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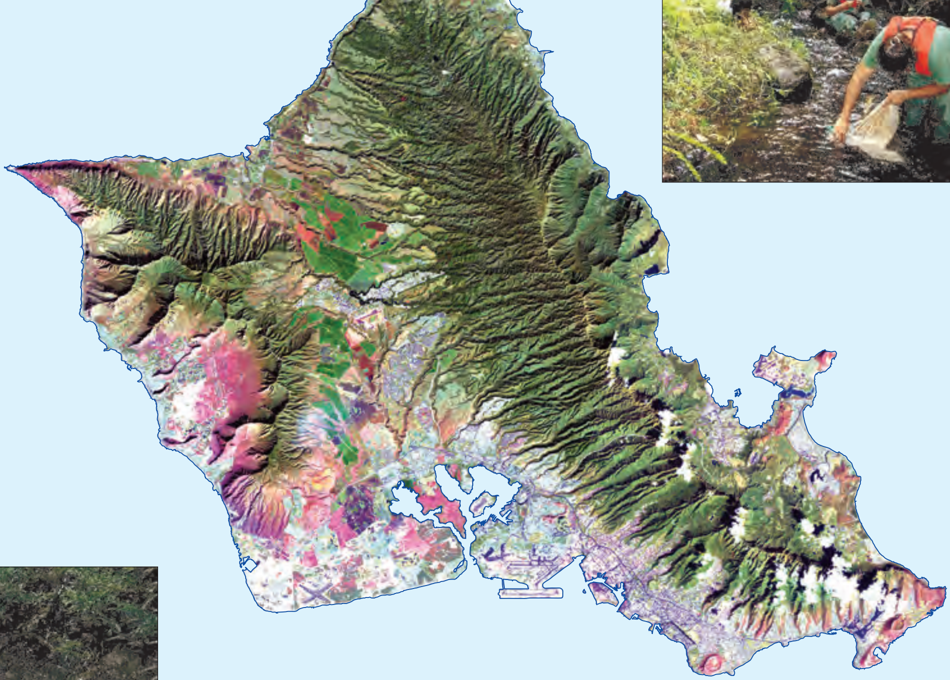
Associations Among Land Use, Habitat Characteristics, and Invertebrate Community Structure in Nine Streams on the Island of Oahu, Hawaii, 1999–2001

U.S. Department of the Interior
U.S. Geological Survey
Water-Resources Investigations Report 03–4256



National Water-Quality Assessment Program

Cover photographs starting clockwise from top left:

Collecting a water sample from the stream.

Collecting benthic invertebrates at a forested site.

Measuring substrate size in a run.

Conducting a habitat assessment in a fast-flowing riffle.

The map shows land use on the island of Oahu (modified from Klasner and Mikami, 2003).

Associations Among Land Use, Habitat Characteristics, and Invertebrate Community Structure in Nine Streams on the Island of Oahu, Hawaii, 1999-2001

By Anne M.D. Brasher, Reuben H. Wolff, and Corene D. Luton

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

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Foreword

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) program to support national, regional, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA program aims to provide science-based insights for current and emerging water issues and priorities. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units (http://water.usgs.gov/nawqa/nawqamap.html). Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings (http://water.usgs.gov/nawqa/natsyn.html).

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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CONVERSION FACTORS, ABBREVIATIONS, AND DATUMS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second

centimeter (cm)	0.3937	inch
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
square meter (m^2)	0.0002471	acre

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

°C= (°F−32)/1.8

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

°F=1.8 (°C) + 32

Abbreviations

µS/cm @ 25°C, microsiemens per centimeter at 25°C
NTU, nephelometric turbidity units
mg/L, milligrams per liter
µg/L, micrograms per liter

Datums

Vertical coordinate information is referenced relative to mean sea level.
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Associations Among Land Use, Habitat Characteristics, and Invertebrate Community Structure in Nine Streams on the Island of Oahu, Hawaii, 1999–2001

