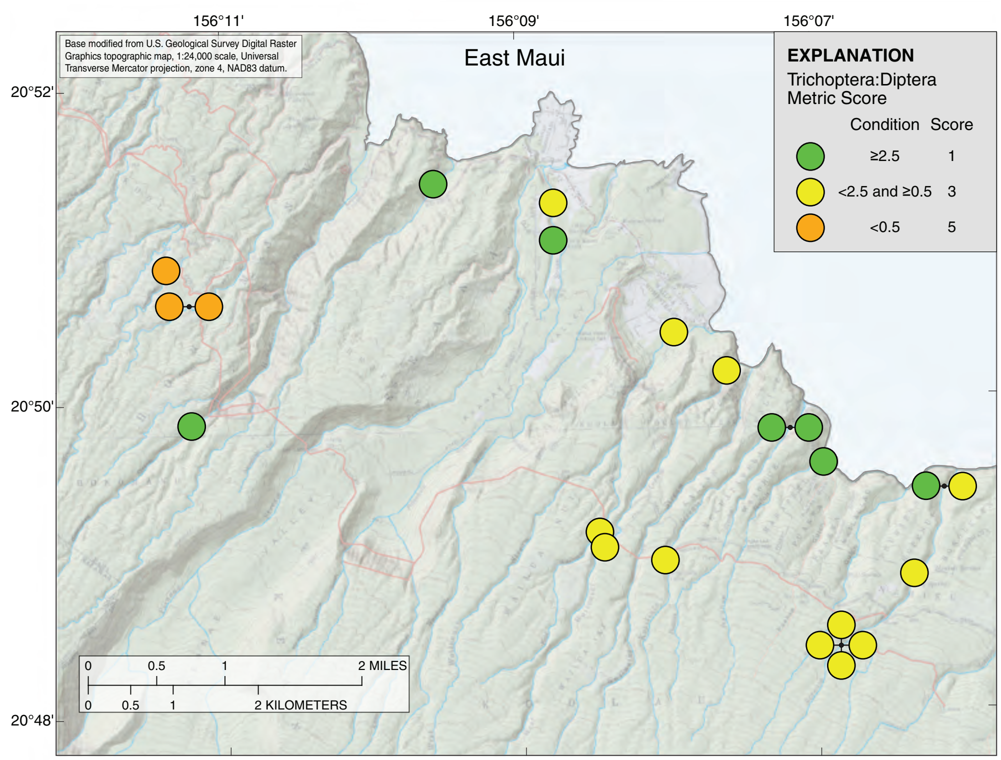


Figure B46. East Maui Invertebrate Community Index (ICI) Trichoptera:Diptera ratio metric scores.

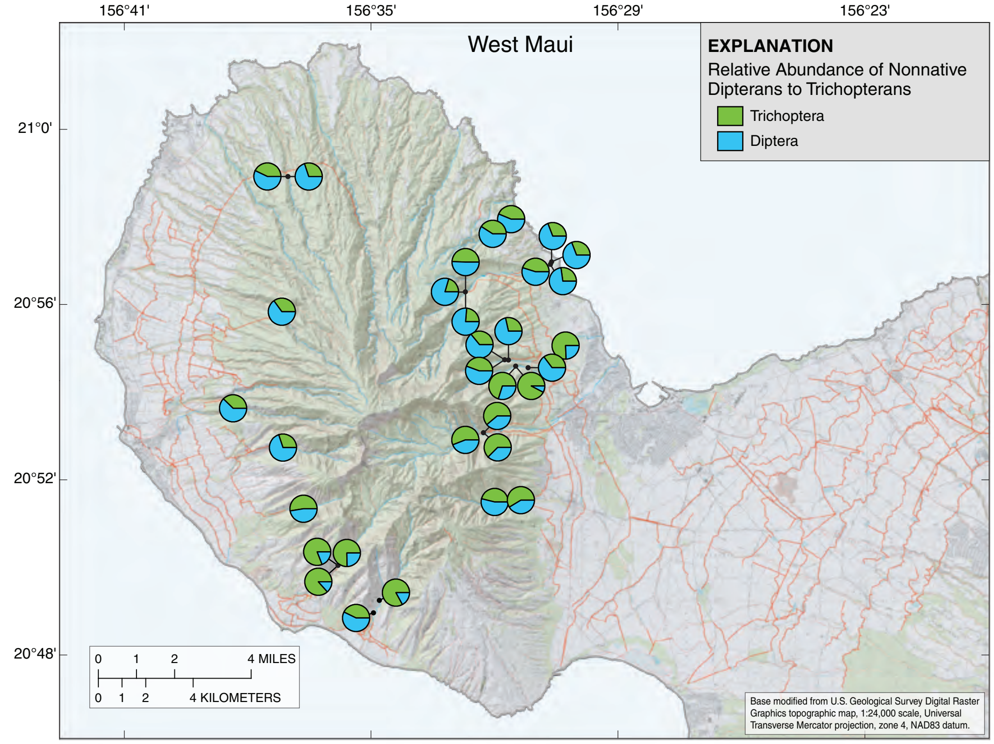


Figure B47. West Maui relative abundance of Trichoptera to Diptera in quantitative samples.

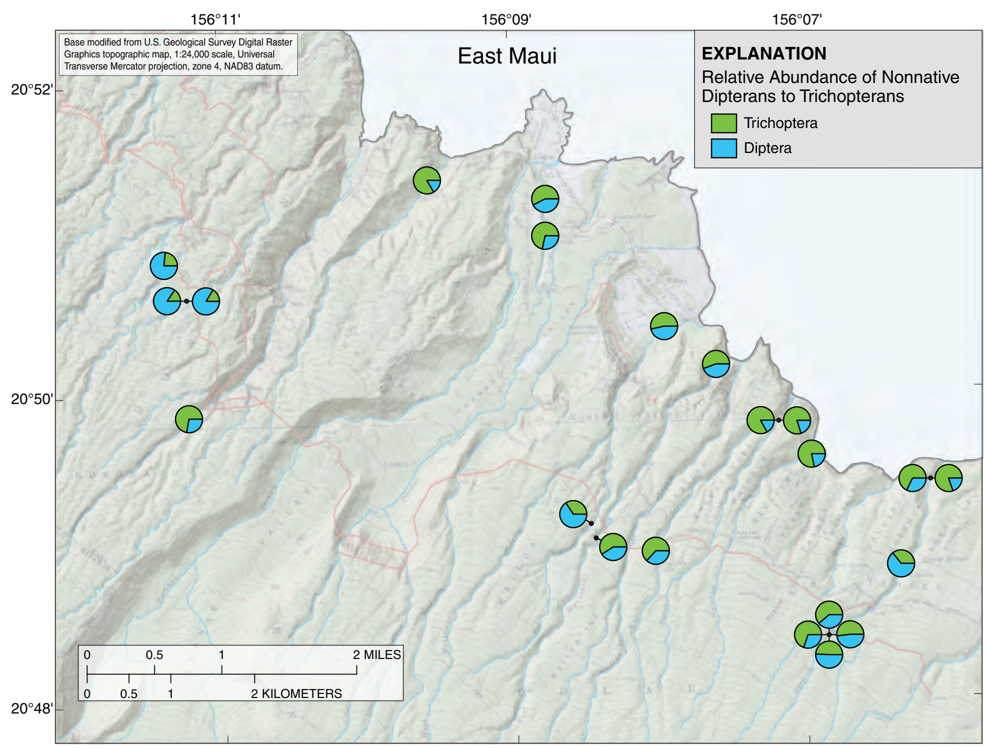


Figure B48. East Maui relative abundance of Trichoptera to Diptera in quantitative samples.

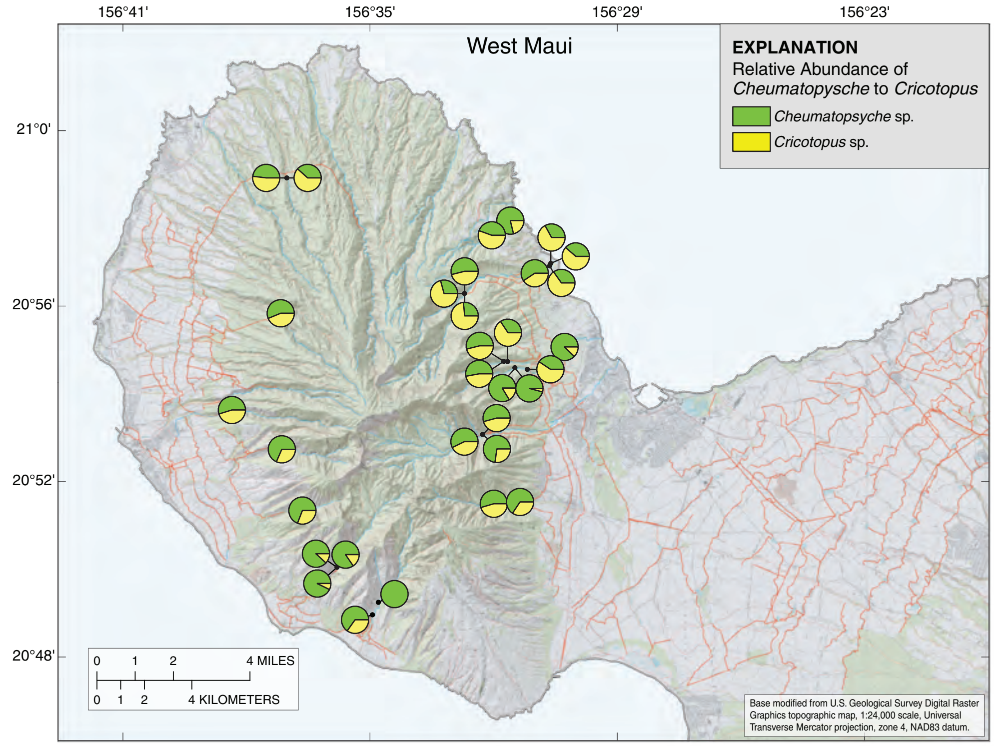


Figure B49. West Maui relative abundance of *Cheumatopsyche* to *Cricotopus* in quantitative samples.

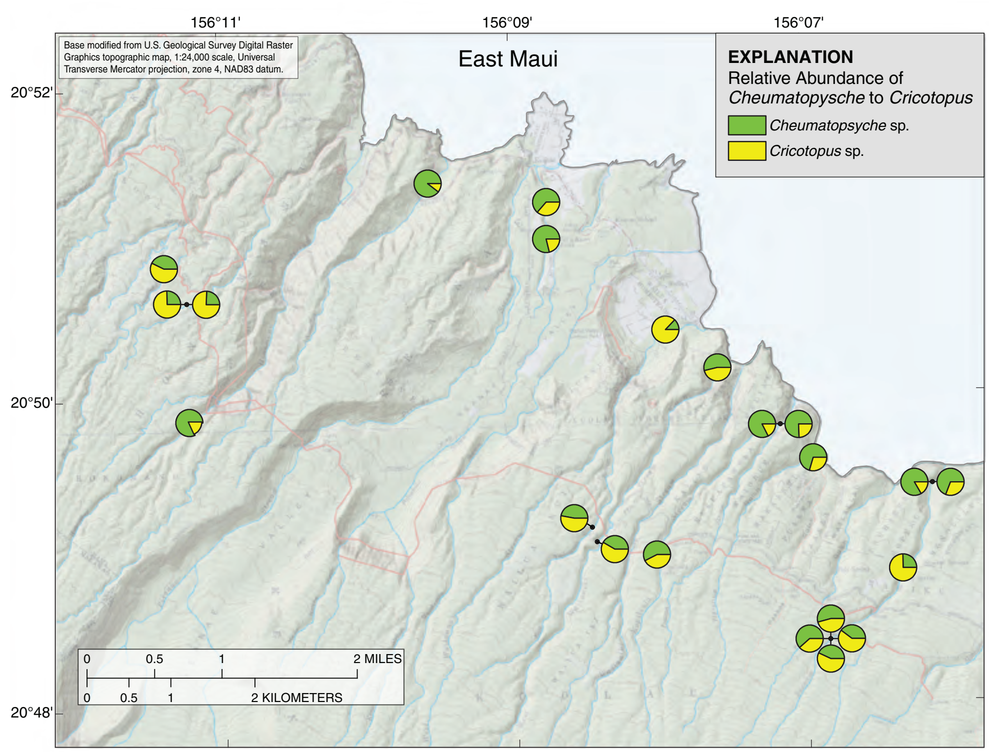


Figure B50. East Maui relative abundance of *Cheumatopsyche* to *Cricotopus* in quantitative samples.

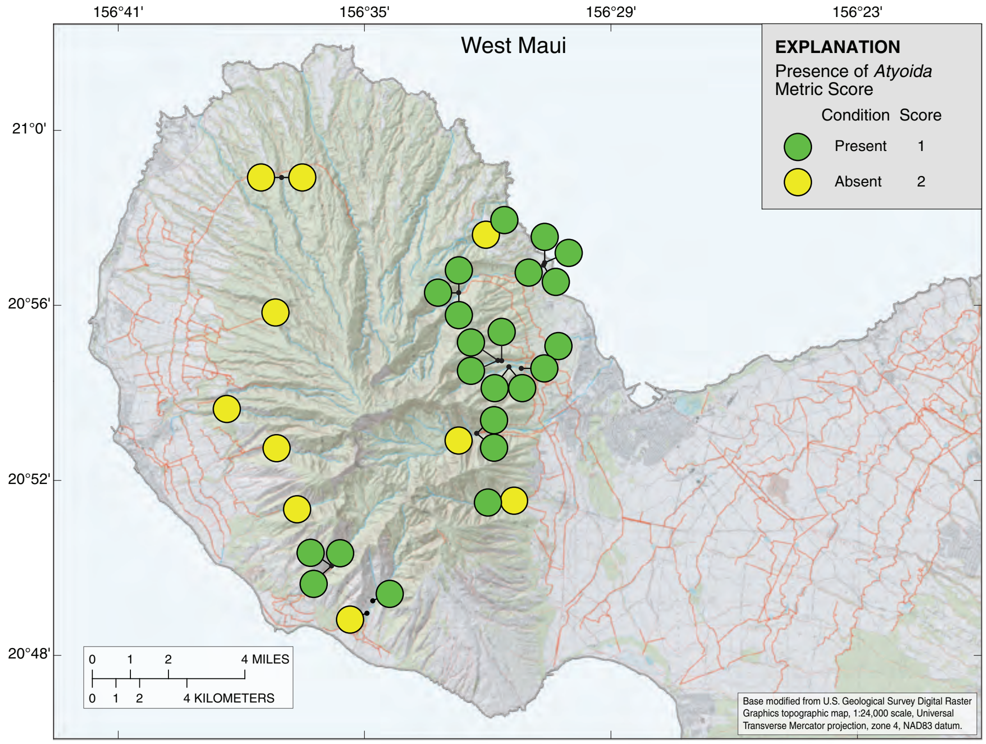


Figure B51. West Maui Invertebrate Community Index (ICI) *Atyoida* (ʻōpae) presence/absence metric scores.

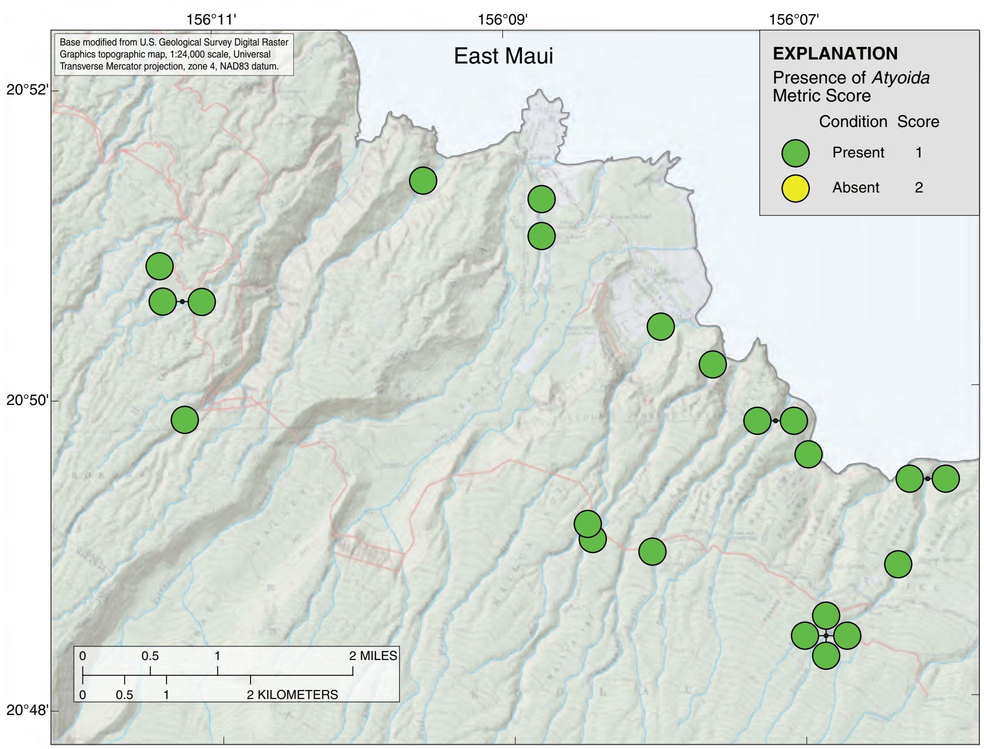


Figure B52. East Maui Invertebrate Community Index (ICI) *Atyoida* (ʻōpae) presence/absence metric scores.

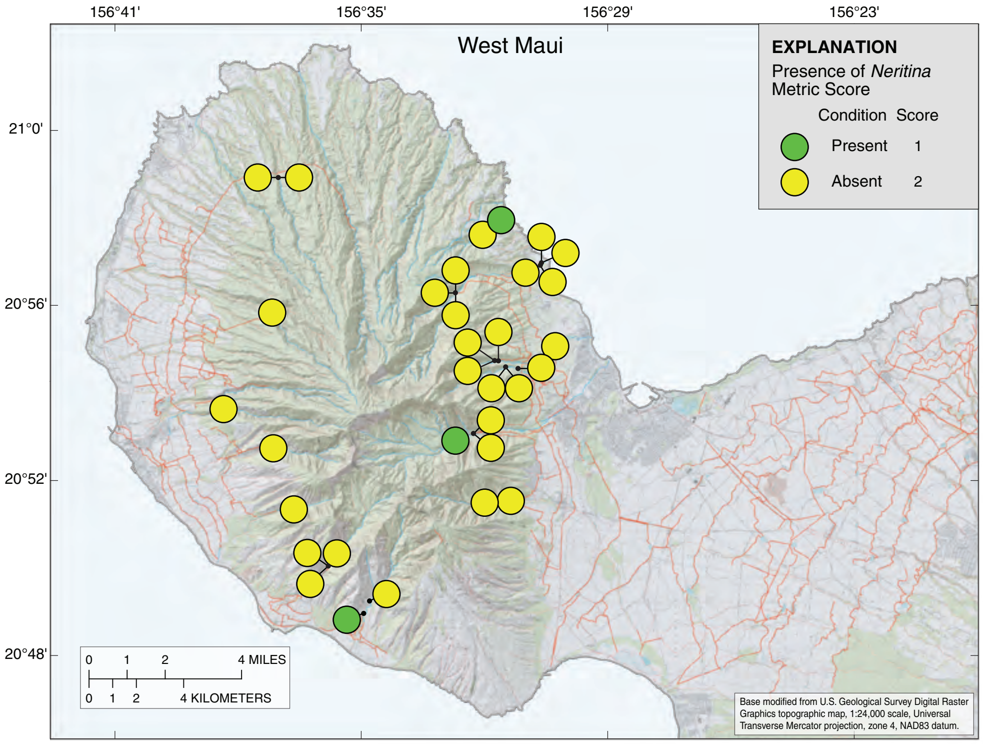


Figure B53. West Maui Invertebrate Community Index (ICI) *Neritina* (hīhīwai) presence/absence metric scores.

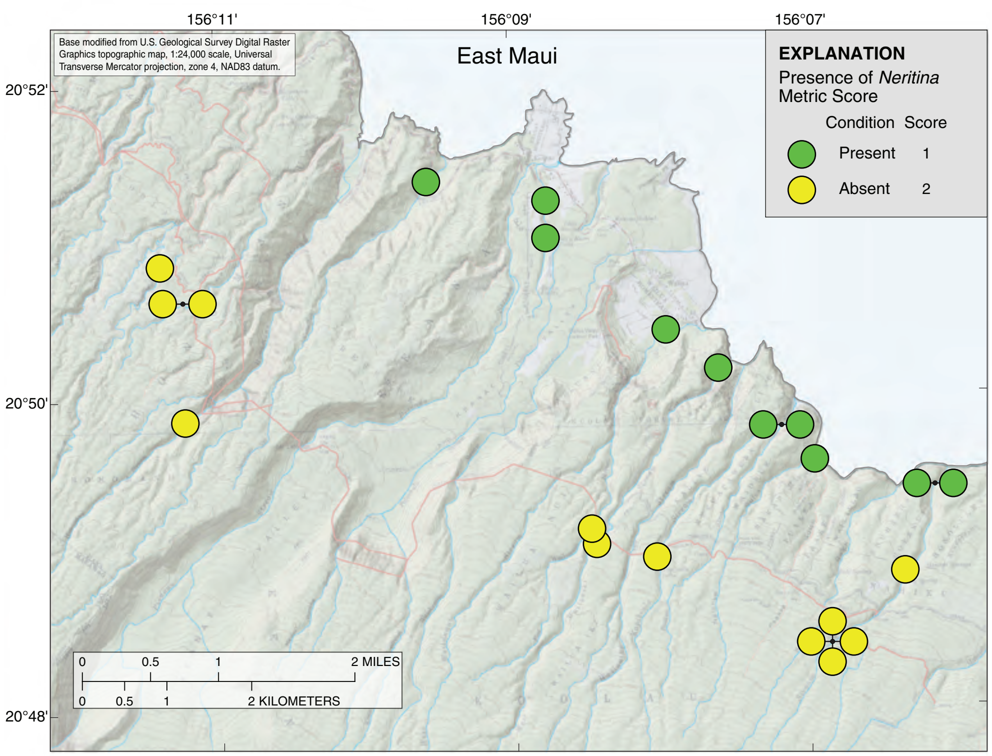


Figure B54. East Maui Invertebrate Community Index (ICI) *Neritina* (hīhīwai) presence/absence metric scores.

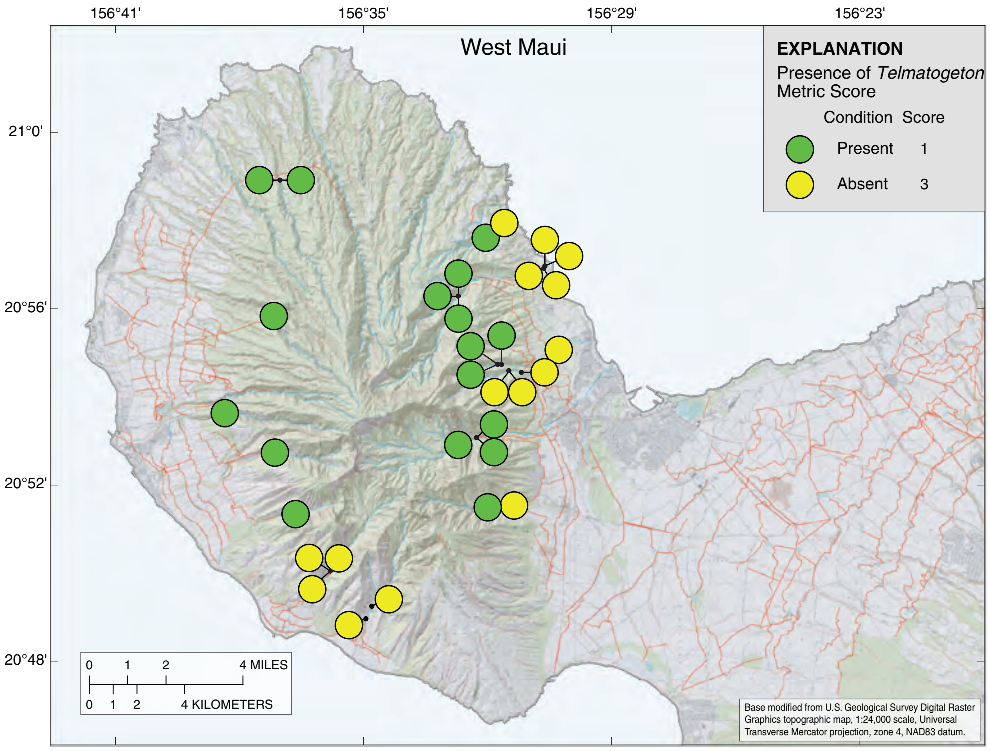


Figure B55. West Maui Invertebrate Community Index (ICI) *Telmatogeton* presence/absence metric scores.

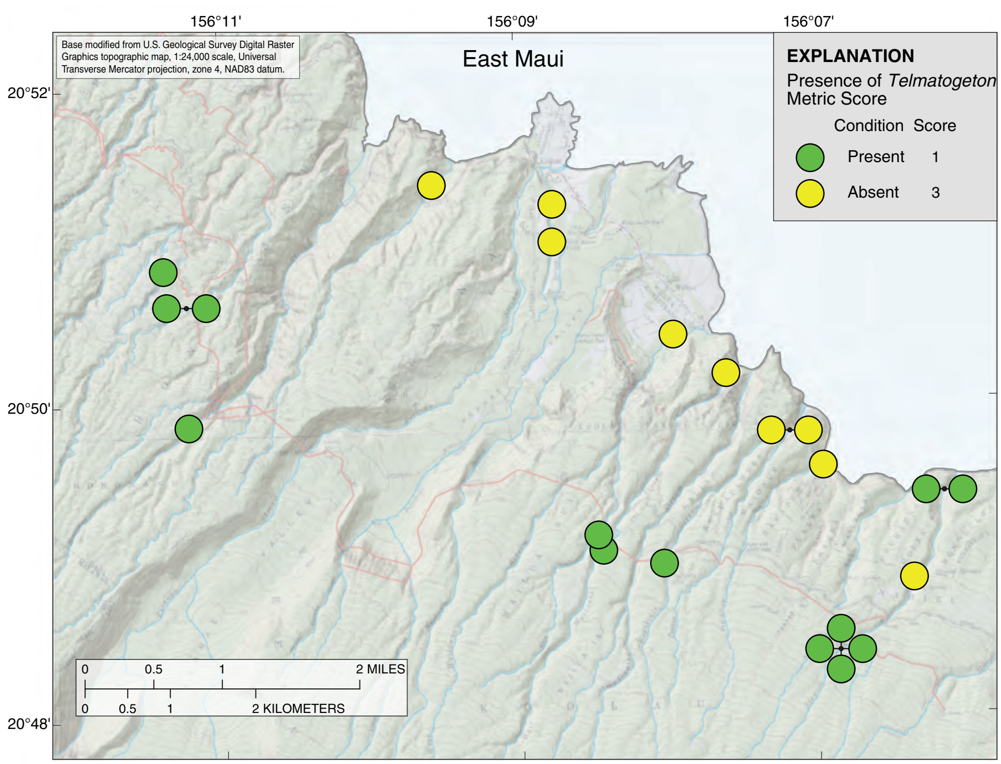


Figure B56. East Maui Invertebrate Community Index (ICI) *Telmatogeton* presence/absence metric scores.

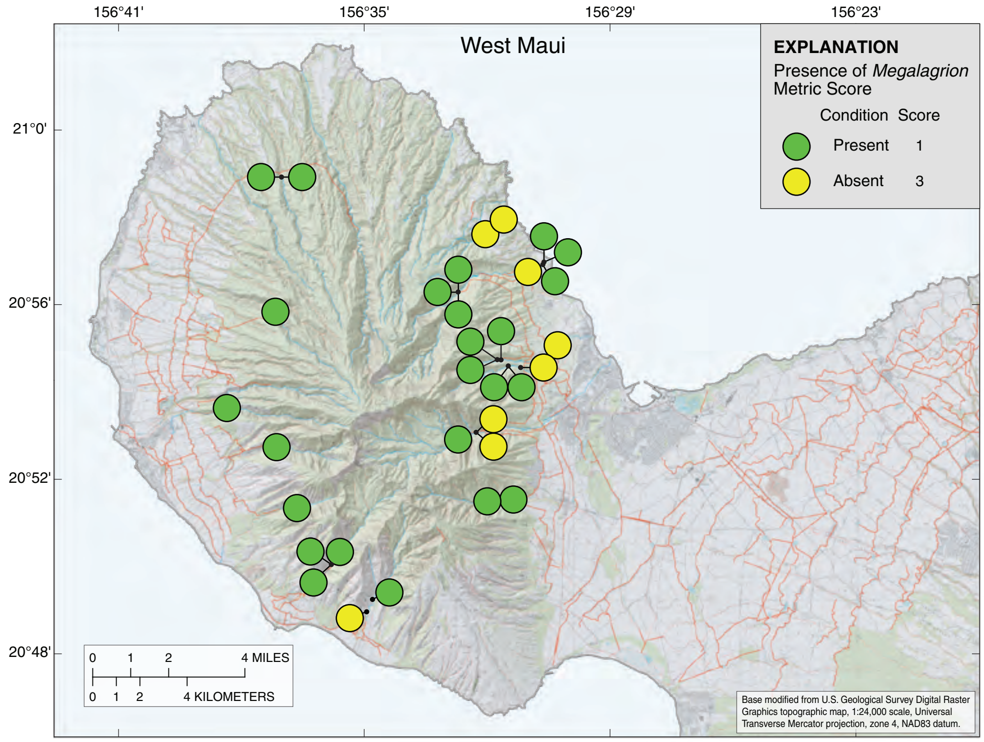


Figure B57. West Maui Invertebrate Community Index (ICI) *Megalagrion* presence/absence metric scores.

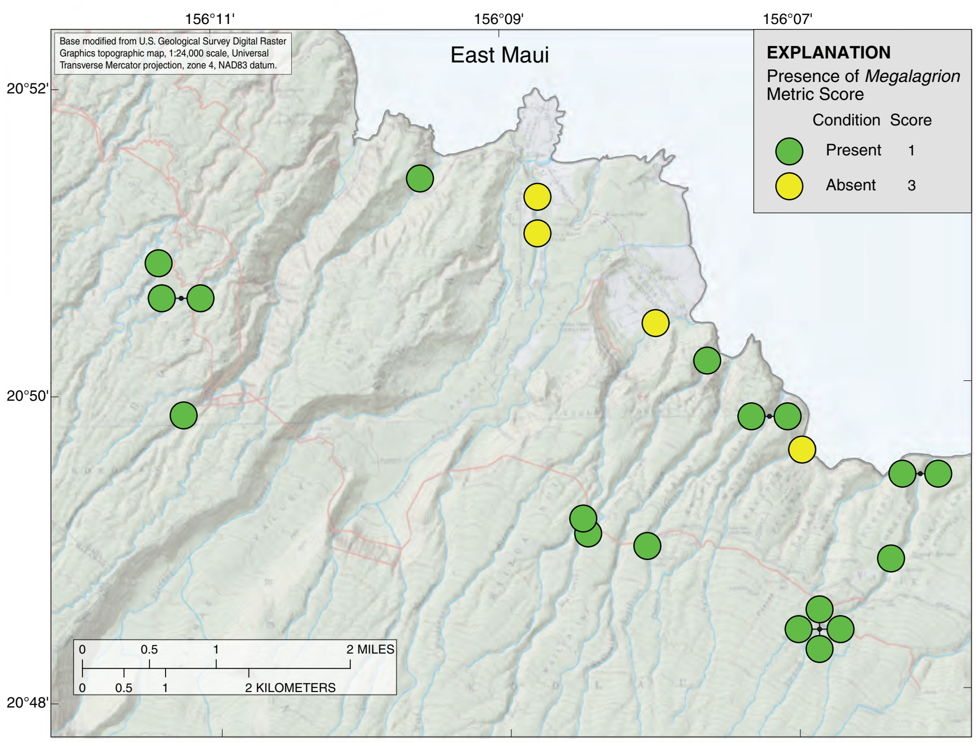


Figure B58. East Maui Invertebrate Community Index (ICI) *Megalagrion* presence/absence metric scores.

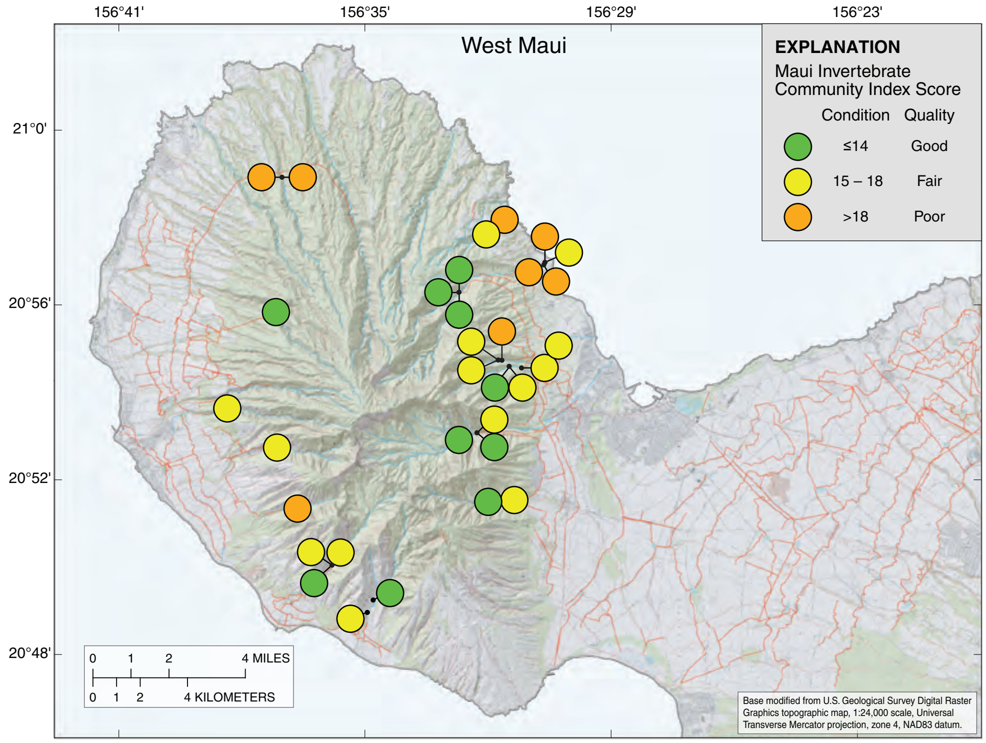


Figure B59. West Maui final Maui Invertebrate Community Index (ICI) scores.

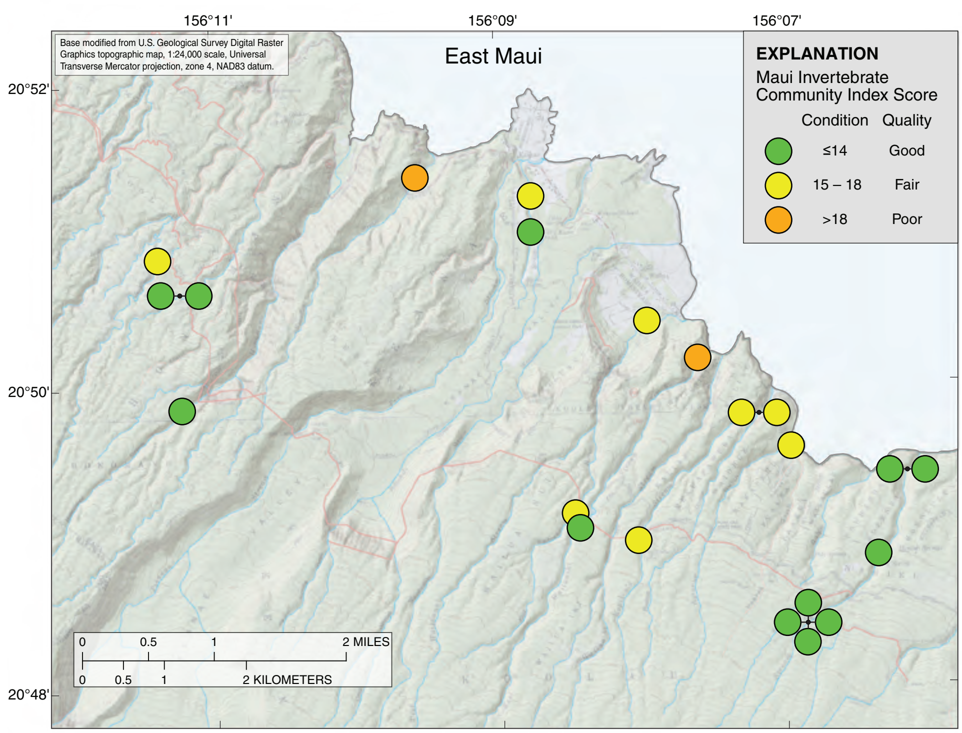


Figure B60. East Maui final Maui Invertebrate Community Index (ICI) scores.

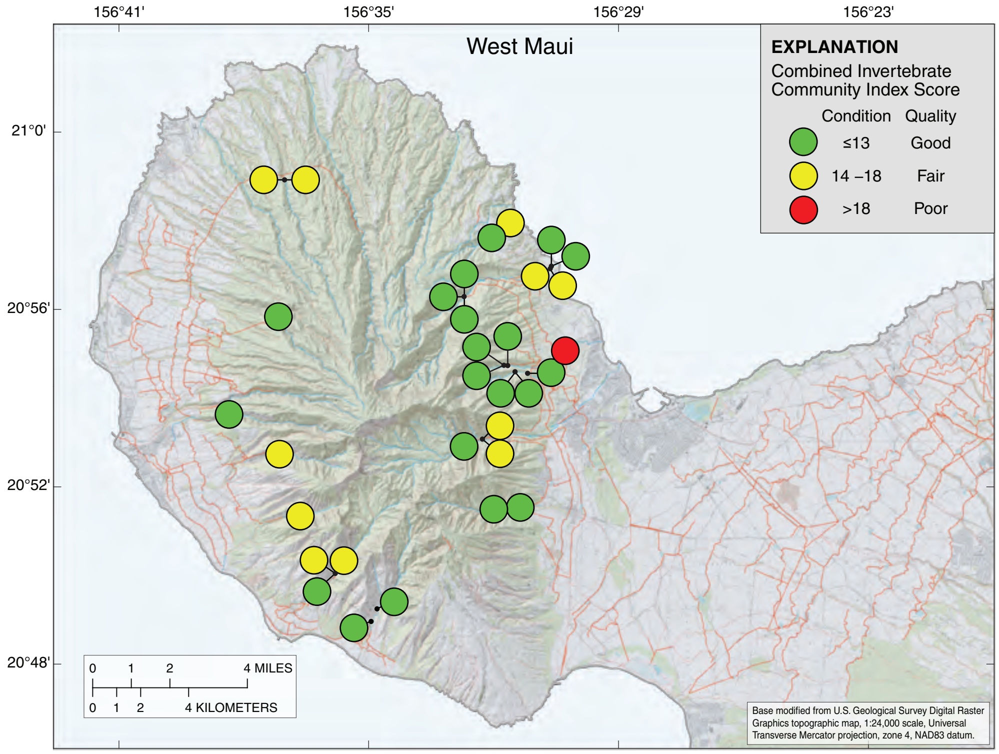


Figure B61. West Maui final combined Invertebrate Community Index (ICI) scores.

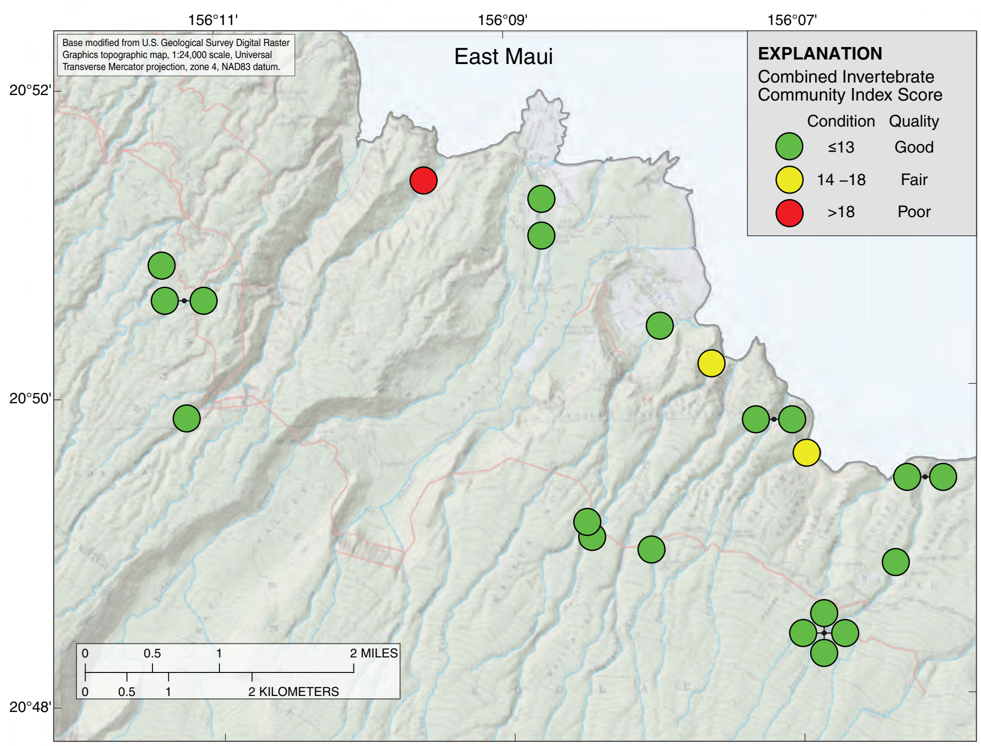


Figure B62. East Maui final combined Invertebrate Community Index (ICI) scores.

Appendix C. O‘ahu Faunal Distribution Maps

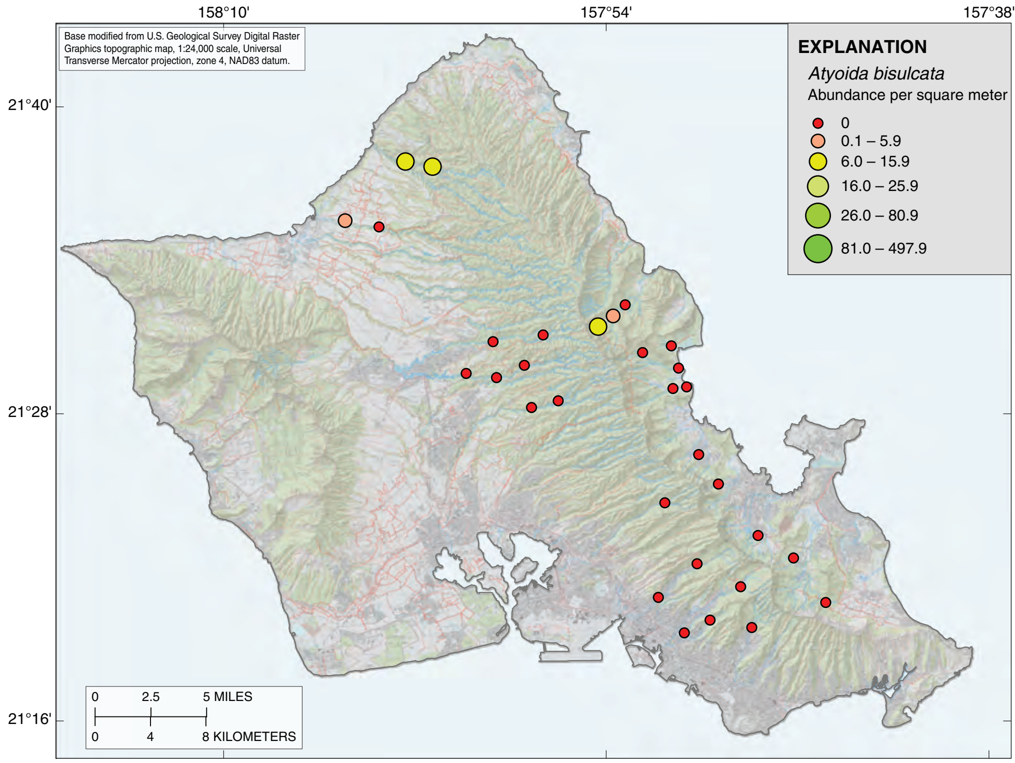


Figure C1. O‘ahu Wadeable Stream Assessment (WSA) abundance of *Atyoida bisulcata* in quantitative samples.

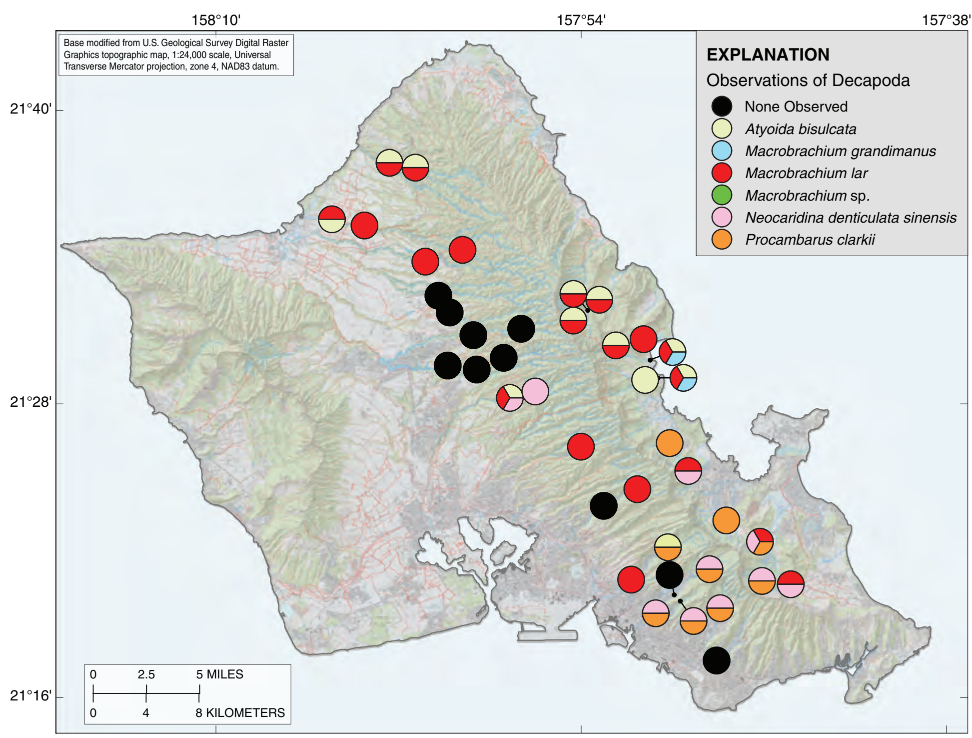


Figure C2. O‘ahu Wadeable Stream Assessment (WSA) observations of Decapoda.

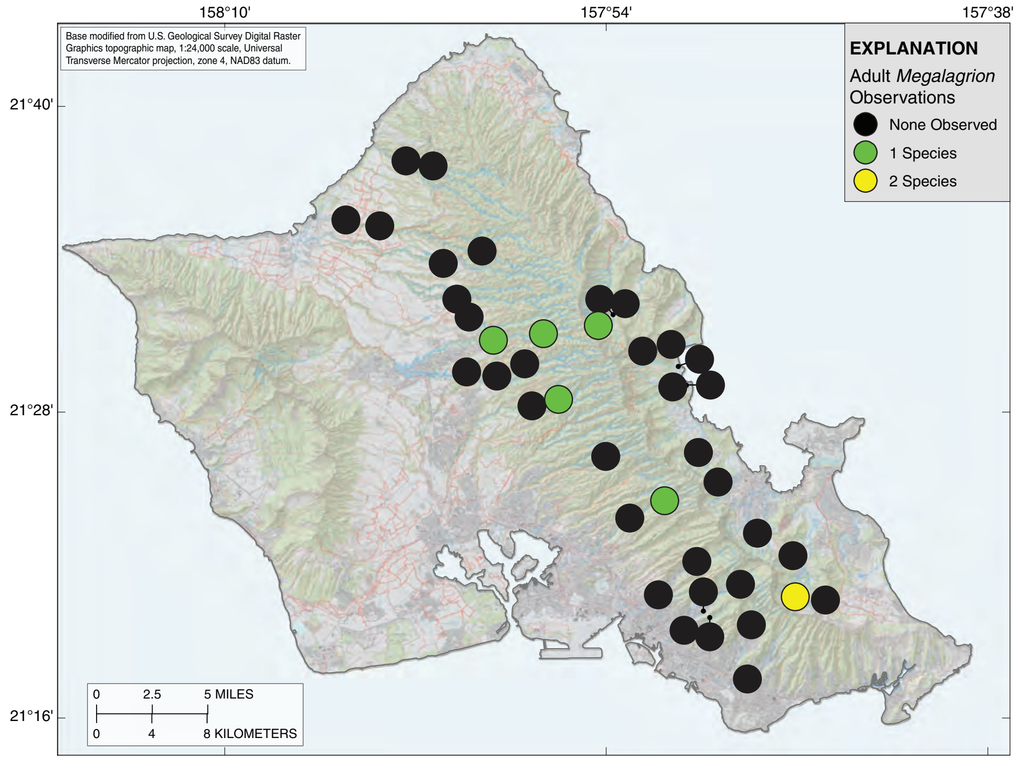


Figure C3. O‘ahu Wadeable Stream Assessment (WSA) observations of adult *Megalagrion*.

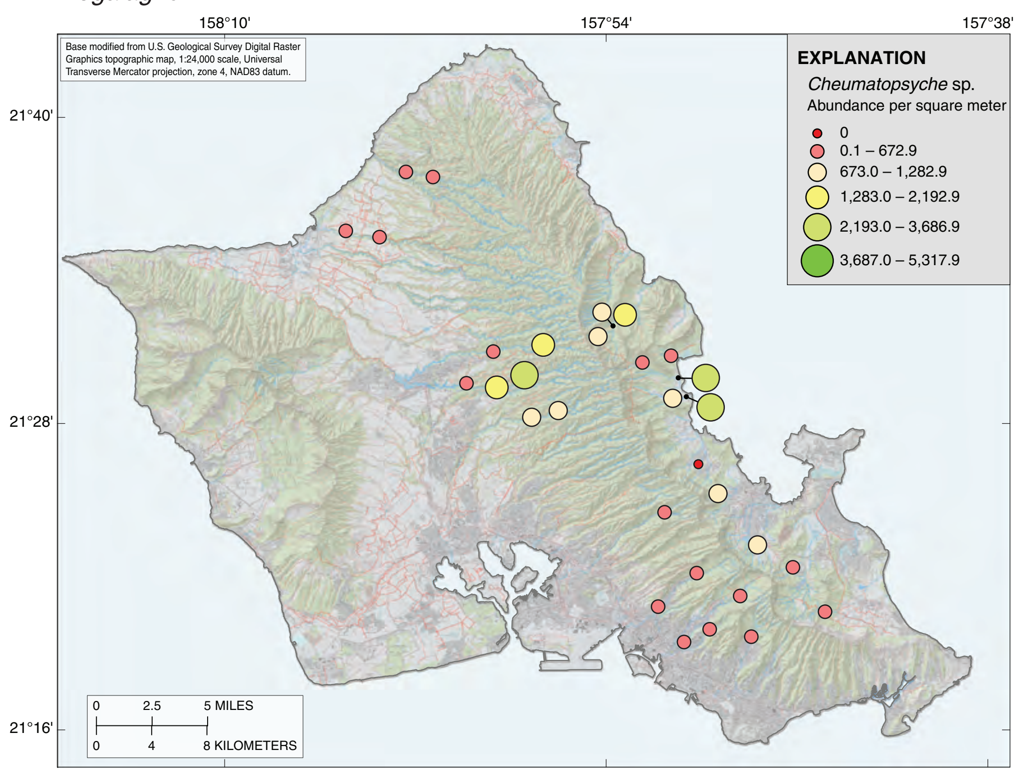


Figure C4. O‘ahu Wadeable Stream Assessment (WSA) abundance of *Cheumatopsyche* in quantitative samples.

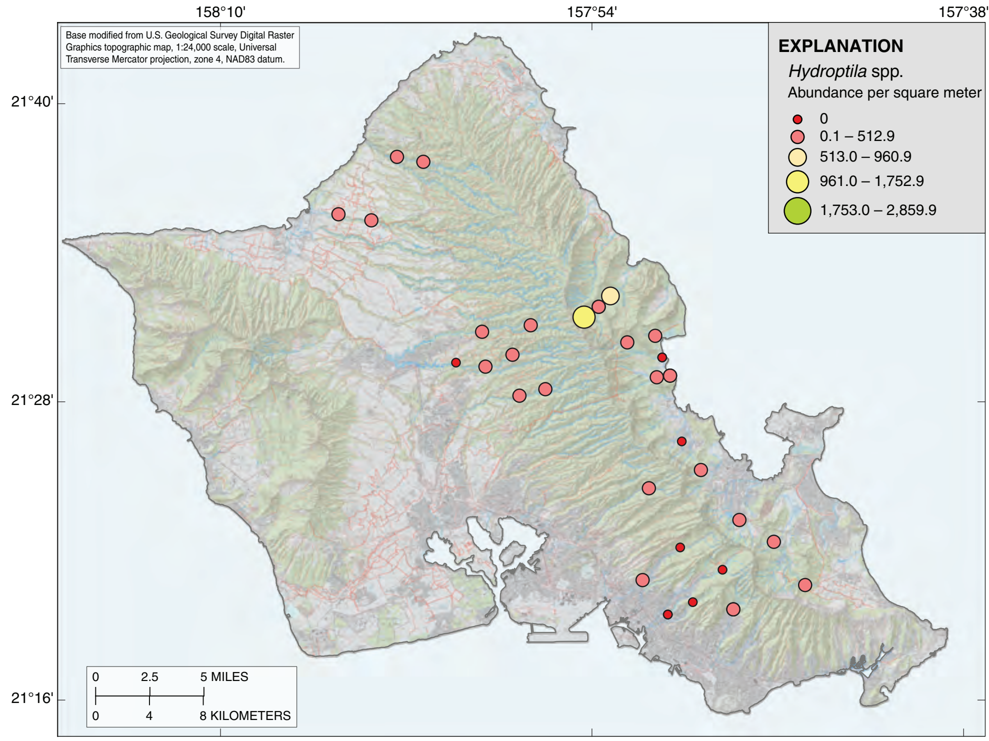


Figure C5. O‘ahu Wadeable Stream Assessment (WSA) abundance of *Hydroptila* in quantitative samples.

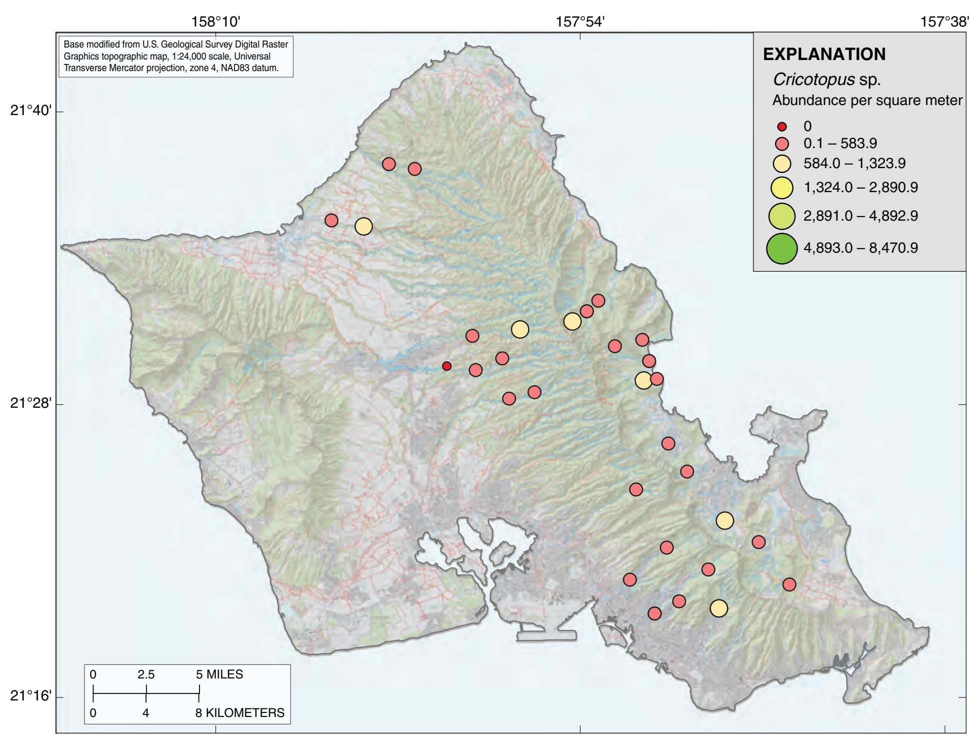


Figure C6. O‘ahu Wadeable Stream Assessment (WSA) abundance of *Cricotopus* in quantitative samples.

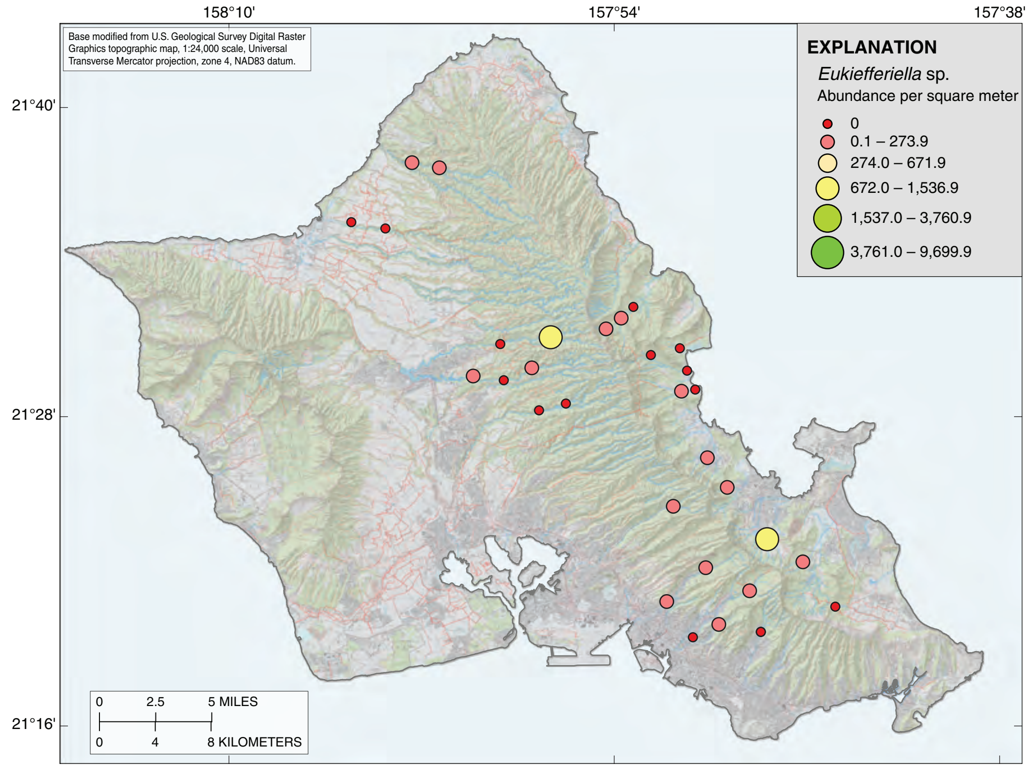


Figure C7. O‘ahu Wadeable Stream Assessment (WSA) abundance of *Eukiefferiella* in quantitative samples.

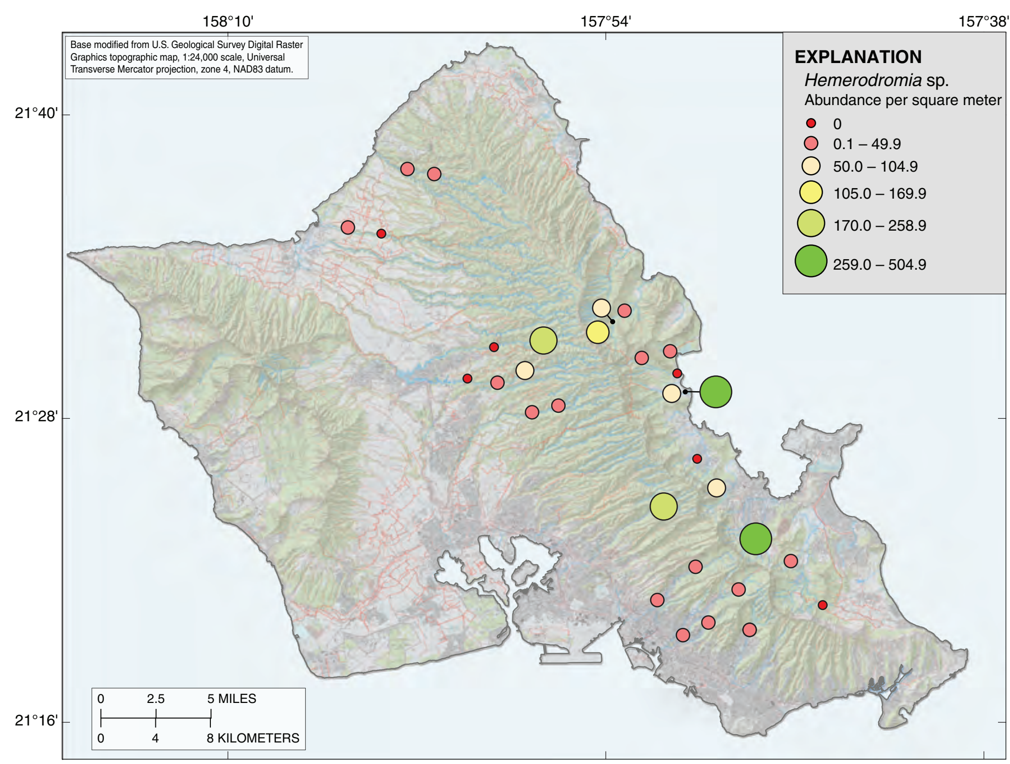


Figure C8. O‘ahu Wadeable Stream Assessment (WSA) abundance of *Hemerodromia* in quantitative samples.

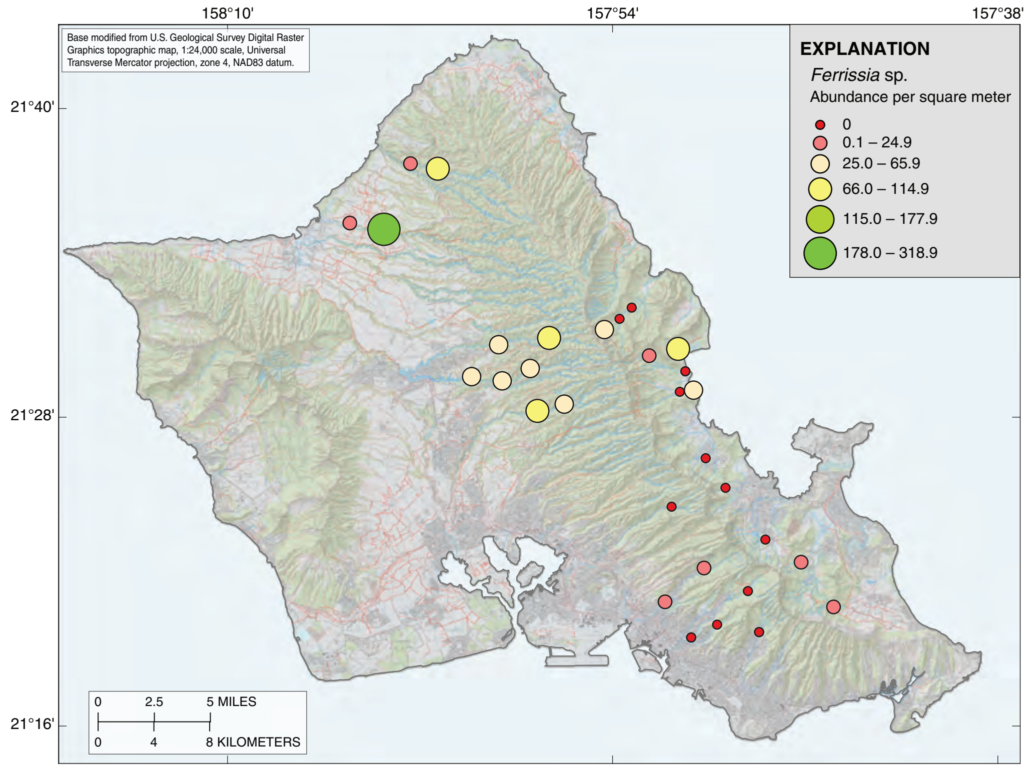


Figure C9. Oʻahu Wadeable Stream Assessment (WSA) abundance of *Ferrissia* in quantitative samples.

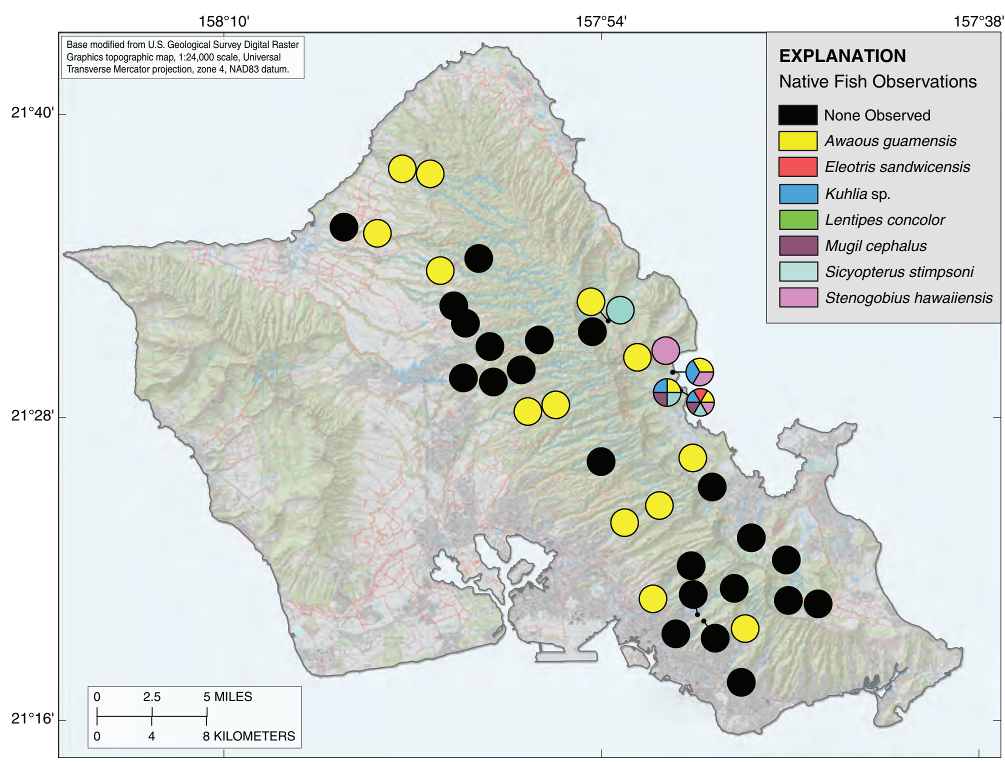


Figure C10. Oʻahu Wadeable Stream Assessment (WSA) native fish observations.

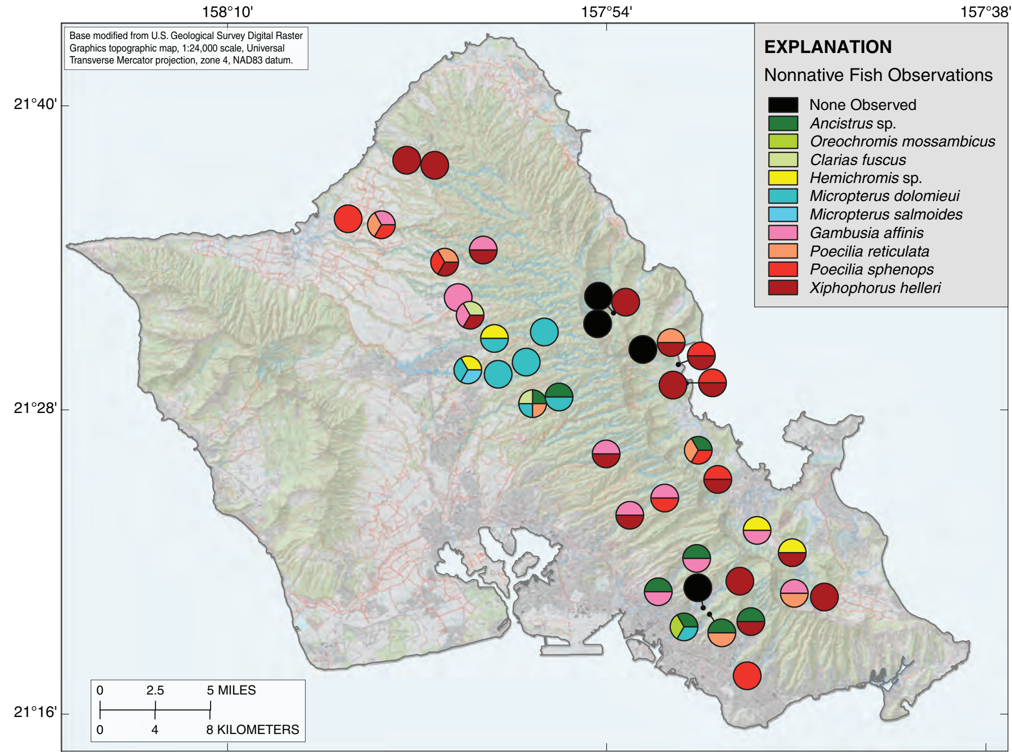


Figure C11. O‘ahu Wadeable Stream Assessment (WSA) observations of nonnative fish.

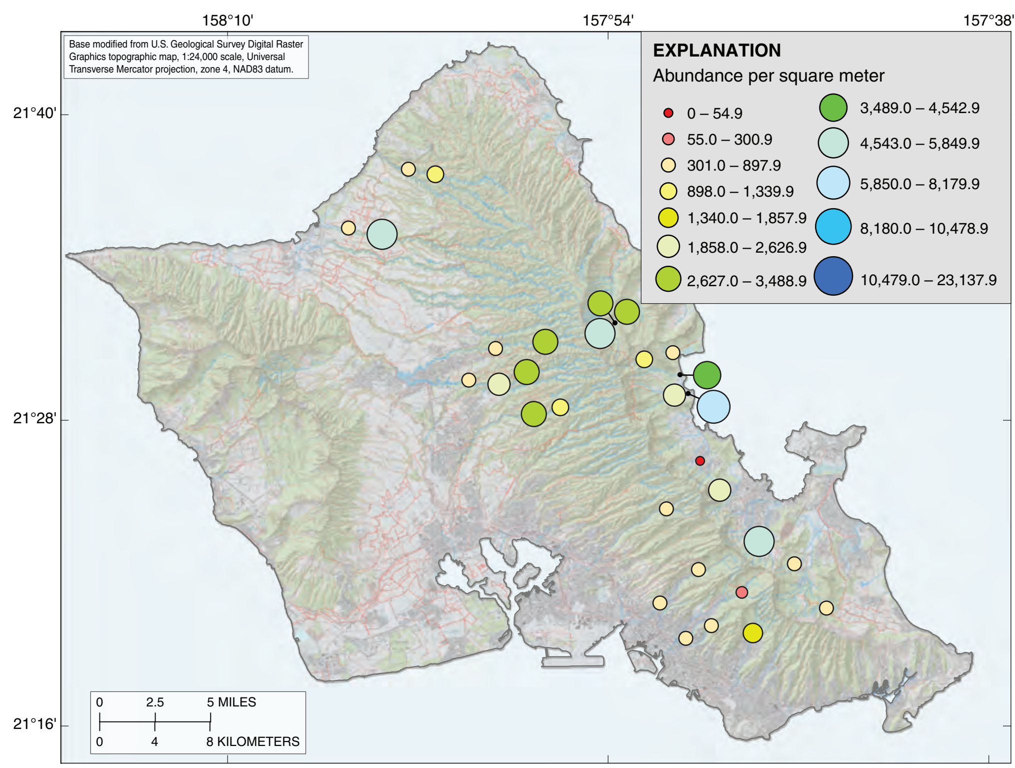


Figure C12. O‘ahu Wadeable Stream Assessment (WSA) total quantitative macroinvertebrate abundances.

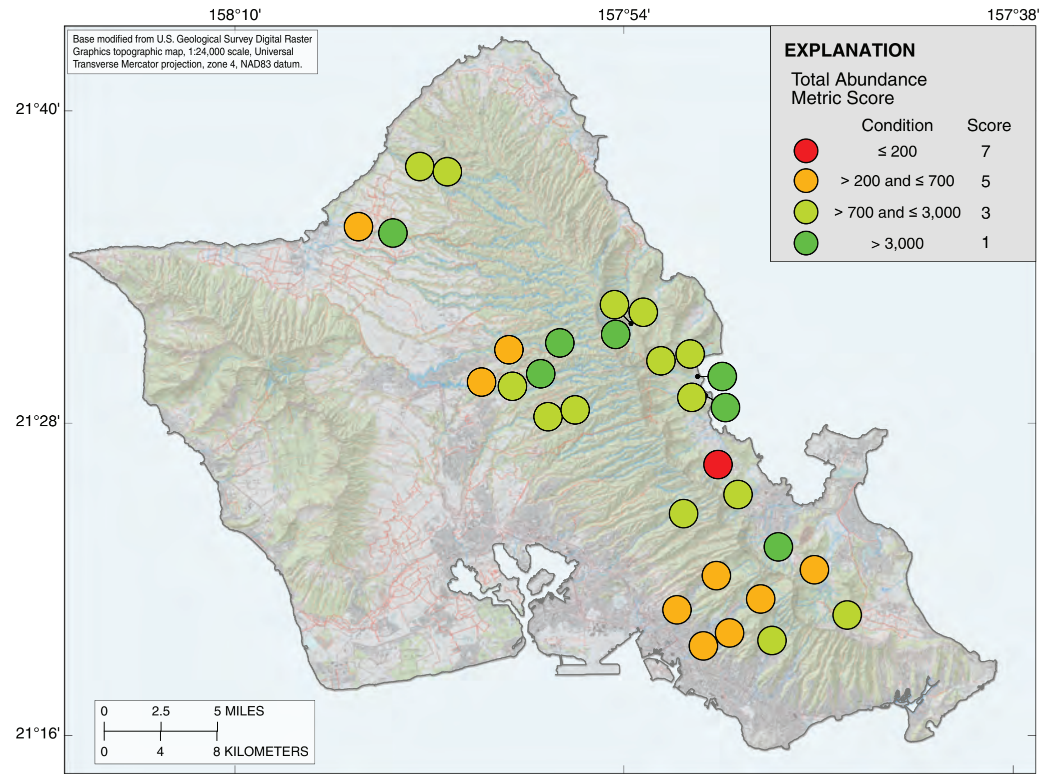


Figure C13. O‘ahu Wadeable Stream Assessment (WSA) Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) abundance metric scores.

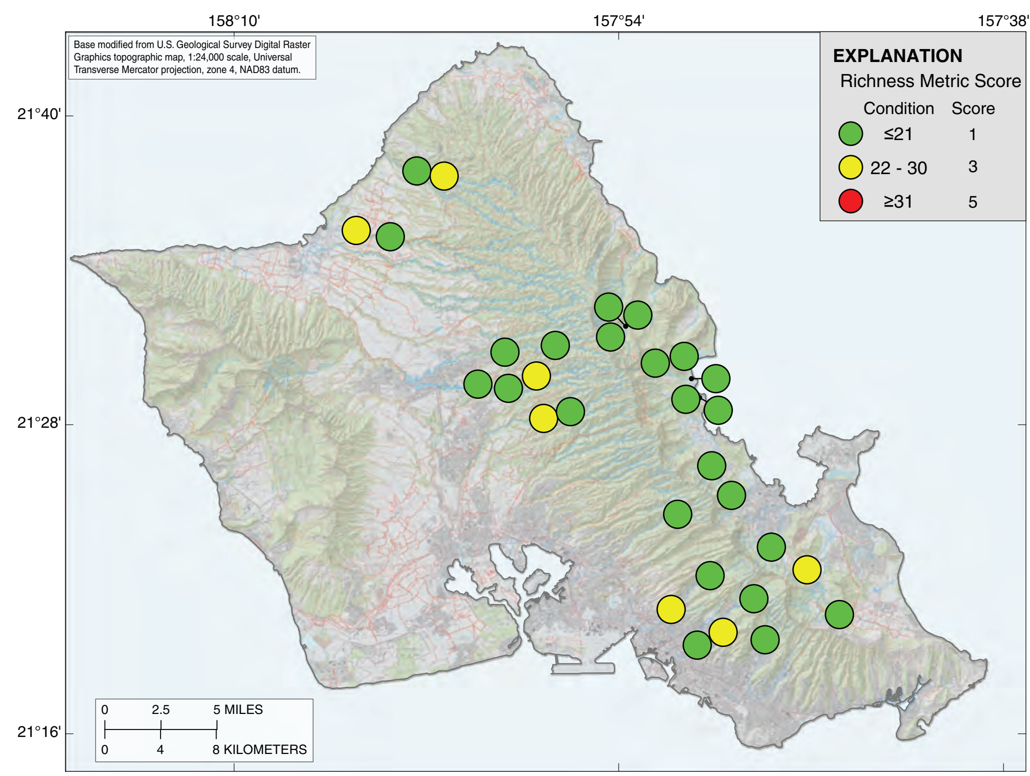


Figure C14. O‘ahu Wadeable Stream Assessment (WSA) Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) richness metric scores.

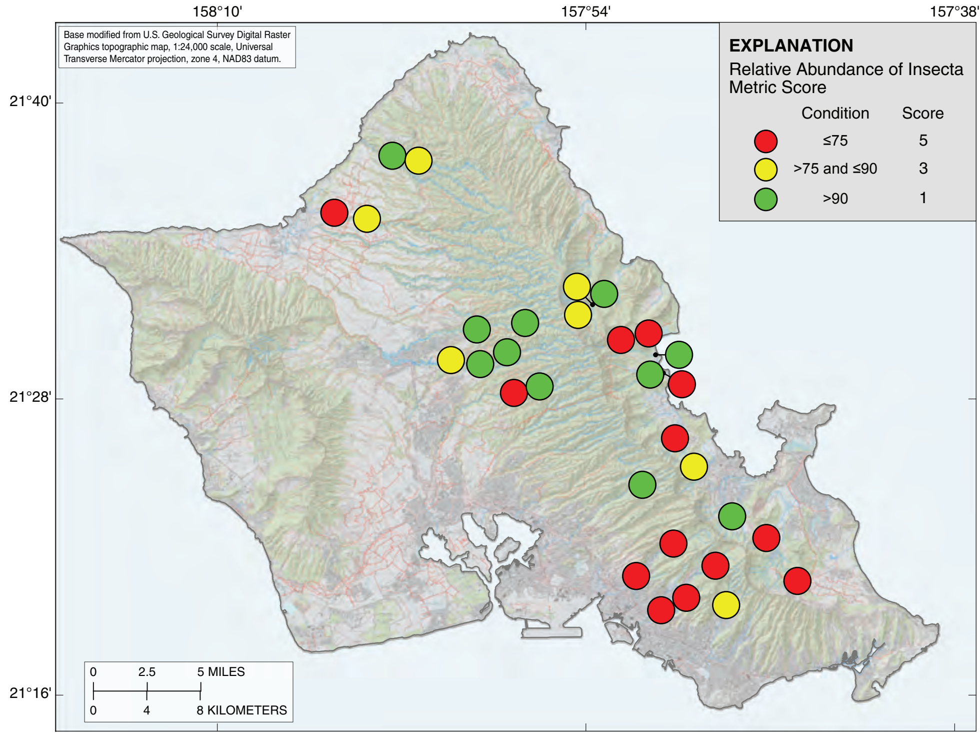


Figure C15. O‘ahu Wadeable Stream Assessment (WSA) Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) percentage of Insecta metric scores.

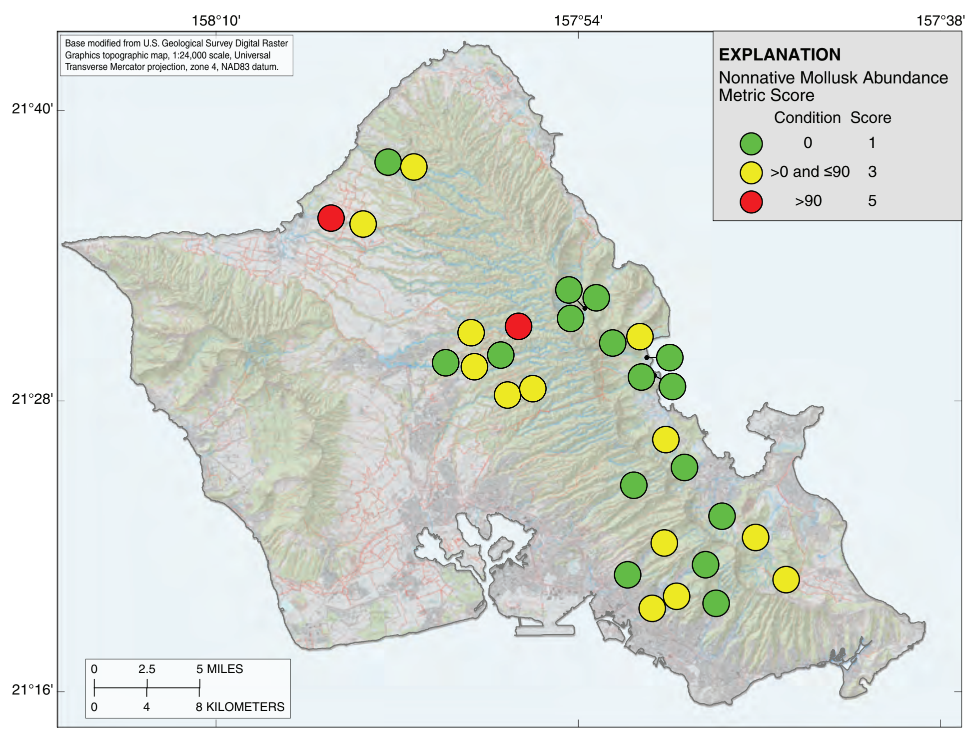


Figure C16. O‘ahu Wadeable Stream Assessment (WSA) Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) nonnative/cryptogenic Mollusca metric scores.

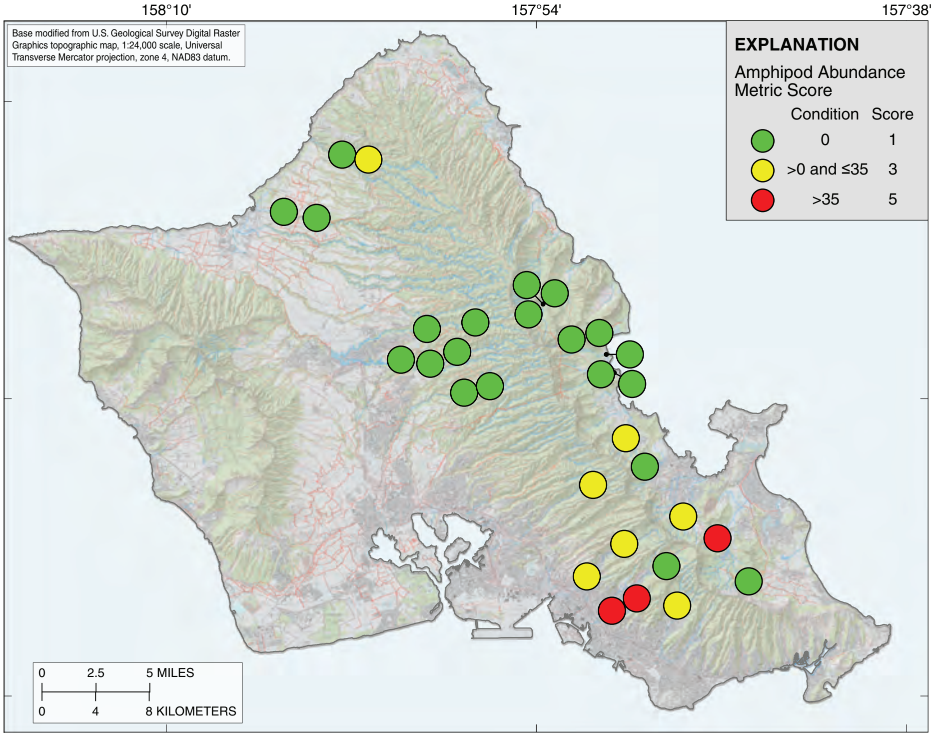


Figure C17. Oʻahu Wadeable Stream Assessment (WSA) Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) Amphipoda metric scores.

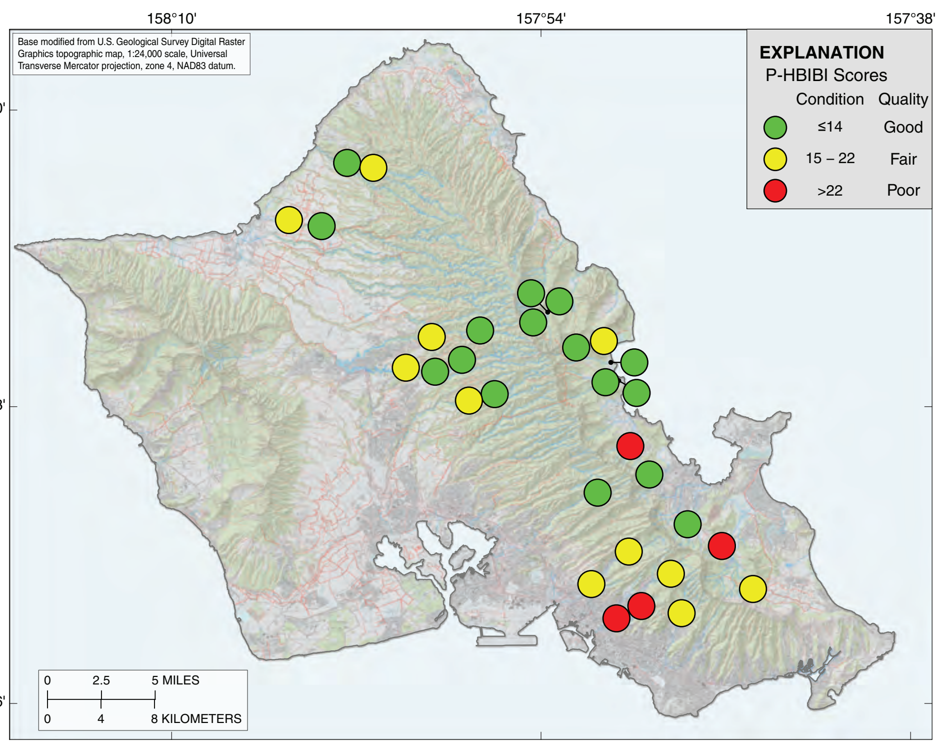


Figure C18. Oʻahu Wadeable Stream Assessment (WSA) Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) final scores.

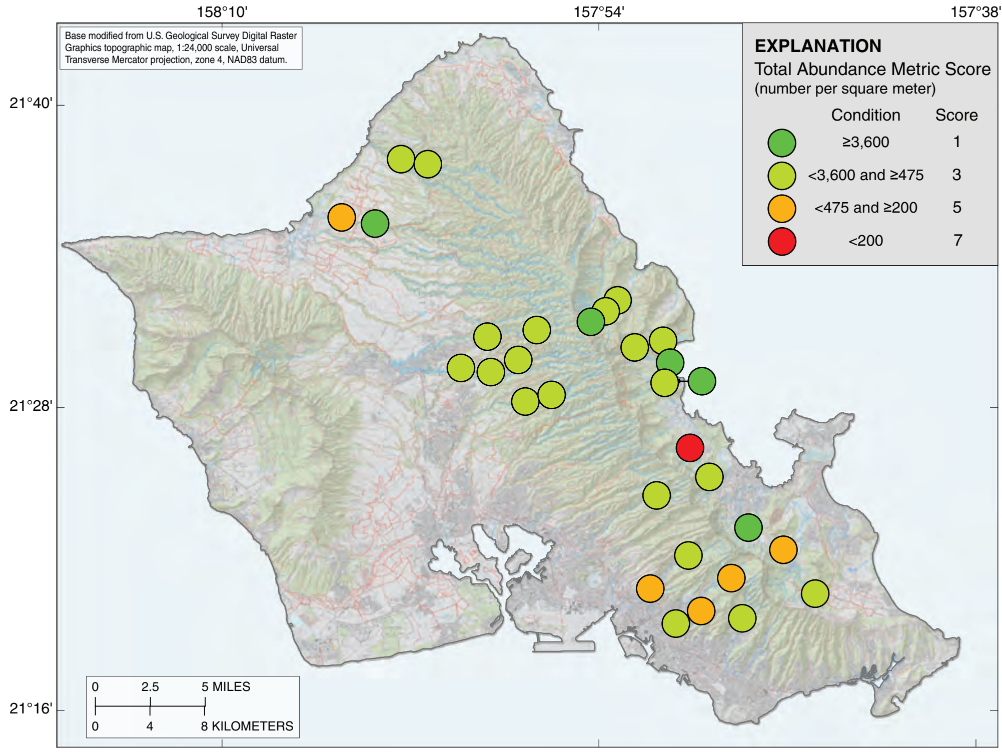


Figure C19. O‘ahu Wadeable Stream Assessment (WSA) Invertebrate Community Index (ICI) revised Total Abundance metric scores.

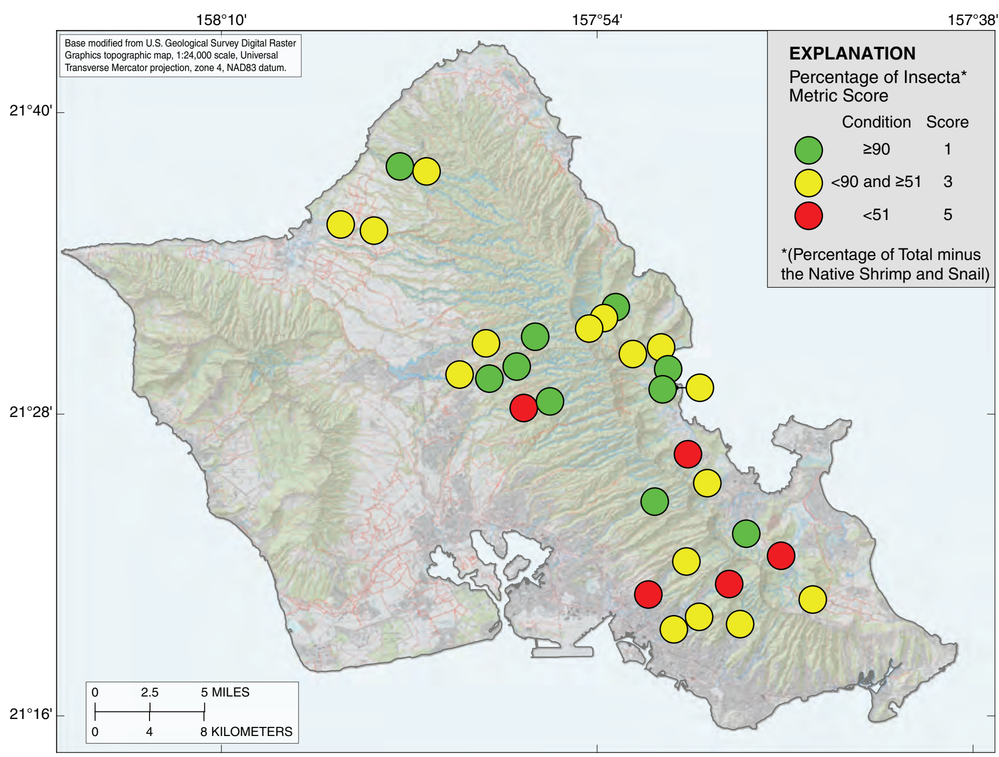


Figure C20. O‘ahu Wadeable Stream Assessment (WSA) Invertebrate Community Index (ICI) revised Percentage of Insecta metric scores.

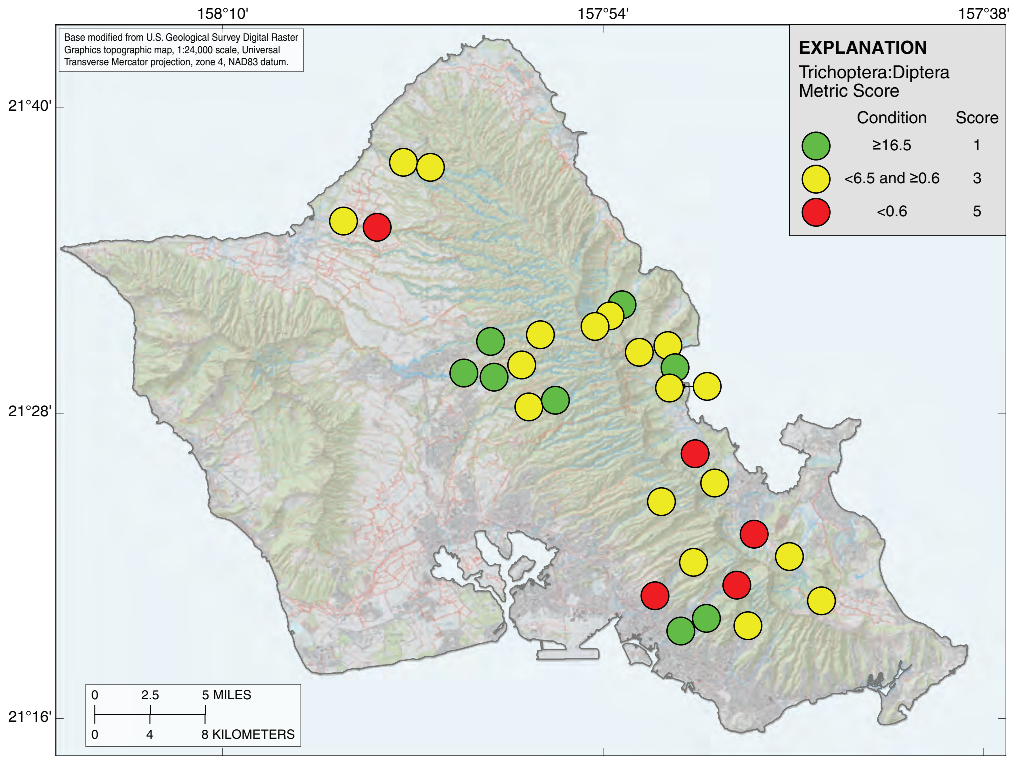


Figure C21. Oʻahu Wadeable Stream Assessment (WSA) Invertebrate Community Index (ICI) Trichoptera:Diptera ratio metric scores.

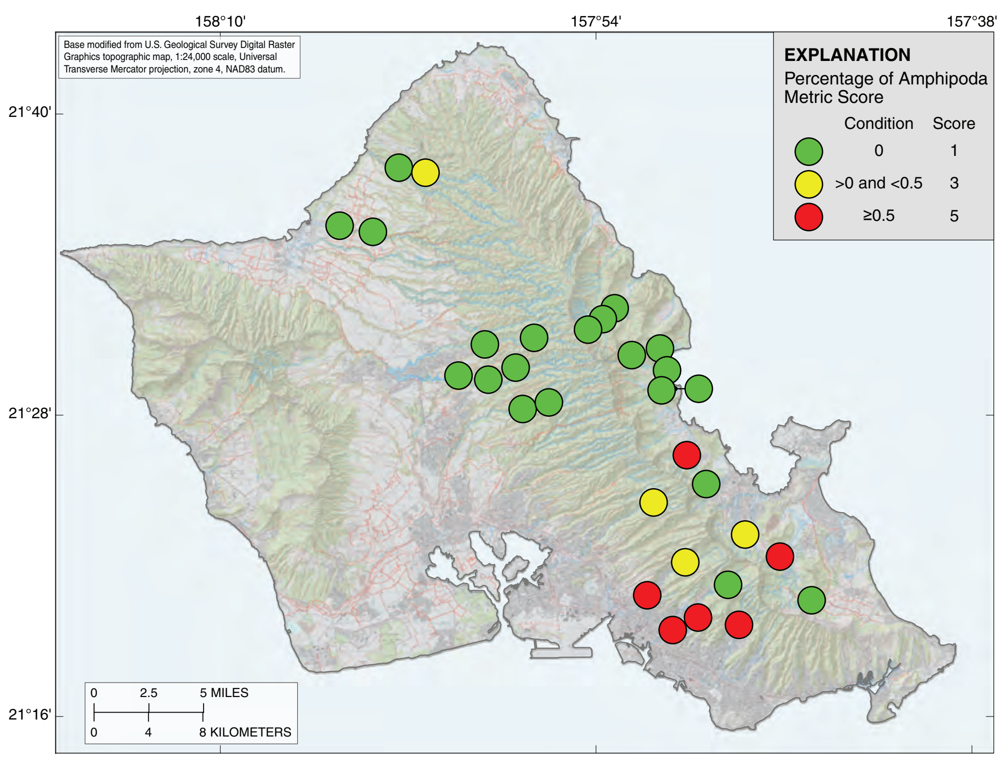


Figure C22. Oʻahu Wadeable Stream Assessment (WSA) Invertebrate Community Index (ICI) revised Percentage of Amphipoda metric scores.

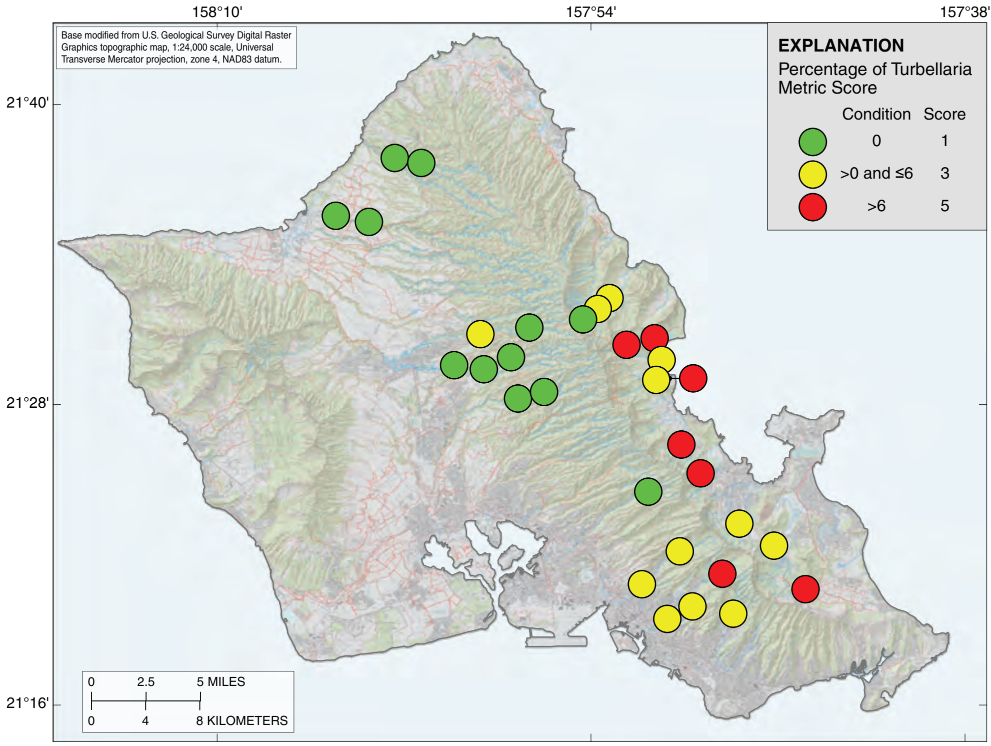


Figure C23. O‘ahu Wadeable Stream Assessment (WSA) Invertebrate Community Index (ICI) Percentage of Turbellaria metric scores.

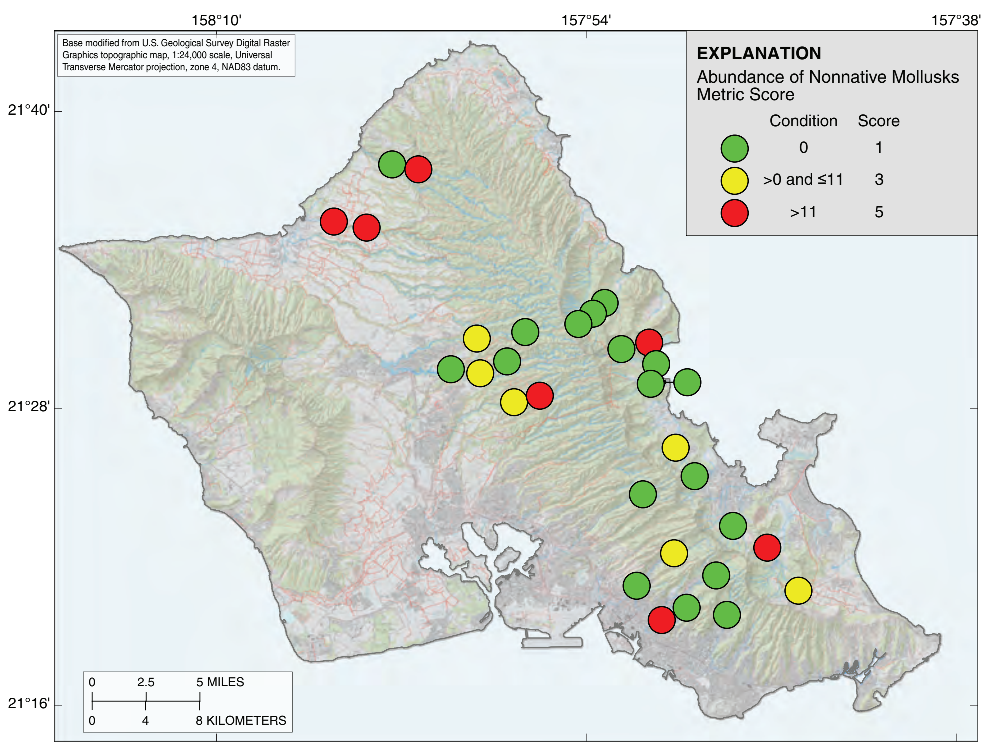


Figure C24. O‘ahu Wadeable Stream Assessment (WSA) Invertebrate Community Index ICI) revised Nonnative Mollusca Abundance metric scores.

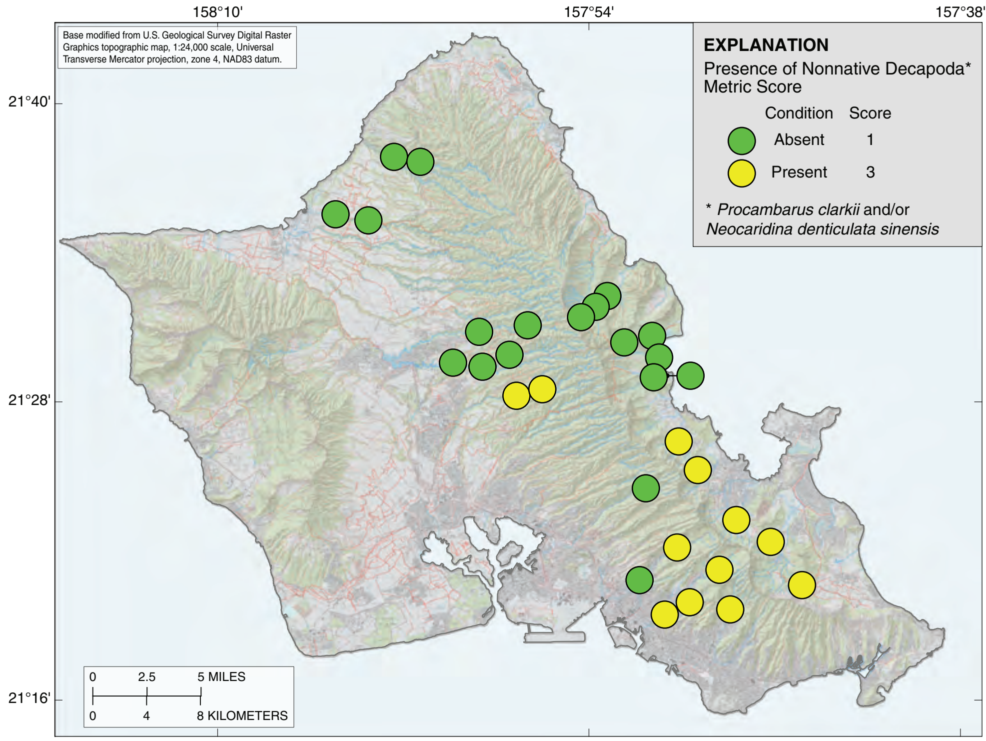


Figure C25. Oʻahu Wadeable Stream Assessment (WSA) Invertebrate Community Index (ICI) revised Nonnative Decapoda Presence/Absence metric scores.

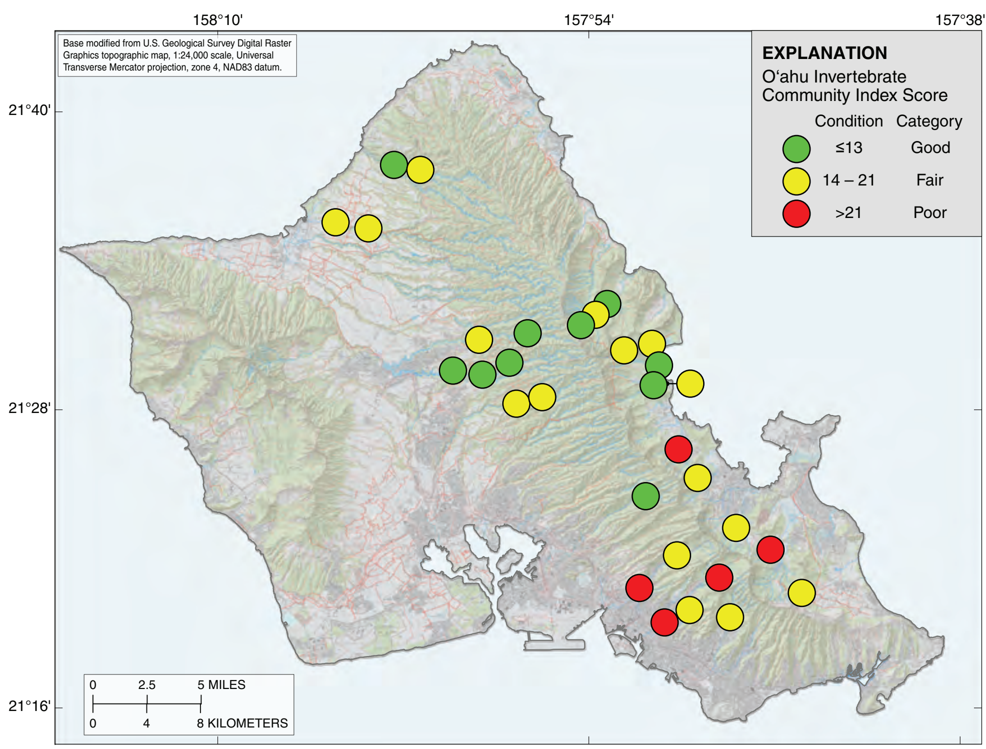


Figure C26. Oʻahu Wadeable Stream Assessment (WSA) final Invertebrate Community Index (ICI) scores.

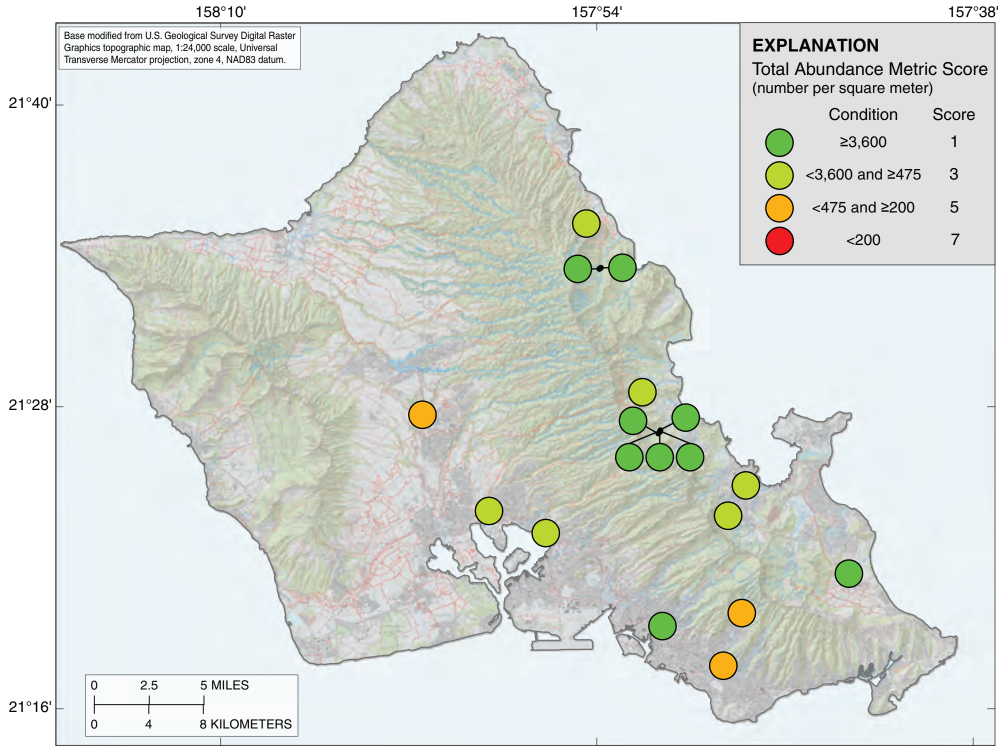


Figure C27. O‘ahu National Water-Quality Assessment (NAWQA) Invertebrate Community Index (ICI) revised Total Abundance metric scores.

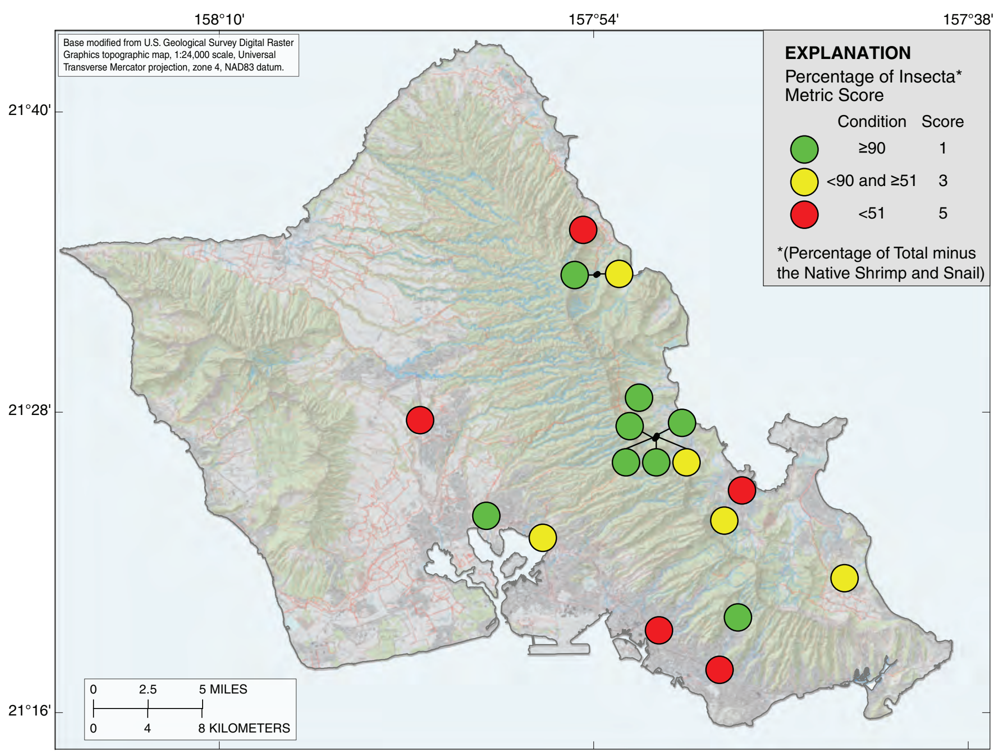


Figure C28. O‘ahu National Water-Quality Assessment (NAWQA) Invertebrate Community Index (ICI) revised Percentage of Insecta metric scores.

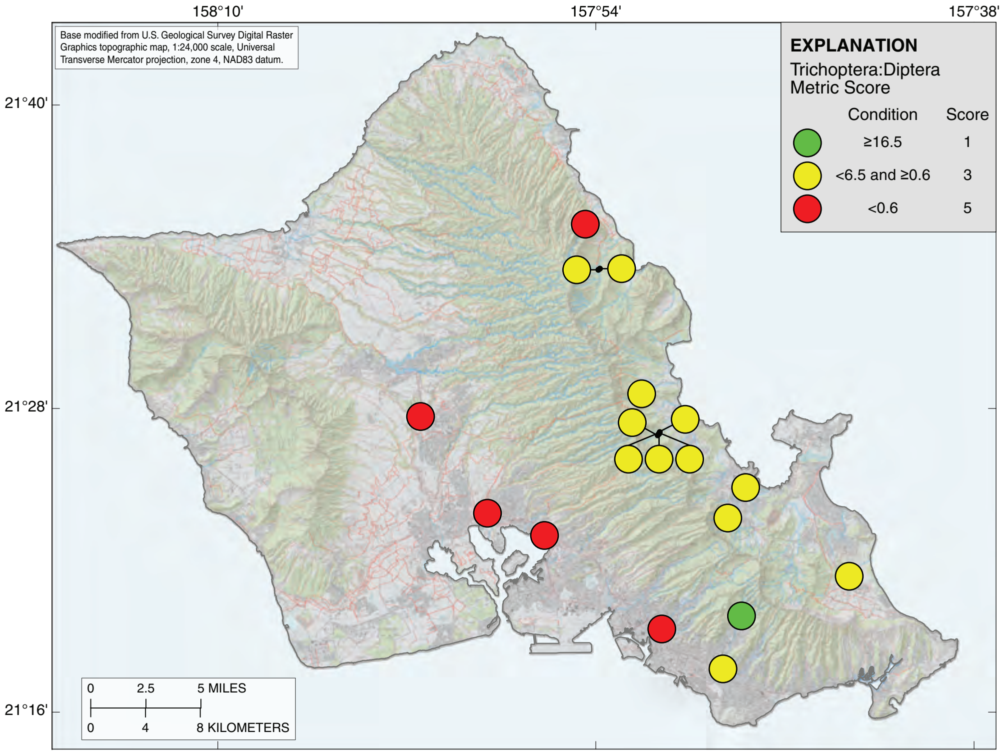


Figure C29. Oʻahu National Water-Quality Assessment (NAWQA) Invertebrate Community Index (ICI) Trichoptera:Diptera ratio metric scores.

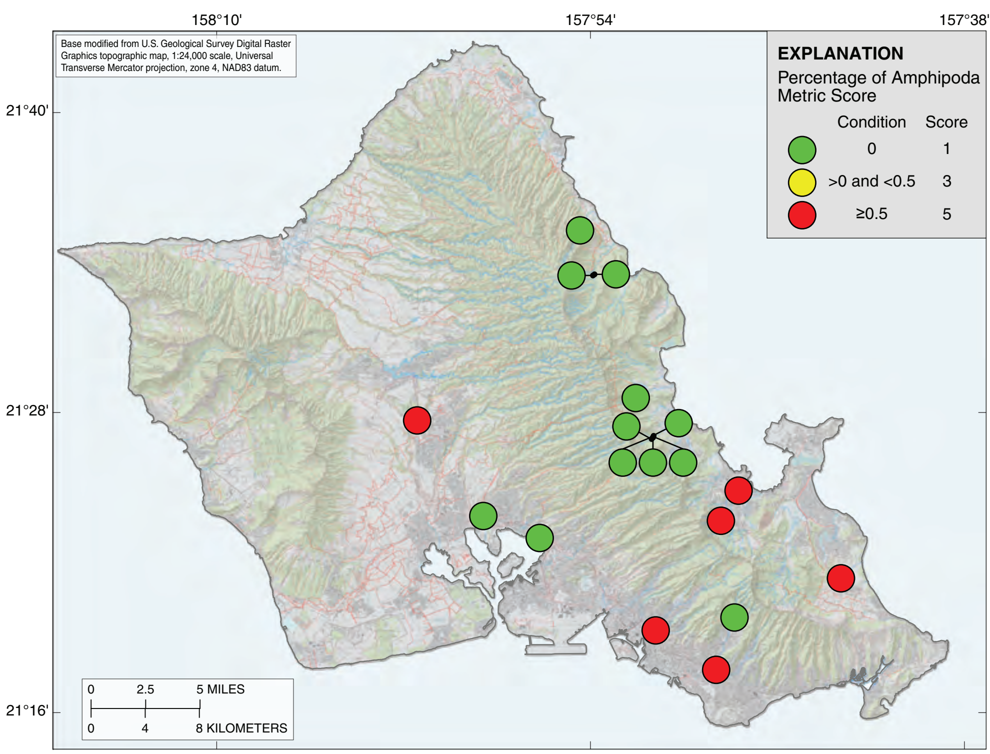


Figure C30. Oʻahu National Water-Quality Assessment (NAWQA) Invertebrate Community Index (ICI) revised Percentage of Amphipoda metric scores.

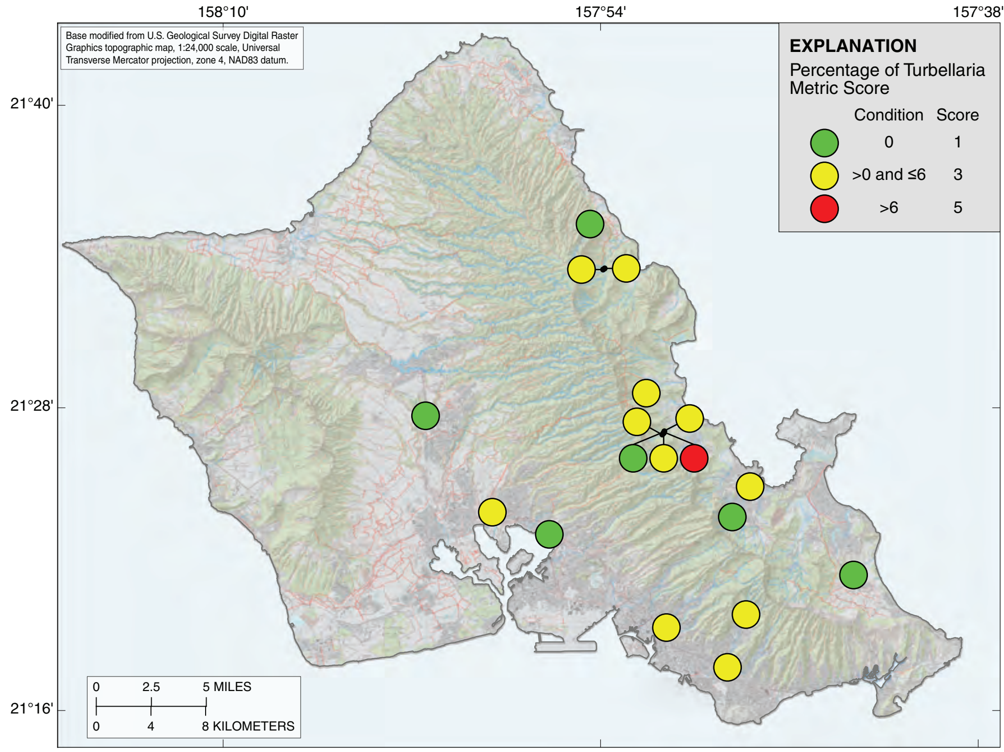


Figure C31. O‘ahu National Water-Quality Assessment (NAWQA) Invertebrate Community Index (ICI) Percentage of Turbellaria metric scores.

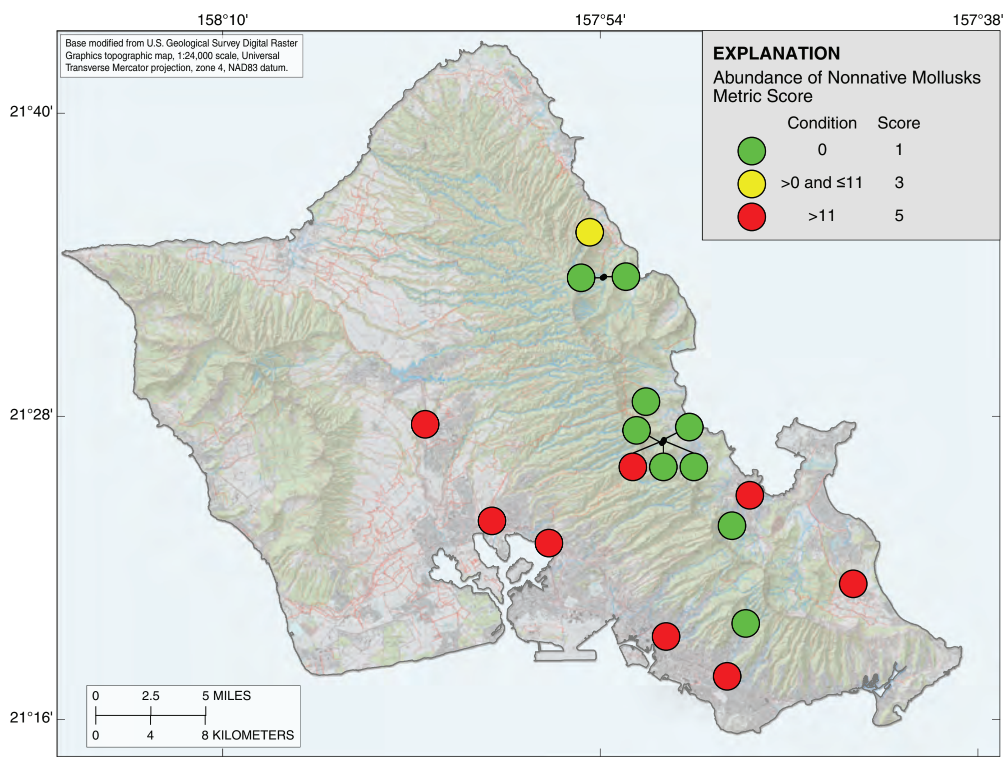


Figure C32. O‘ahu National Water-Quality Assessment (NAWQA) Invertebrate Community Index (ICI) revised Nonnative Mollusca Abundance metric scores.

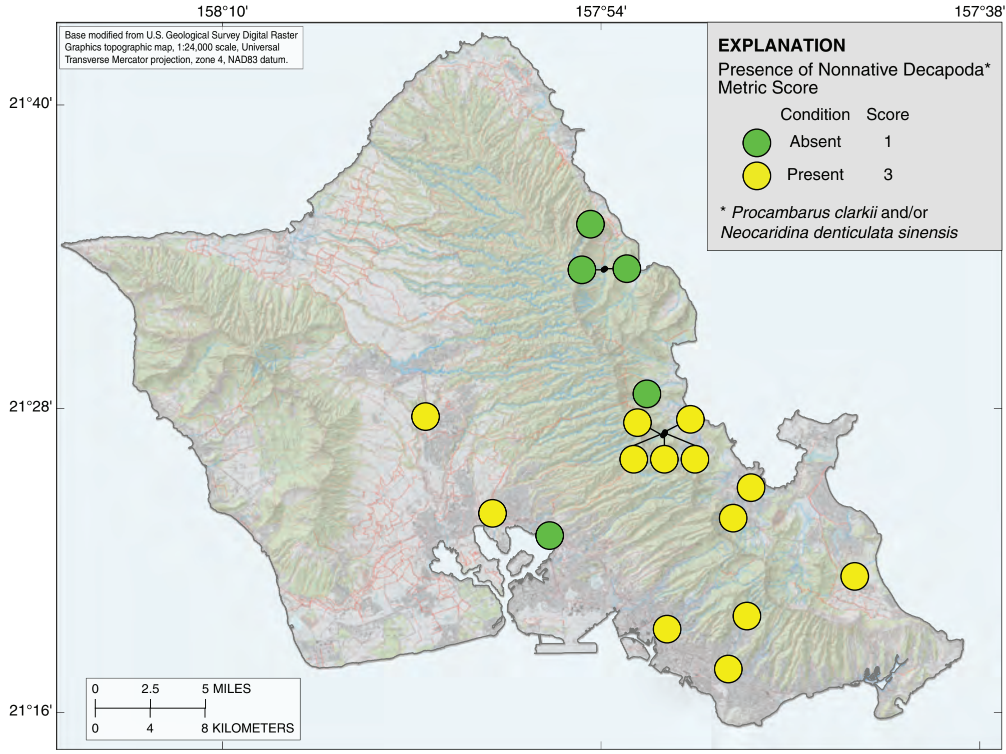


Figure C33. O‘ahu National Water-Quality Assessment (NAWQA) Invertebrate Community Index (ICI) revised Nonnative Decapoda metric scores.

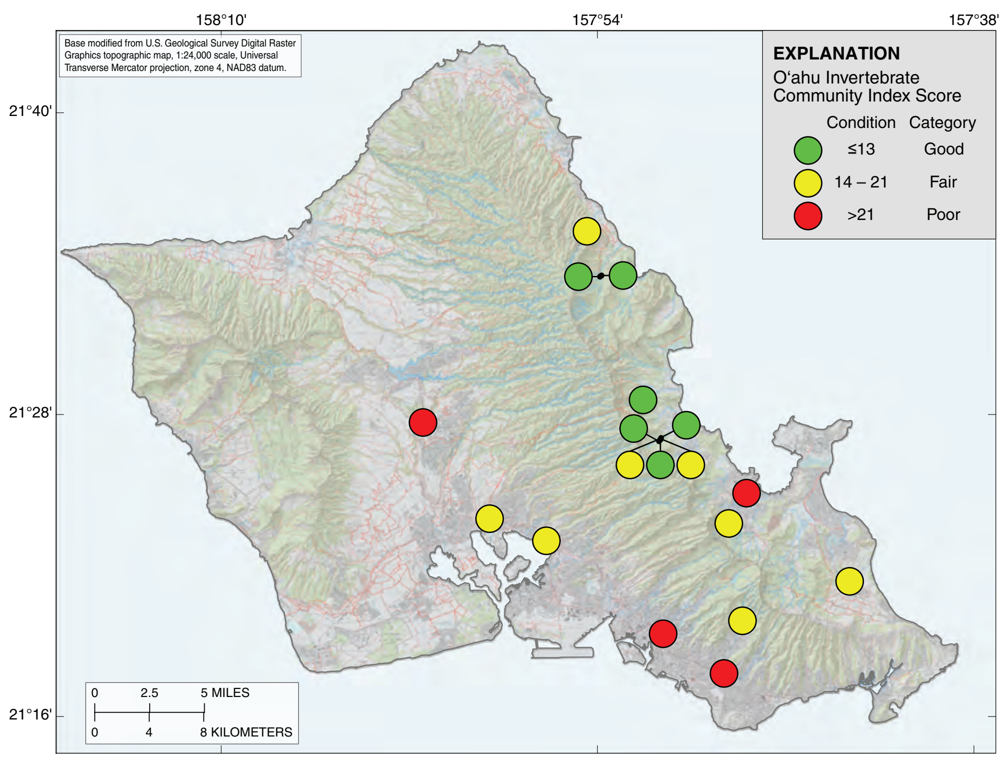


Figure C34. O‘ahu National Water-Quality Assessment (NAWQA) final Invertebrate Community Index (ICI) scores.

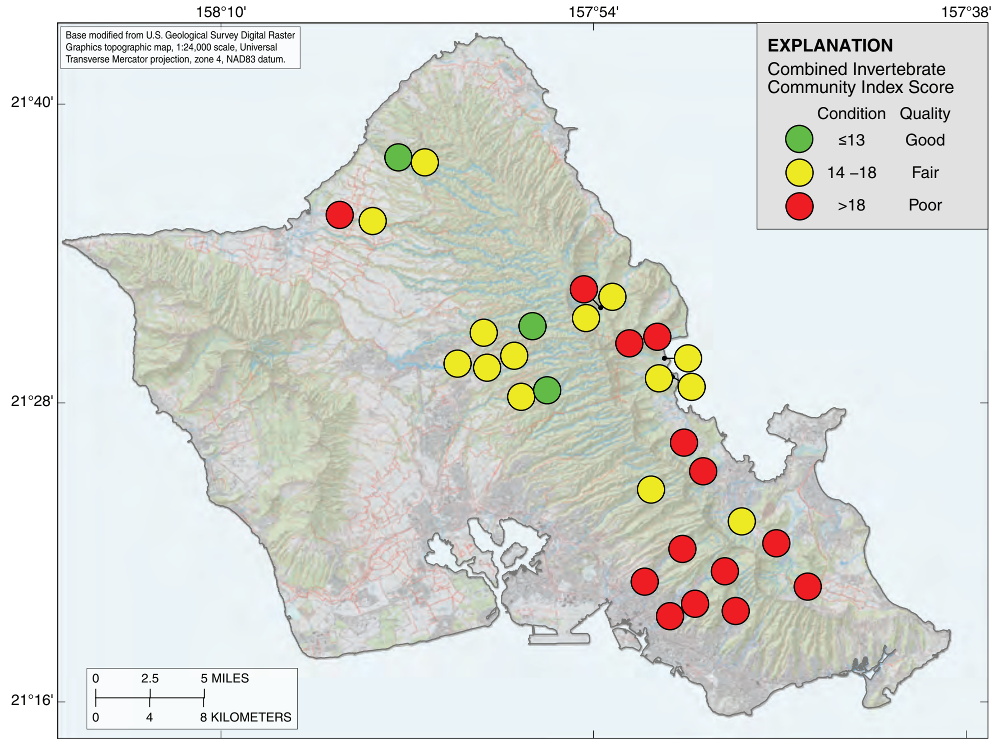


Figure C35. O‘ahu Wadeable Stream Assessment (WSA) combined final Invertebrate Community Index (ICI) scores.

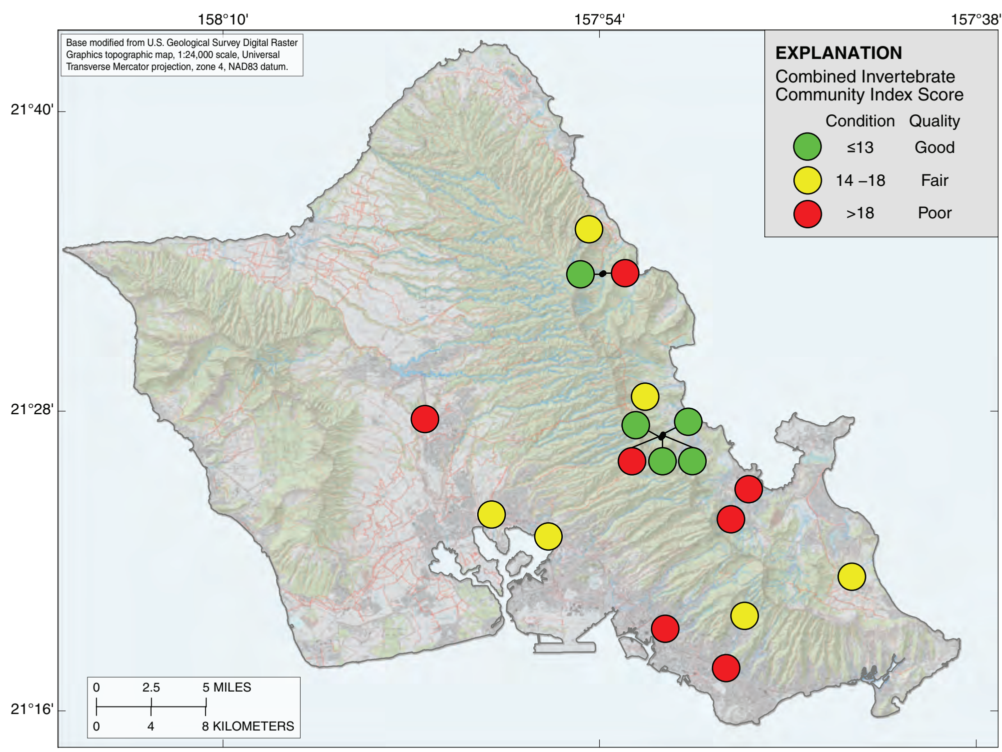


Figure C36. O‘ahu National Water-Quality Assessment (NAWQA) combined final Invertebrate Community Index (ICI) scores.

Appendix D. Photographs of Stream Fauna

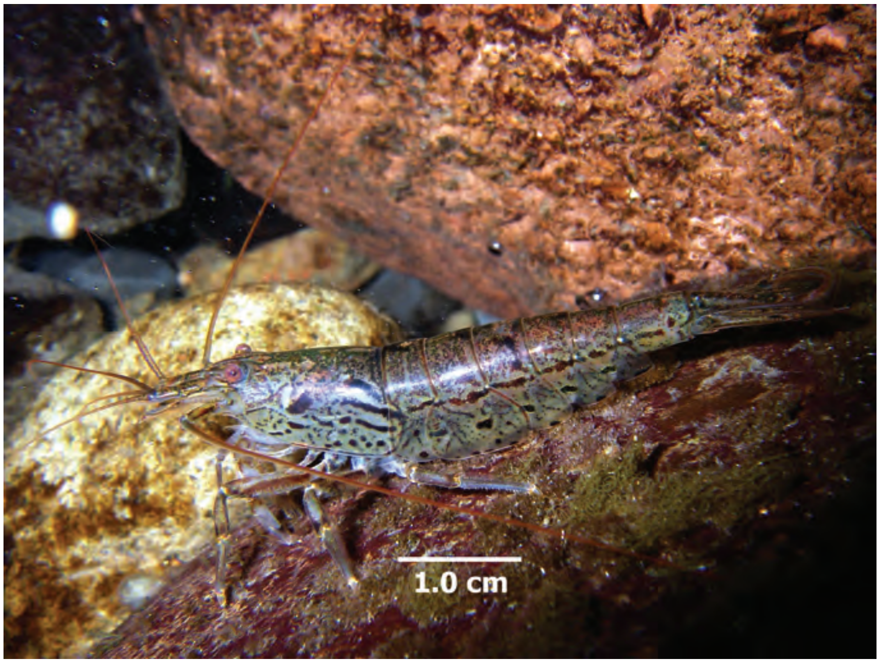


Figure D1. *Atyoida bisulcata* (ʻōpaekalaʻole) adult.

Figure D2. *Atyoida bisulcata* (ʻōpaekalaʻole) recruits.

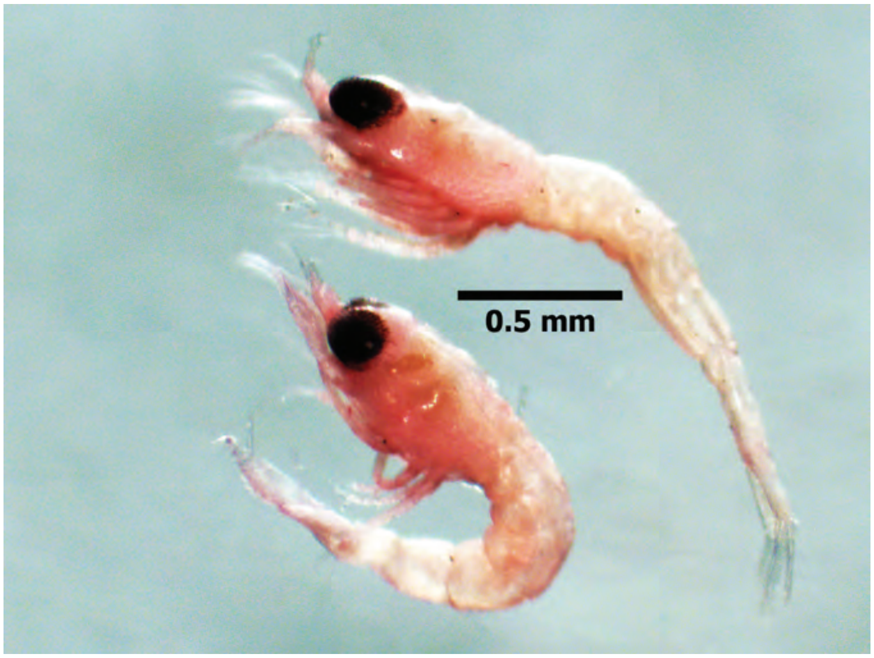


Figure D3. *Atyoida bisulcata* (ʻōpaekalaʻole) larvae. Specimens preserved in 70-percent methanol.

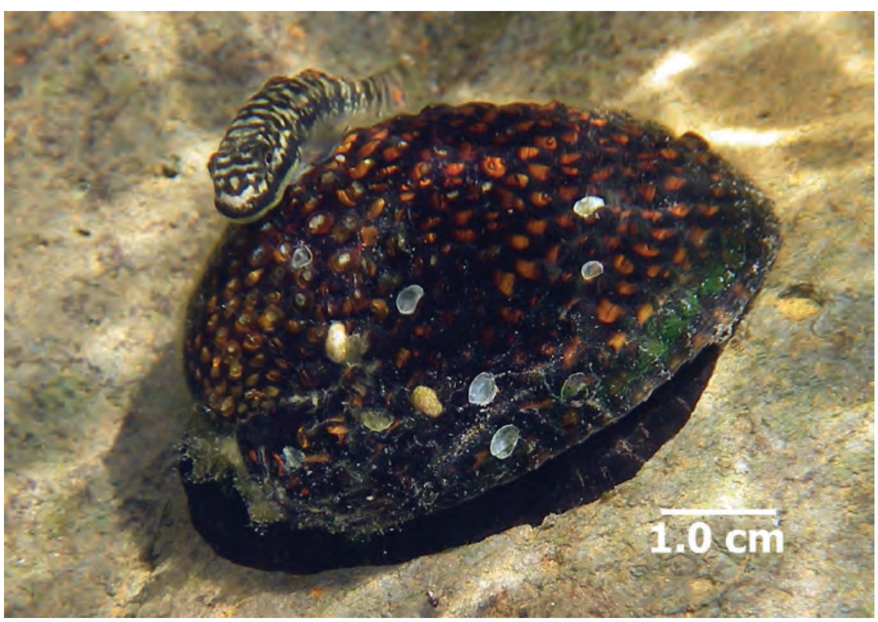


Figure D4. *Neritina granosa* (hīhīwai); *Sicyopterus stimpsoni* (ʻoʻopu nōpili).

Figure D5. *Telmatogeton* sp. larvae. Specimens preserved in 70-percent methanol.

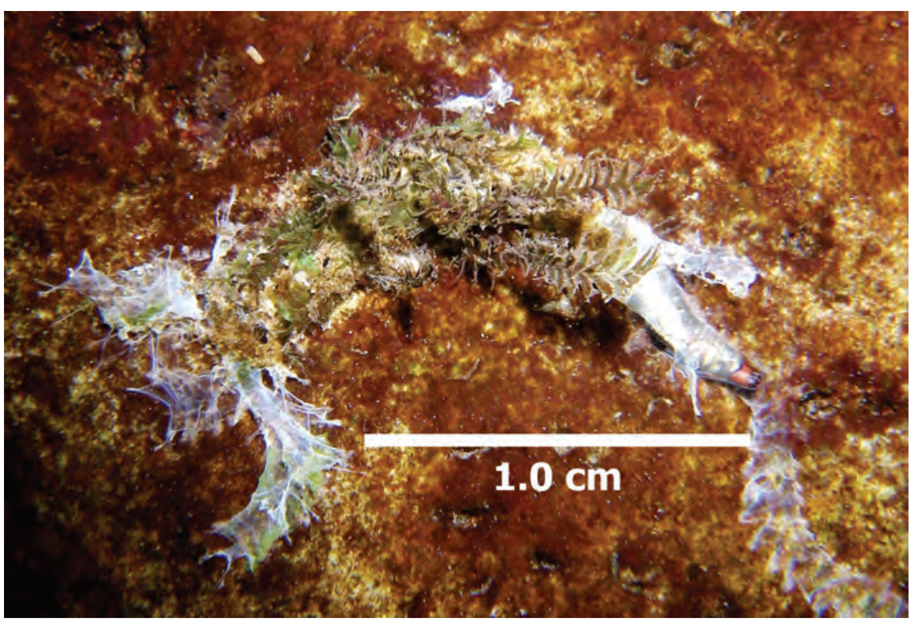


Figure D6. *Telmatogeton* sp. larva in case.

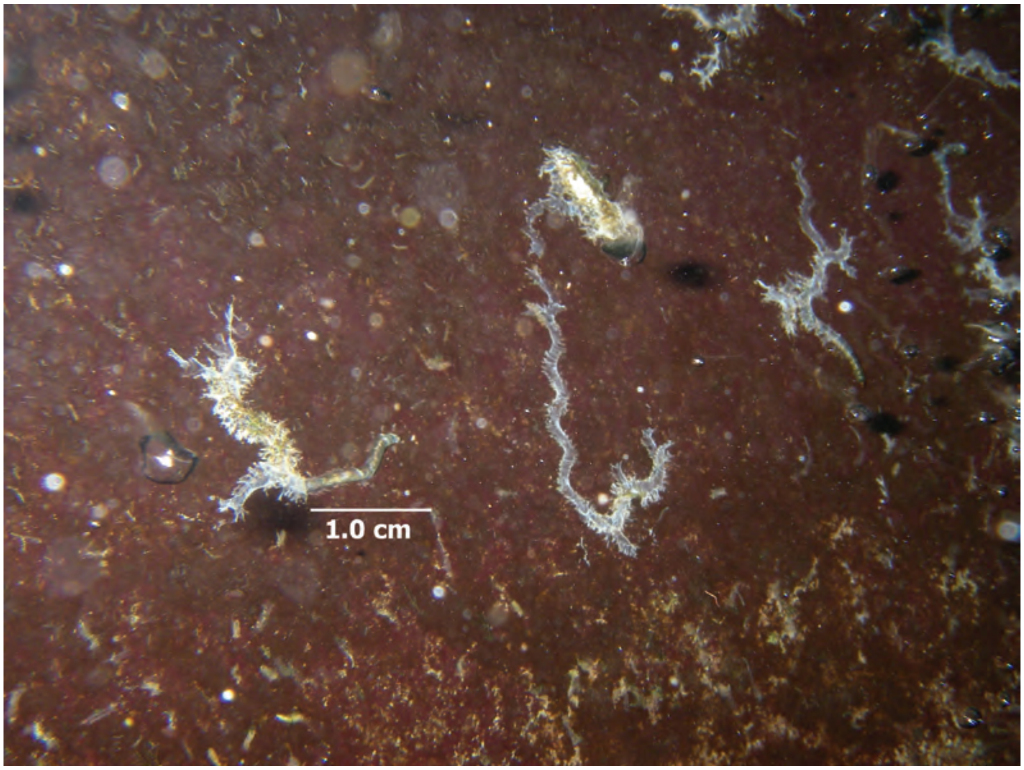


Figure D7. *Telmatogeton* sp. larvae in cases.

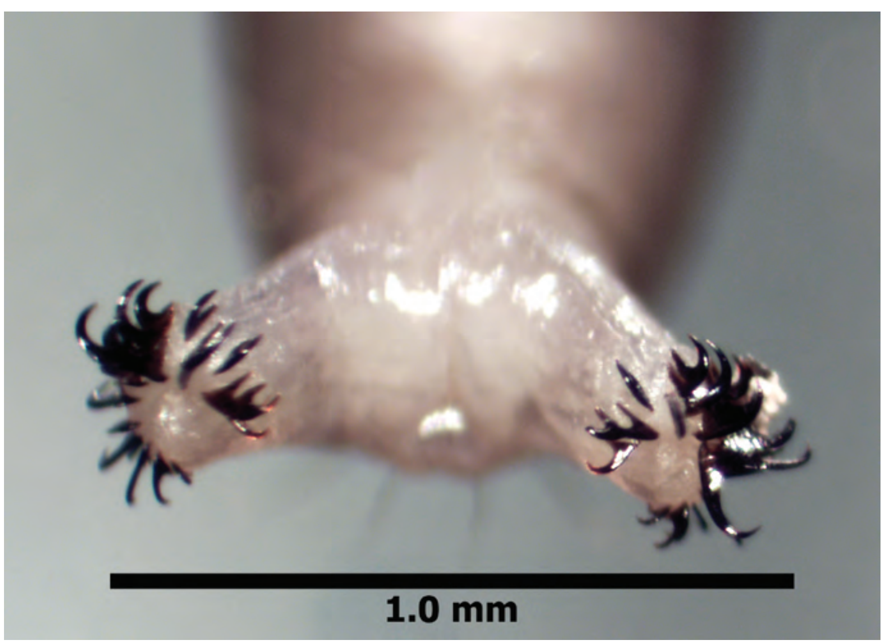


Figure D8. *Telmatogeton* sp. larva, posterior. Specimen preserved in 70-percent methanol.

Figure D9. *Telmatogeton* habitat 1.

Figure D10. *Telmatogeton* habitat 2.

Figure D11. *Megalagrion nigrohamatum nigrolineatum* (Blackline Hawaiian damselfly) adult.

Figure D12. *Megalagrion blackburni* (Blackburn’s Hawaiian damselfly) adult.

Figure D13. *Megalagrion nigrohamatum nigrohamatum* (Blackhook Hawaiian damselfly) adult.

Figure D14. *Megalagrion* sp. naiad. Specimen preserved in 70-percent methanol.

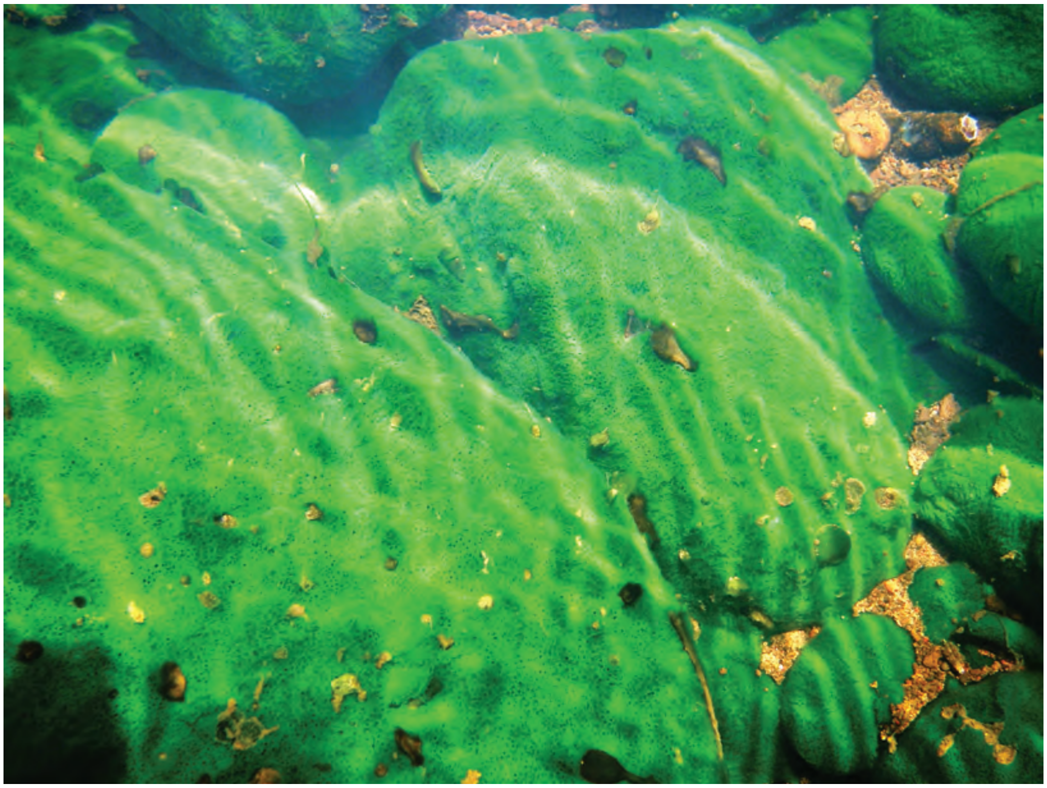


Figure D15. *Heteromeyenia baileyi* (native freshwater sponge).

Figure D16. Trichoptera larvae: (A) *Cheumatopsyche analis*; (B) *C. analis*; (C) *Hydroptila icona*; (D) *Hydroptila potosina*; (E) *Oxyethira maya*. Specimens preserved in 70-percent methanol. Scale in millimeters.

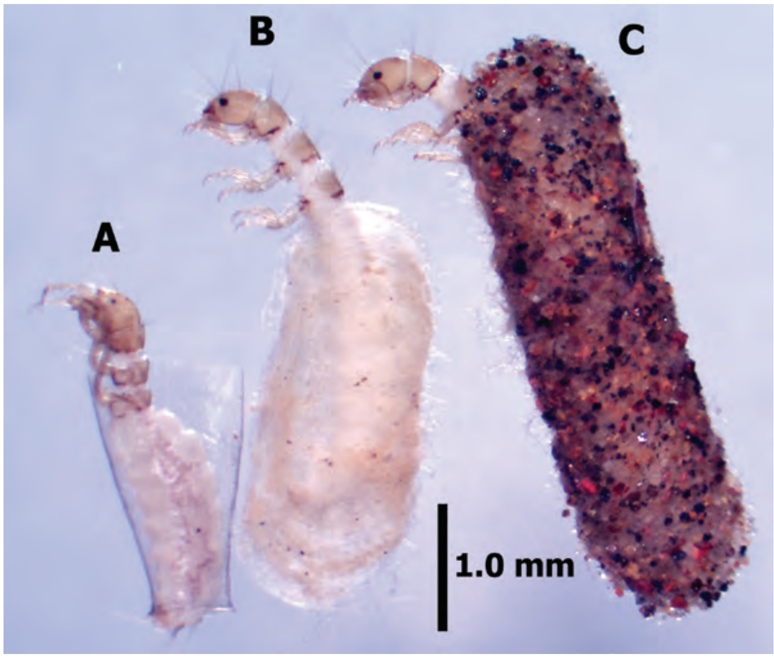


Figure D17. Hydroptilidae larvae: (A) *Oxyethira maya*; (B) *Hydroptila icona*; (C) *Hydroptila potosina*. Specimens preserved in 70-percent methanol.

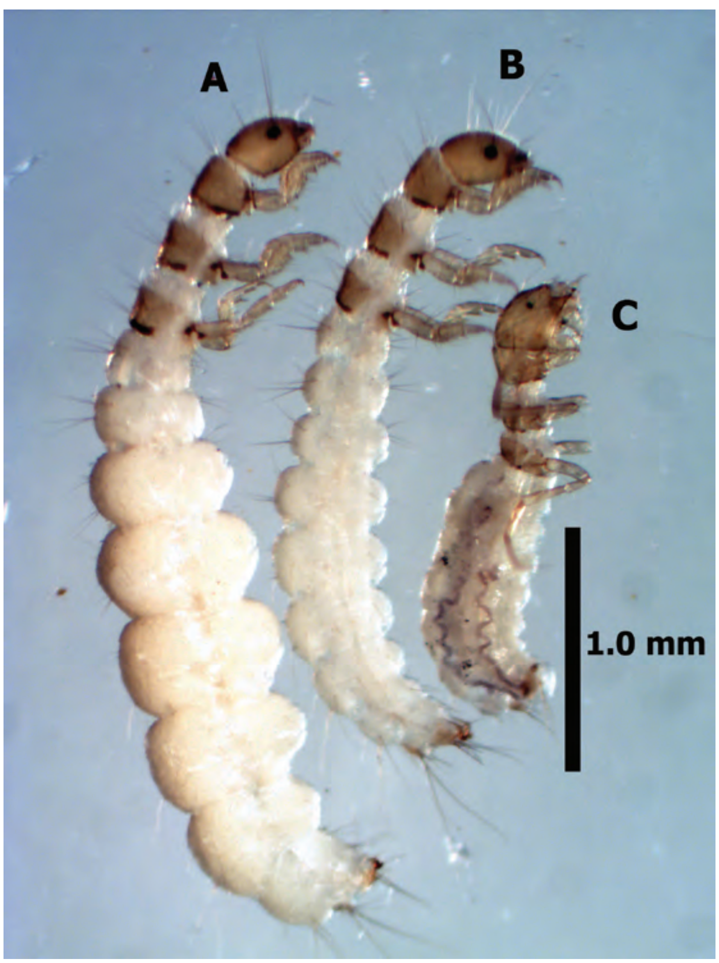


Figure D18. Hydroptilidae larvae: (A) *Hydroptila potosina*; (B) *Hydroptila icona*; (C) *Oxyethira maya*. Specimens preserved in 70-percent methanol.

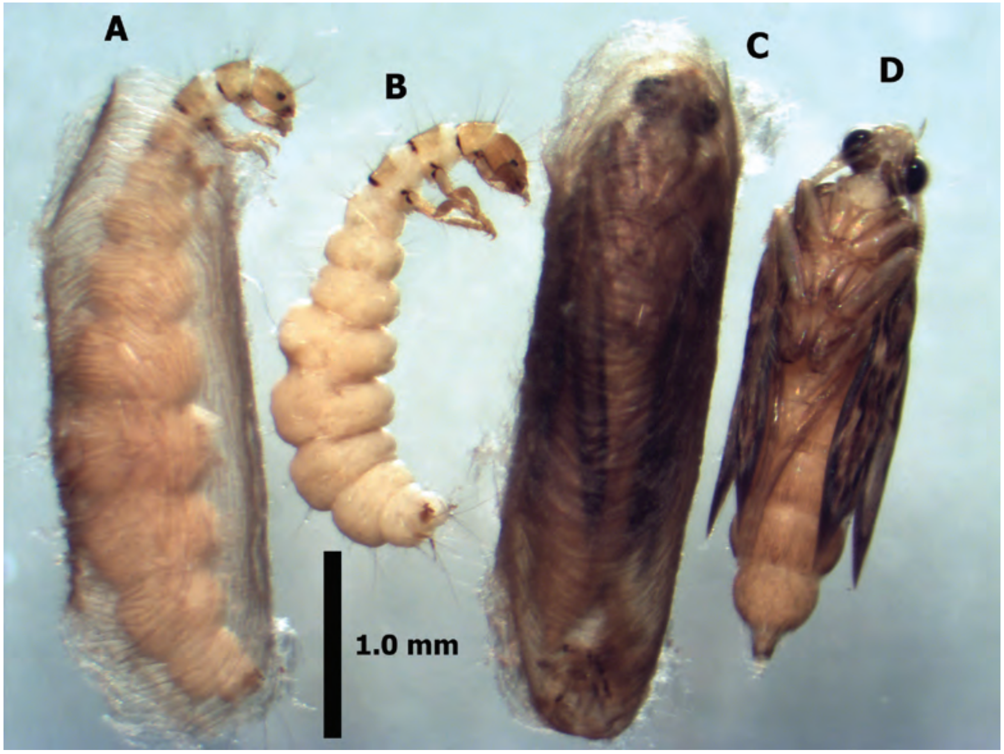


Figure D19. *Hydroptila icona*: (A) larva in case; (B) larva; (C) pupa in cocoon; (D) pupa. Specimens preserved in 70-percent methanol.

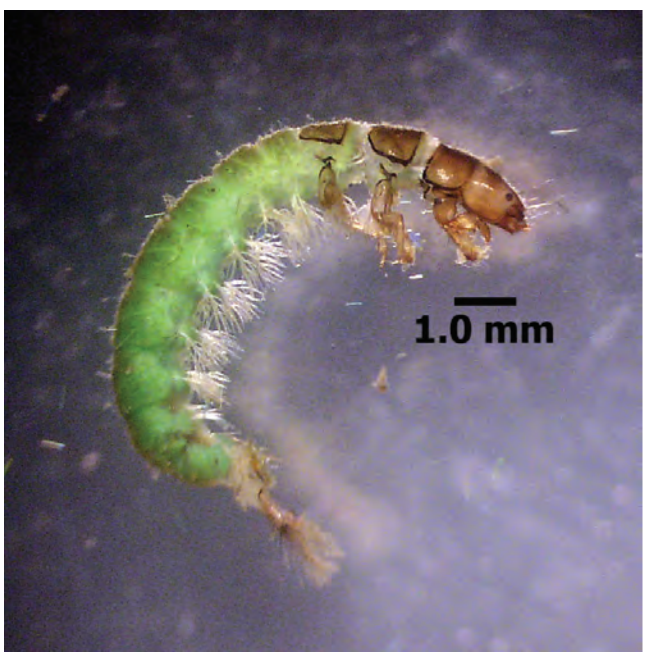


Figure D20. *Cheumatopsyche analis* larva. Specimens preserved in 70-percent methanol.

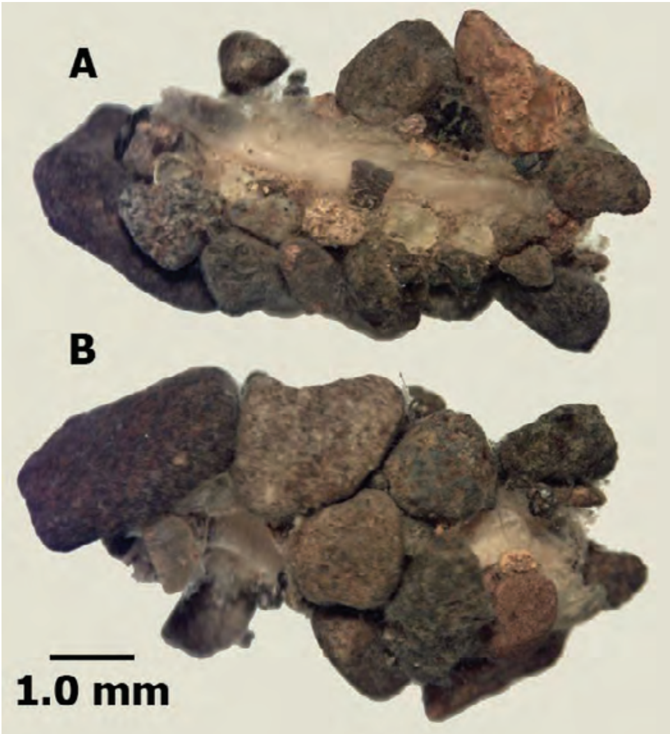


Figure D21. *Cheumatopsyche analis* case: (A) ventral view; (B) dorsal view. Specimens preserved in 70-percent methanol.

Figure D22. *Cheumatopsyche analis* larva.

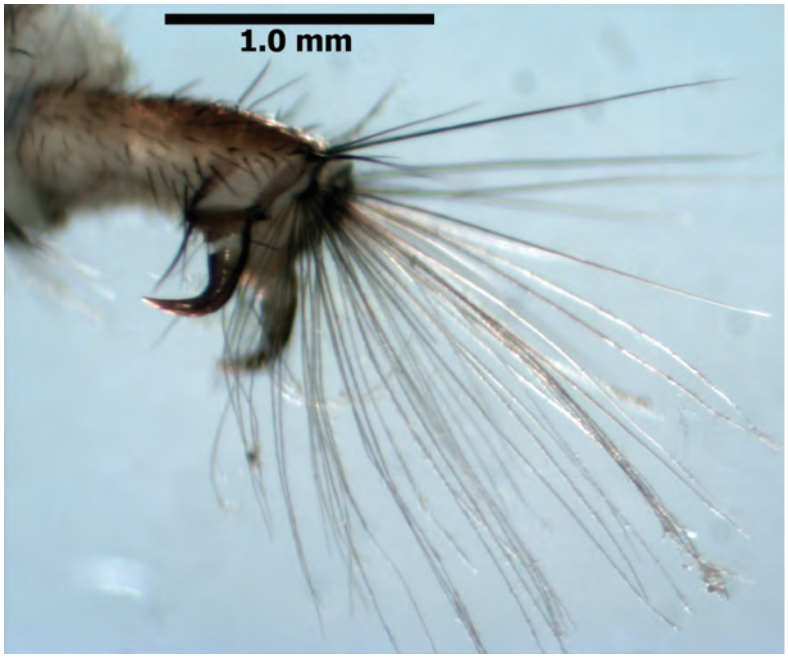


Figure D23. *Cheumatopsyche analis* larva, posterior. Specimens preserved in 70-percent methanol.

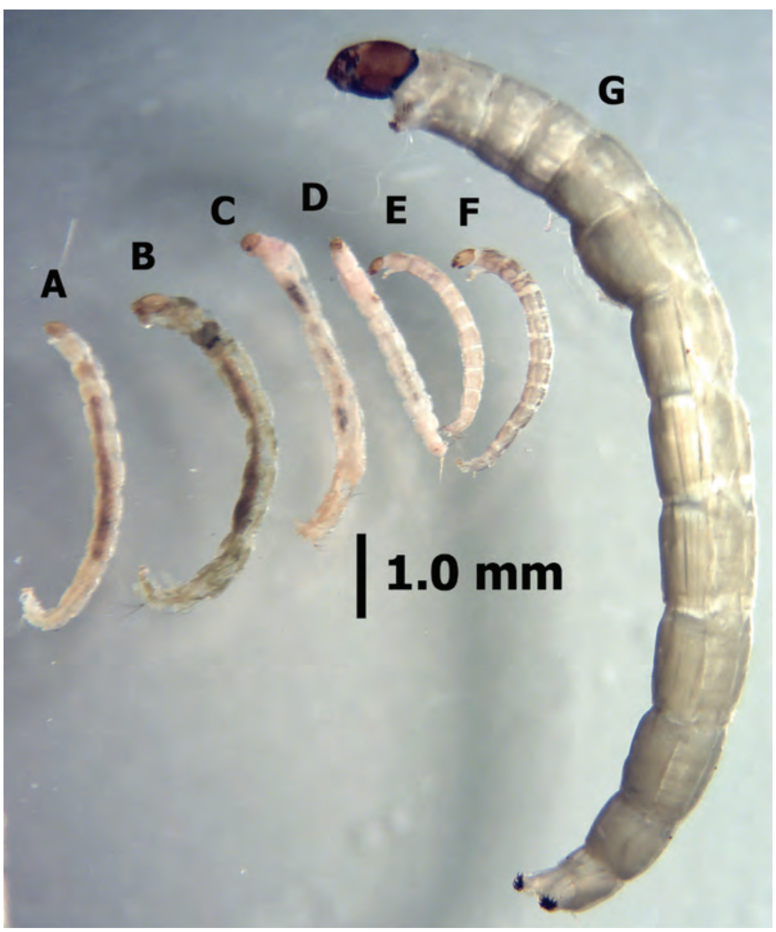


Figure D24. Assorted Chironomidae larvae: (A) *Polypedilum* sp.; (B) *Goeldichironomus* sp.; (C) *Tanytarsus* sp.; (D) *Apedilum* sp.; (E) *Eukiefferiella* sp.; (F) *Cricotopus* sp.; (G) *Telmatogeton* sp. Specimens preserved in 70-percent methanol.

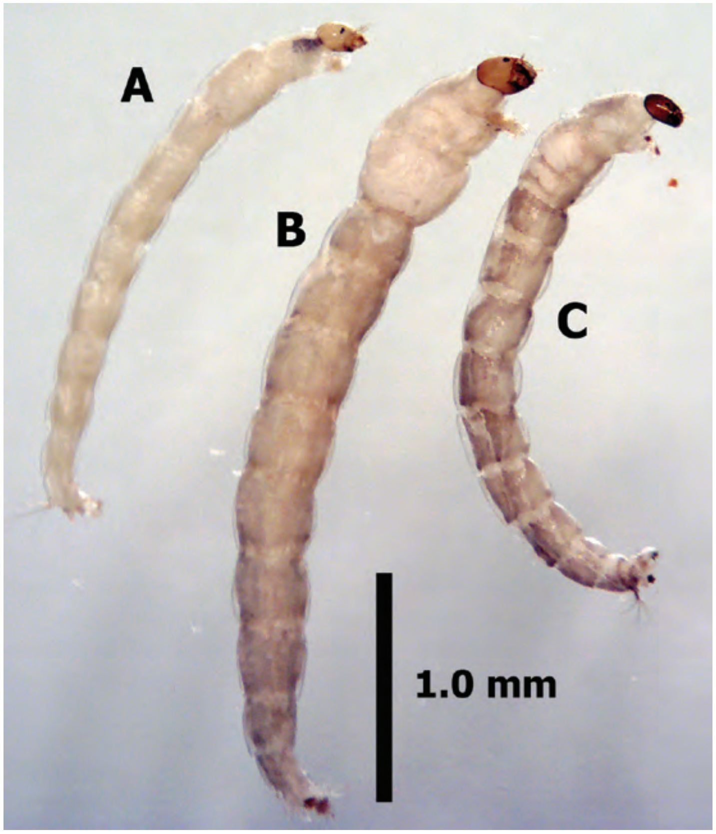


Figure D25. Assorted Chironomidae larvae: (A) *Apedilum* sp., (B) *Cricotopus* sp., (C) *Eukiefferiella* sp. Specimens preserved in 70-percent methanol.

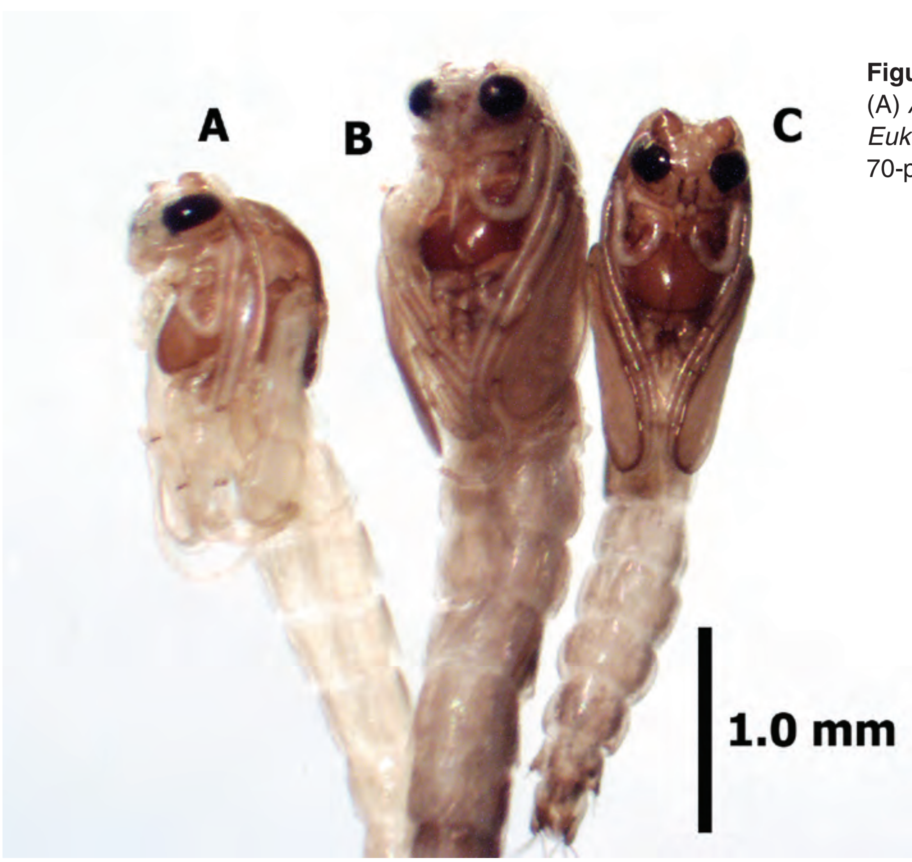


Figure D26. Assorted Chironomidae pupae: (A) *Apedilum* sp., (B) *Cricotopus* sp., (C) *Eukiefferiella* sp. Specimens preserved in 70-percent methanol.

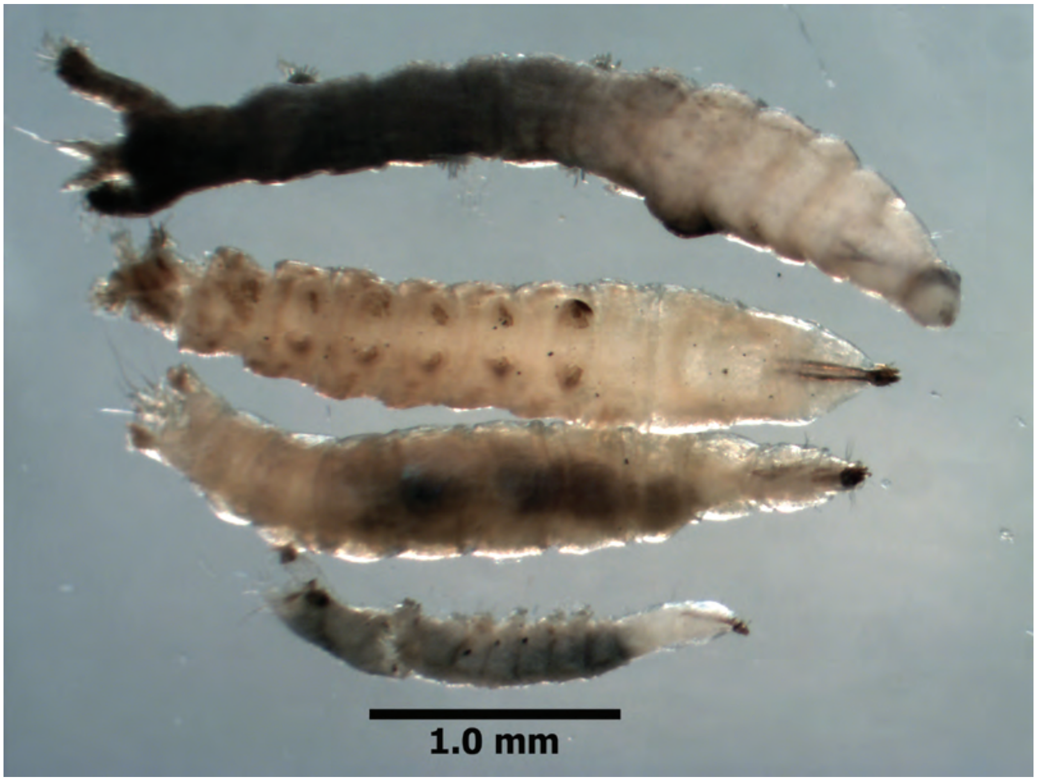


Figure D27. *Hemerodromia stellaris* larval stages. Specimens preserved in 70-percent methanol.

Figure D28. *Hemerodromia stellaris* pupal stages. Specimens preserved in 70-percent methanol.

Figure D29. *Macrobrachium lar* (Tahitian prawn) adult.

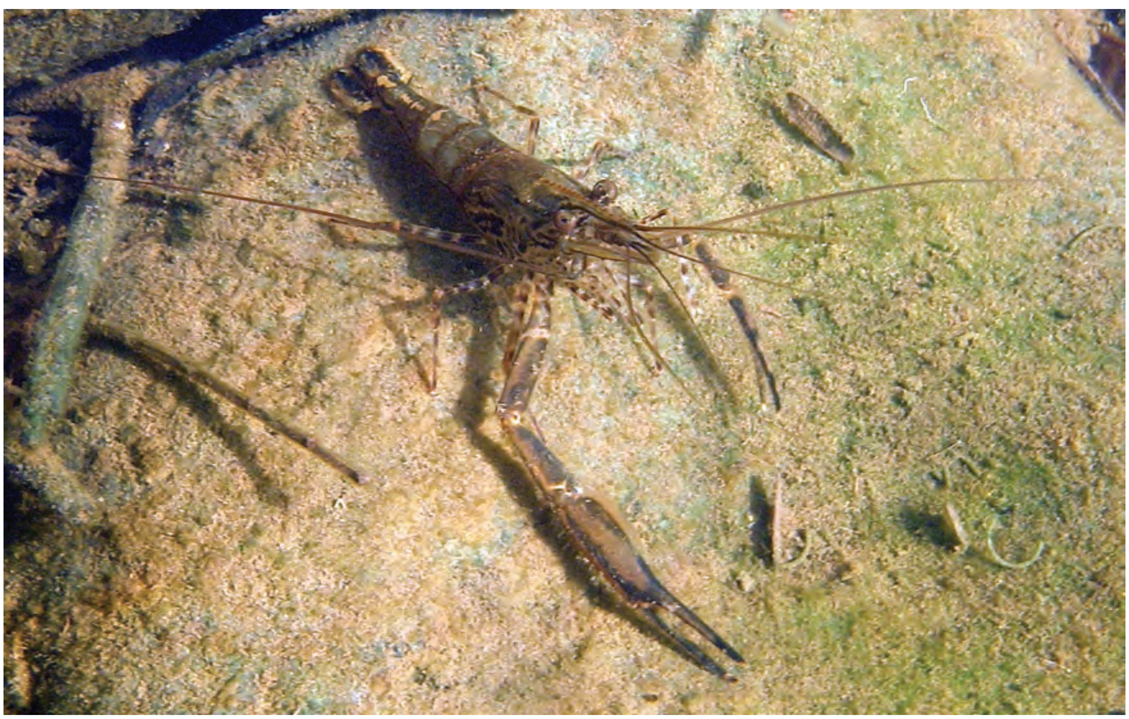


Figure D30. *Macrobrachium grandimanus* (‘ōpae ‘oeha‘a) adult.

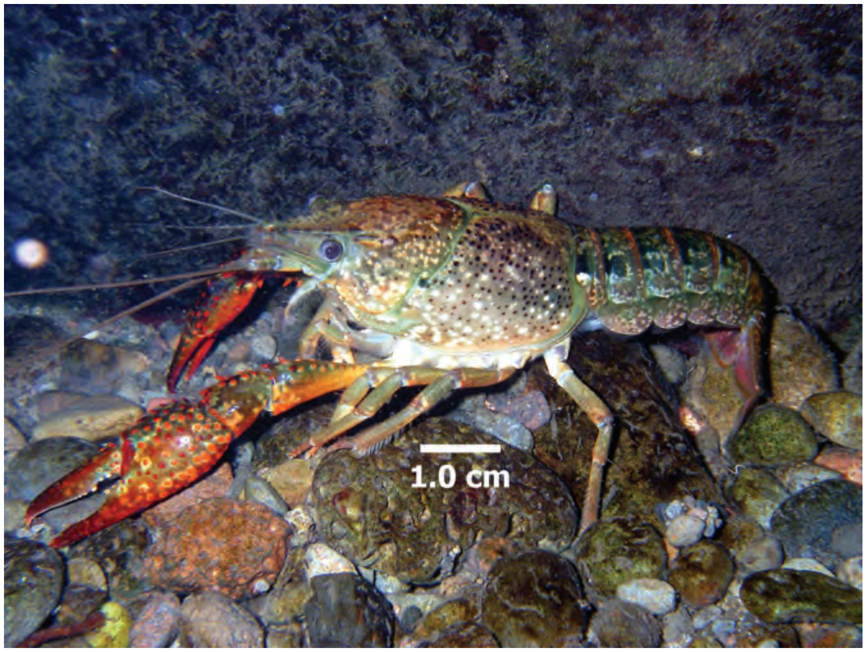


Figure D31. *Procambarus clarkii* (Louisiana swamp crayfish) adult.

Figure D32. *Neocaridina denticulata sinensis* (Taiwan blue shrimp) adult. Specimen preserved in 70-percent methanol.

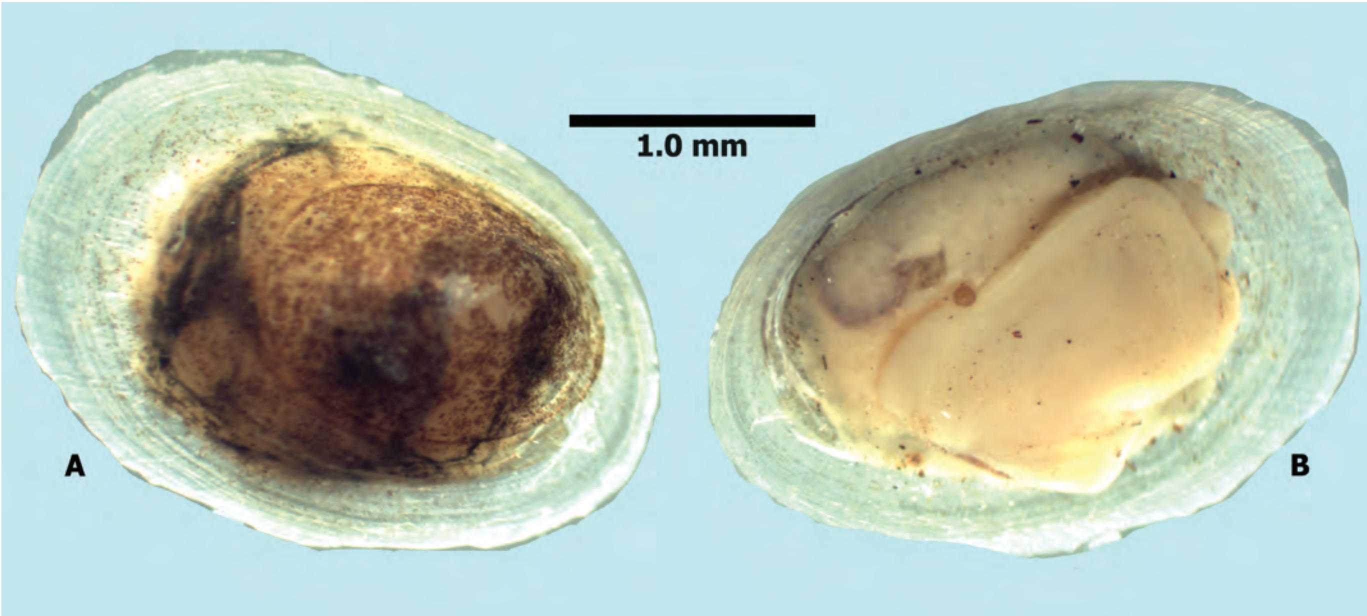


Figure D33. *Ferrissia sharpi*: (A) dorsal view; (B) ventral view. Specimen preserved in 70-percent methanol.

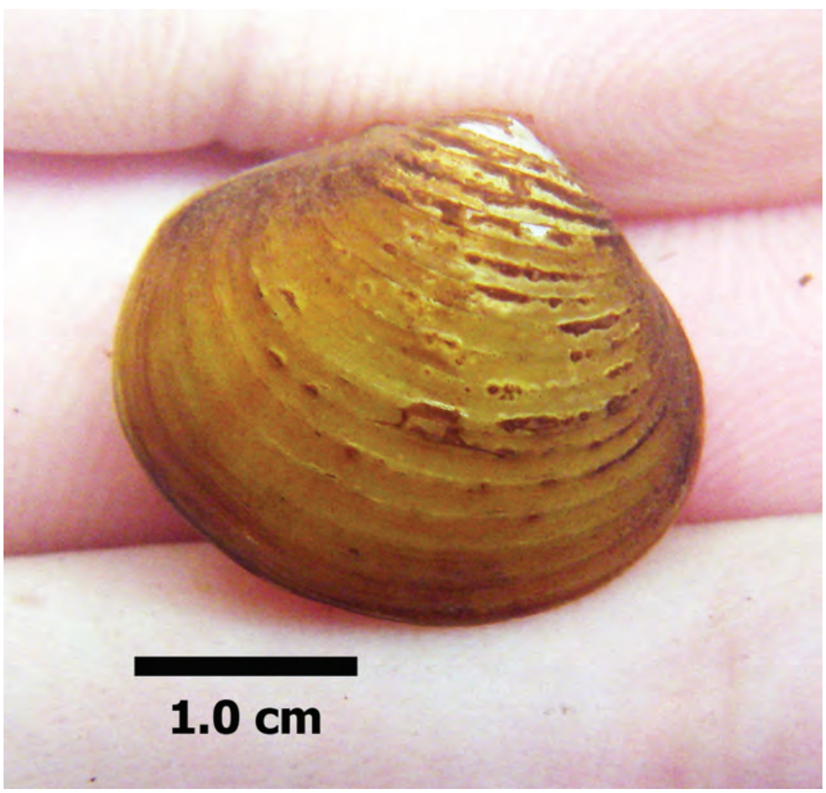


Figure D34. *Corbicula fluminea* (Asian clam).

Figure D35. Oligochaeta (worms). Specimens preserved in 70-percent methanol.

Figure D36. Oligochaeta (worms). Specimens preserved in 70-percent methanol.

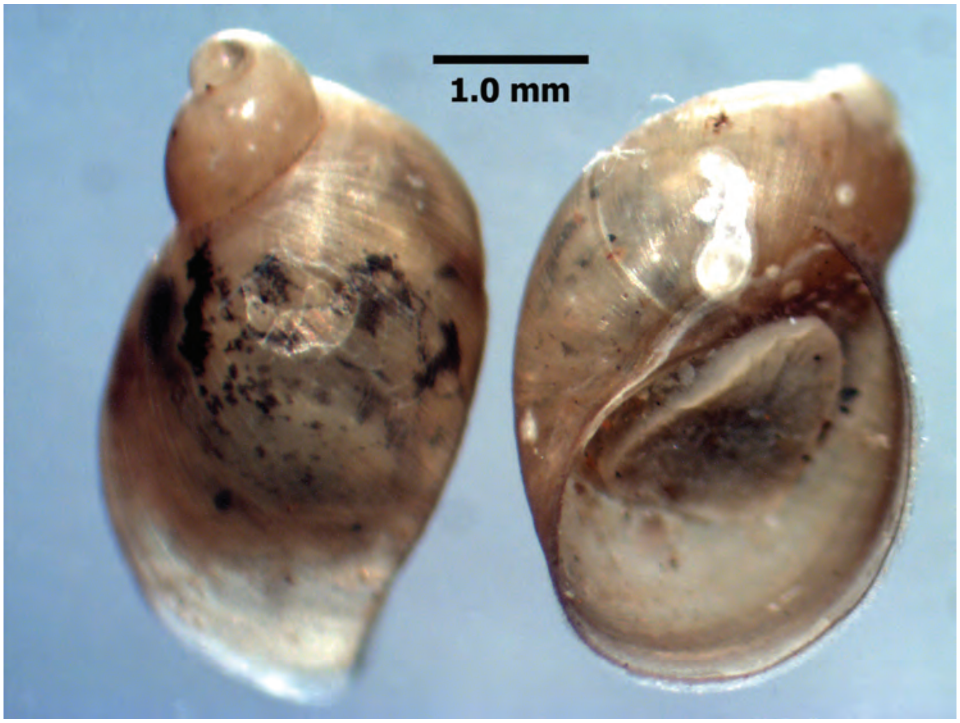


Figure D37. *Pseudosuccinea columella* (nonnative Lymnaeidae). Specimen preserved in 70-percent methanol.

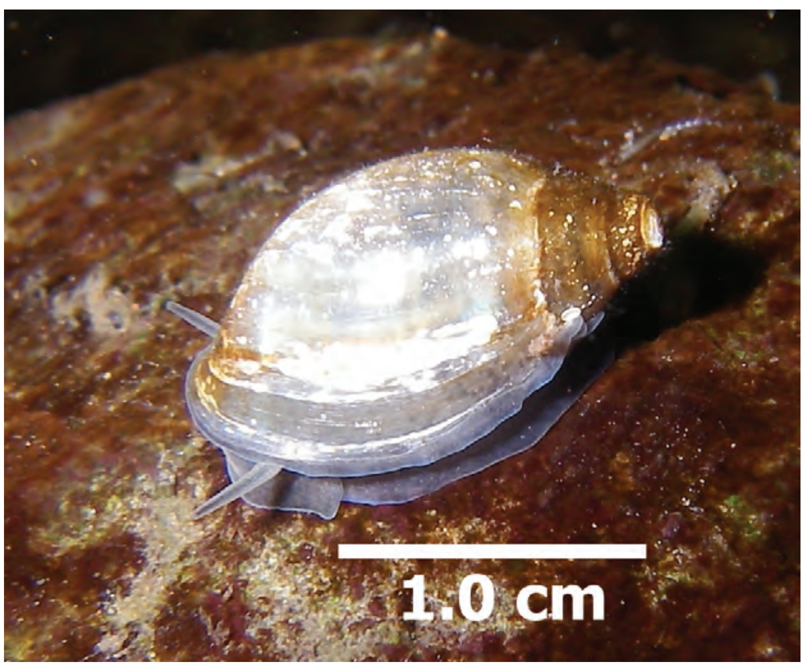


Figure D38. Physidae snail.

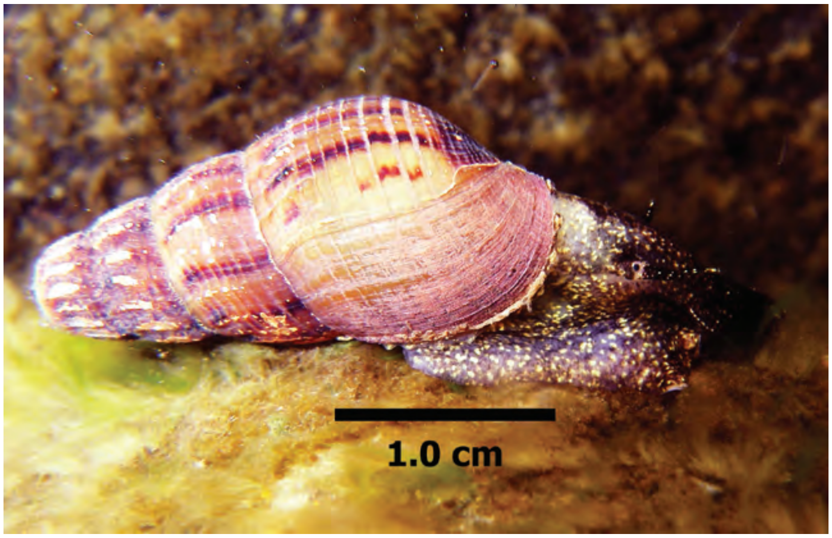


Figure D39. *Melanoides tuberculata* (Red-rimmed melania).

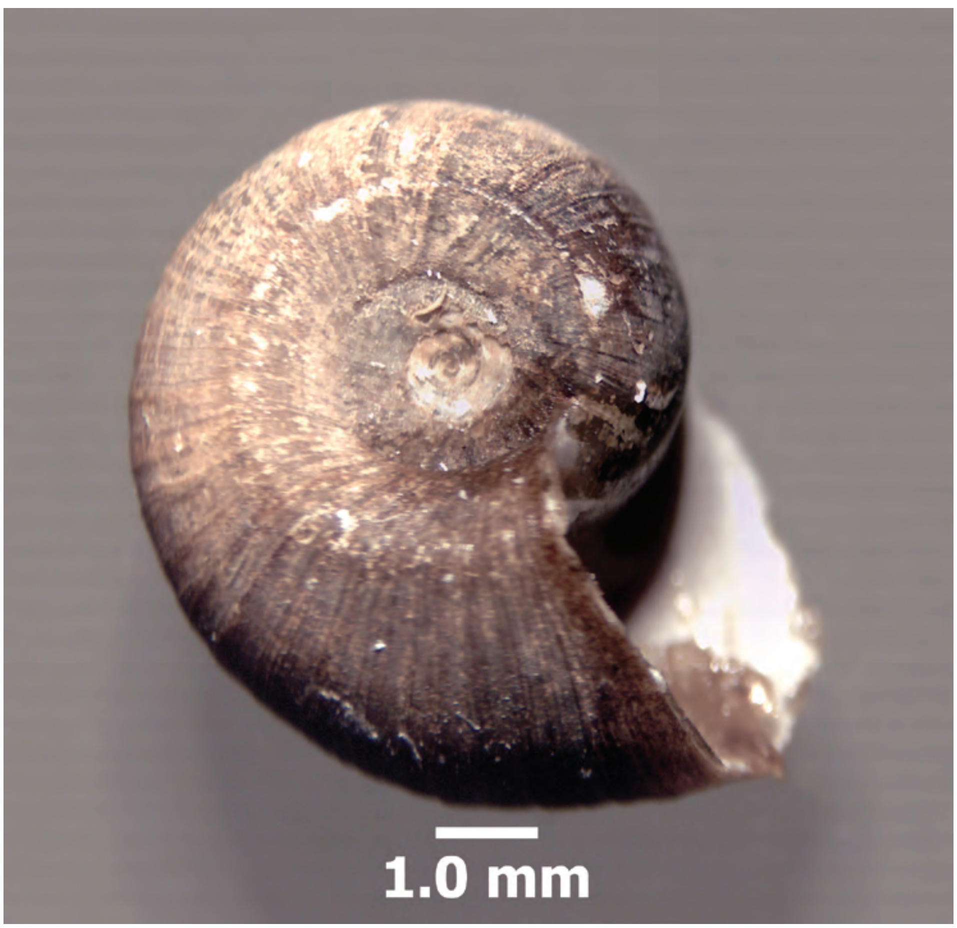


Figure D40. *Planorbella duryi* (Seminole rams-horn snail). Specimen preserved in 70-percent methanol.

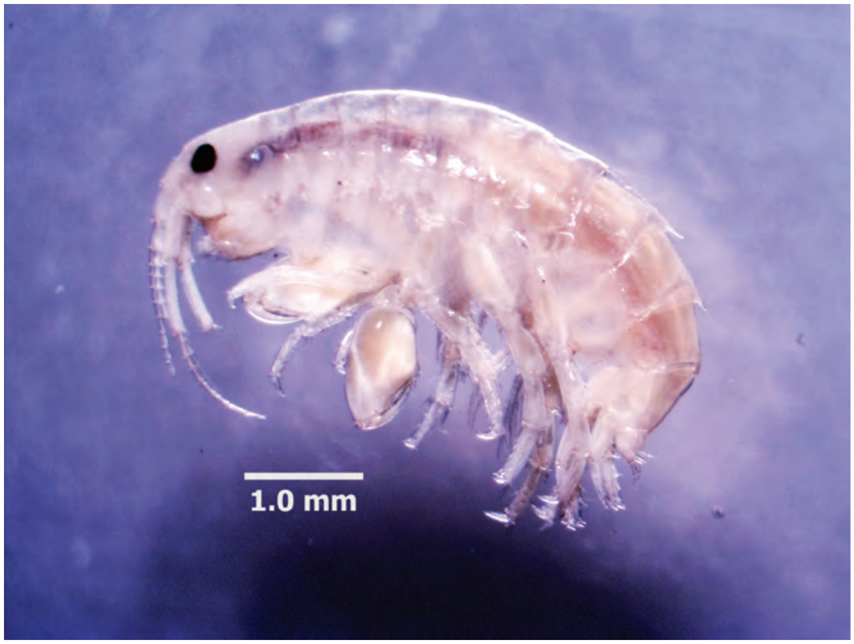


Figure D41. Amphipod. Specimen preserved in 70-percent methanol.

Figure D42. Turbellaria; Planarian (flatworm). Specimen preserved in 70-percent methanol. Scale in millimeters.

Figure D43. Assorted macroinvertebrates: (A) Ephydridae larva; (B) mite; (C) *Ferrissia sharpi*; (D) *Cheumatopsyche analis* larva. Specimens preserved in 70-percent methanol.

Figure D44. *Anax strenuus* (native dragonfly) adult.

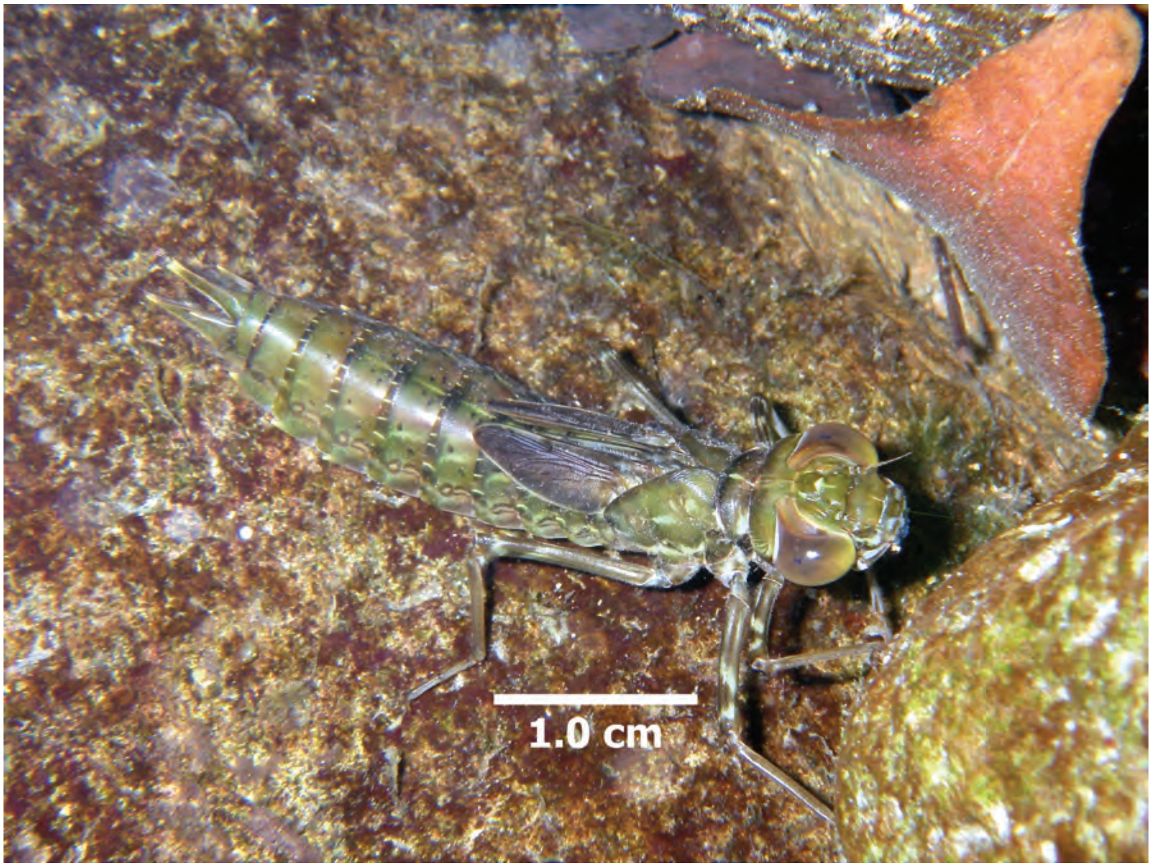


Figure D45. *Anax strenuus* (native dragonfly) naiad.

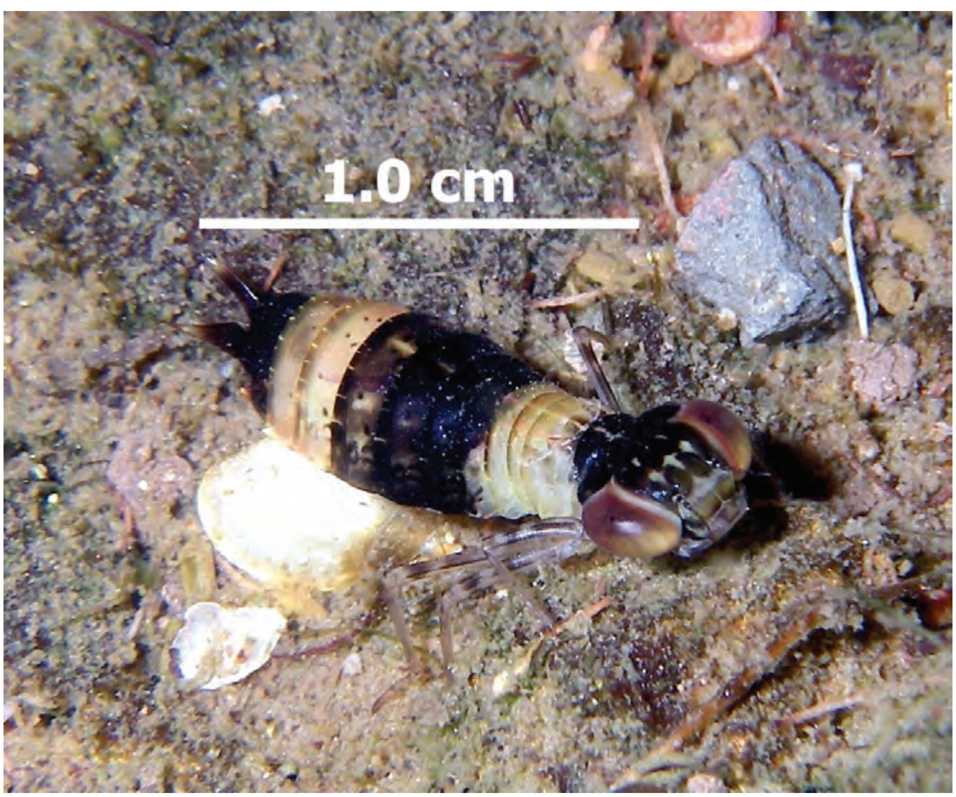


Figure D46. *Anax strenuus* (native dragonfly) *naiad*.

Figure D47. Mite adult. Specimen preserved in 70-percent methanol.

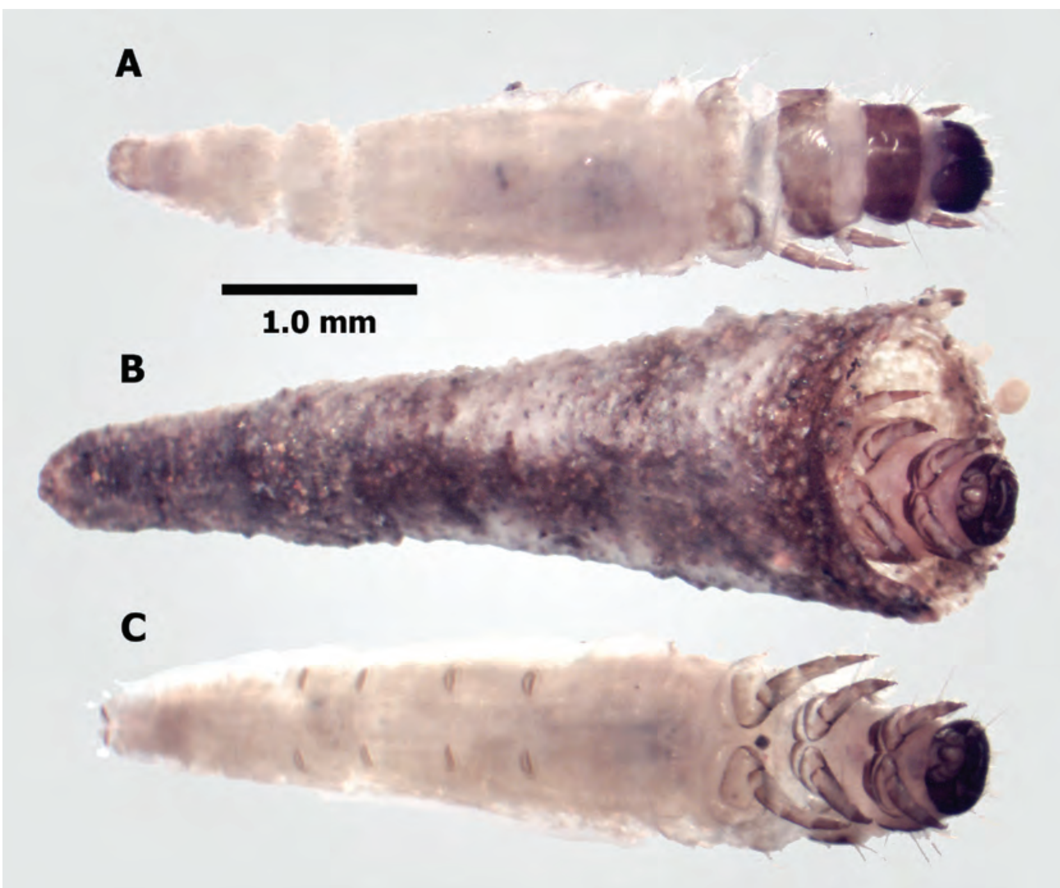


Figure D48. *Hyposmocoma* sp. (native Lepidoptera) larva: (A) dorsal view; (B) cocoon view; (C) ventral view. Specimen preserved in 70-percent methanol.

Figure D49. Canacidae larva: (A) ventral view; (B) dorsal view. Specimen preserved in 70-percent methanol.

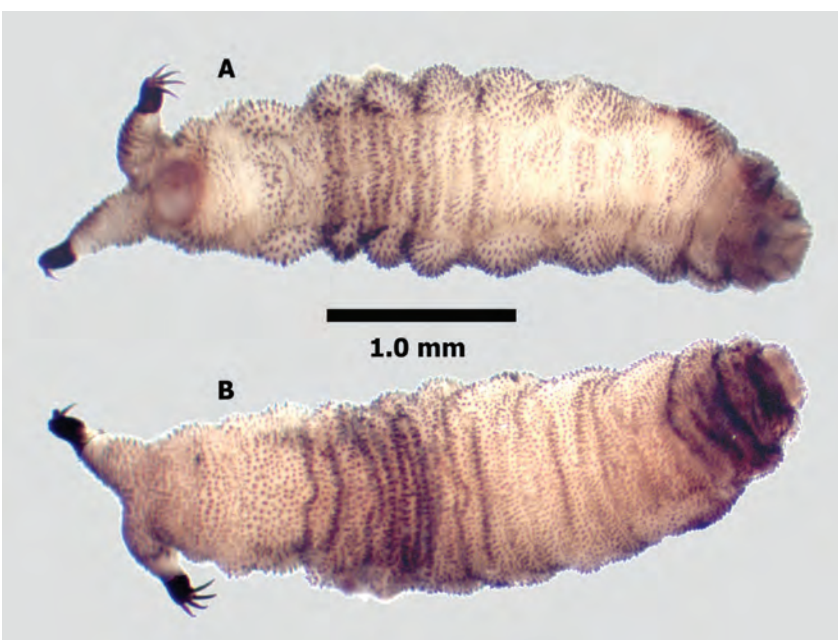


Figure D50. Ephydridae larva: (A) ventral view; (B) dorsal view. Specimen preserved in 70-percent methanol.

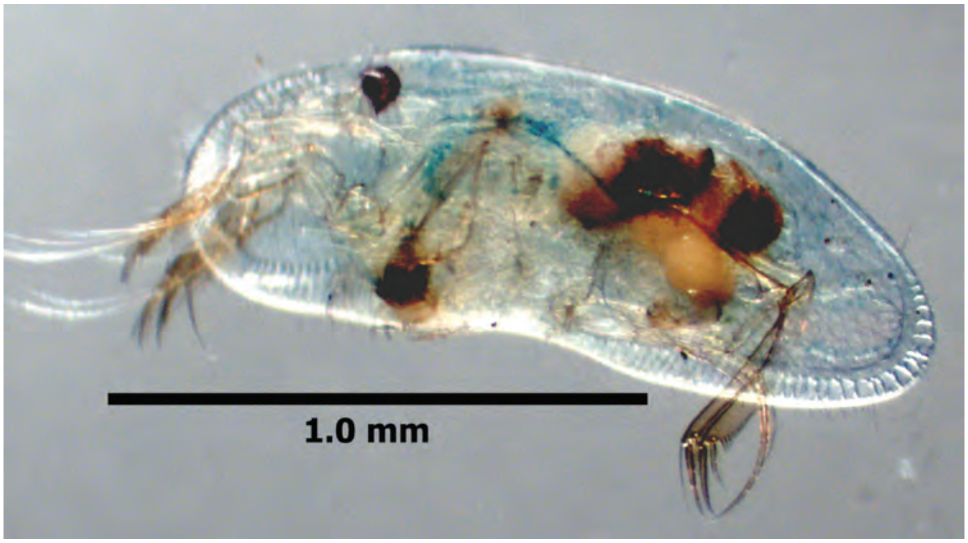


Figure D51. Ostracoda adult. Specimen preserved in 70-percent methanol.

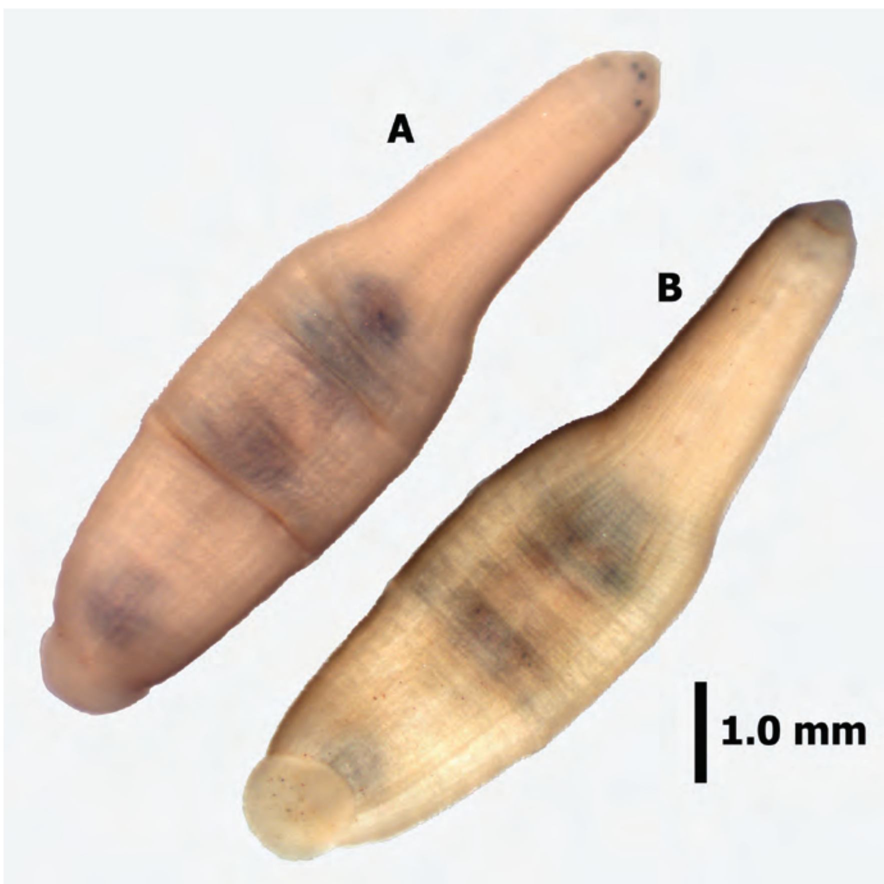


Figure D52. Glossiphoniidae (leech) adult: (A) dorsal view; (B) ventral view. Specimen preserved in 70-percent methanol.

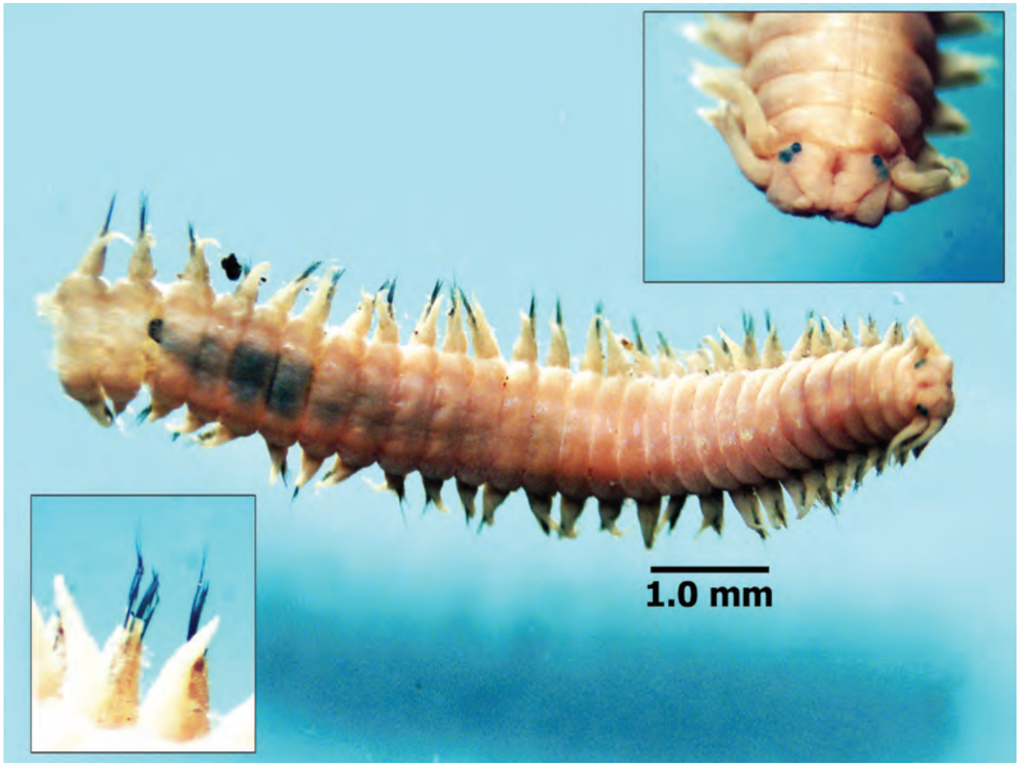


Figure D53. *Namalycastis abiuma* (native Polychaeta) adult. Specimen preserved in 70-percent methanol.

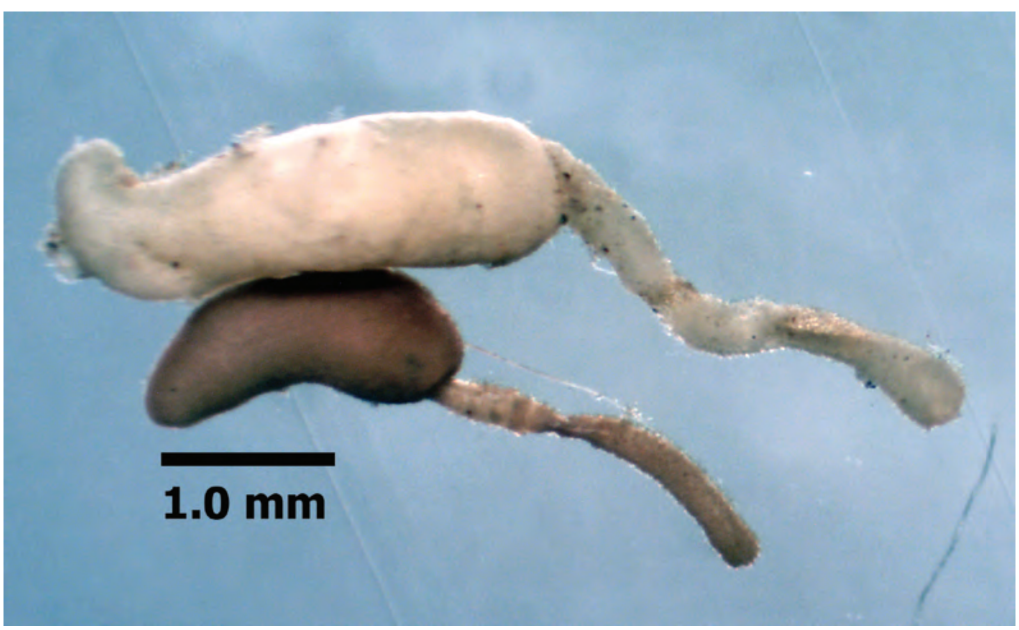


Figure D54. *Prostoma* sp. (Proboscis worms). Specimens preserved in 70-percent methanol.

This page intentionally left blank.

Menlo Park Publishing Service Center, California
Manuscript approved for publication October 21, 2011
Edited by Chet Zenone and Peter Stauffer
Layout and design by Judy Weathers

Wolff—**Development of Invertebrate Community Indexes of Stream Quality for the Islands of Maui and O‘ahu, Hawai‘i—Scientific Investigations Report 2012–5055**