By Anne M.D. Brasher, Reuben H. Wolff, and Corene D. Luton

Abstract

The island of Oahu is 1 of 51 study units established as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) program to assess the status and trends of the Nation's surface and ground-water resources, and to link status and trends with an understanding of the natural and human factors that affect water quality. As part of the NAWQA program, benthic invertebrate communities were surveyed at 10 sites in 9 streams representing the three main types of land use on Oahu: urban, agriculture, and forested. At each sampling site, habitat characteristics were determined at a range of spatial scales including drainage basin, segment, reach, transect, and point. Associations among land use, habitat characteristics, and benthic invertebrate community structure were examined. The rapid population growth and increasing urbanization on Oahu has resulted in substantial stream habitat alteration. Instream habitat characteristics at the urban and mixed (urban and agriculture) land-use sites were markedly different from those at the forested sites. Urban and mixed land-use sites, most of which were channelized, tended to have less riparian vegetation, higher water temperatures, smaller substrate, and higher levels of embeddedness and siltation than sites in forested watersheds. The majority of invertebrate taxa identified during this study were nonnative. Invertebrate abundance was lower at urban and mixed land-use sites than at forested sites, while species richness (the number of different species) showed the opposite pattern. Multivariate analyses indicated that invertebrate species composition was similar at sites with similar land use. Aquatic insects of the orders Diptera and Trichoptera were the most common insects in all samples. The ratio of Diptera to Trichoptera abundance varied with urbanization. Forested sites were dominated by Trichoptera, and urban and mixed land-use sites were dominated by Diptera. Molluscs typically occurred in channelized urban streams although no native molluscs were collected during this study. The most abundant molluscs were pan-tropical thiarid snails, the introduced clam *Corbicula fluminea*, and the limpet *Ferrissia sharpi*. Two native and four introduced species of Crustacea were collected at the sampling sites. To effectively manage Hawaiian watersheds for native species and the communities they form, the ways in which these species respond to human-induced changes needs to be understood. This report provides information describing the usefulness of invertebrates as indicators of stream quality conditions and how an integrated assessment of stream quality will allow for the development of appropriate monitoring and management strategies.

Introduction

The U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) program was established to describe water-quality conditions of the Nation's ground-water and surface-water resources, and to link current stream conditions with natural and human factors that affect water quality (Gilliom and others, 1995). Oahu was 1 of 51 NAWQA study units established across the Nation between 1991 and 1997. The NAWQA study design balances unique local requirements of hydrologic systems with a nationally consistent design structure that incorporates a multiscale, interdisciplinary approach.

Oahu has undergone major land-use changes in the past 100 years, and the resident population has more than doubled since 1950 (State of Hawaii, 2000). Honolulu, the capital city located on the island of Oahu, is now considered the most densely populated city in the Nation (Fulton and others, 2001). Urbanization on Oahu has been accompanied by substantial alterations to stream systems, including changes in water quality, instream habitat, riparian habitat, and the introduction of nonnative species. To effectively manage Hawaiian watersheds for native species and the communities they form, the ways in which species respond to human-induced changes need to be understood.

The NAWQA program assesses watersheds as integrated systems using multiple lines of evidence including physical, chemical, and biological conditions (Gurtz, 1994). In addition to water samples, stream-quality assessments commonly include sampling algae, benthic invertebrates, and fish (Lenat and Barbour, 1994). Benthic macroinvertebrates are by far the most commonly used group of organisms for this purpose (Rosenberg and Resh, 1993). Some examples of benthic invertebrates include molluscs (snails), annelids (worms), insects (flies), and crustaceans (shrimp). Some groups such as aquatic molluscs live their entire lives in or near the water, while other groups, including many species of insects, have aquatic larval stages and terrestrial adult stages.

Benthic macroinvertebrates offer many advantages in bioassessment and biomonitoring (adapted from Rosenberg and Resh, 1993): (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, because different species require different habitat and water conditions; (3) their basic sedentary nature allows effective spatial analyses of pollutants or disturbance effects; and (4) they have relatively long life cycles, which allows elucidation of temporal changes caused by perturbation.

Purpose and Scope

This report describes the composition of benthic macroinvertebrate communities collected at 10 sites in 9 streams on the island of Oahu during surveys conducted during the summers of 1999–2001. Detailed habitat assessments are described for each site. Both quantitative (allows comparisons of abundances between sites) and qualitative (provides a comprehensive species list for a given site) invertebrate samples were collected (Cuffney and others, 1993). Habitat characteristics were determined at a range of spatial scales including basin, segment, reach, habitat, and microhabitat/point (Fitzpatrick and others, 1998).

Associations among land use, habitat characteristics (physical and chemical), and benthic invertebrate community structure on the island of Oahu are examined. Of particular interest is the effect of urbanization on habitat characteristics and how this relates to invertebrate communities. Results of this study indicate that information on the association between invertebrate species composition and abundance and habitat characteristics can be a useful part of a comprehensive assessment of stream quality.

Acknowledgments

Fieldwork for this project was made possible with the assistance of Federal and State agencies, local organizations, and numerous student volunteers. We especially would like to thank: Chad Durkin, Paige Little, Gordon Smith, Terrell Kelley, Donna Ashizawa, Susan Burr, Matt Monte, Anne Williams, Ann Yokoyama, Philip Anderson, Jake Douglas, and Chris Wellise. Terry Short, Steve Goodbred, Ian Waite, and Wade Bryant also provided advice and assistance. Brady Richards sorted and identified the invertebrate samples, and Les Watley identified the amphipods.

Environmental Setting

Physiography

The island of Oahu is the third largest island of the State of Hawaii (fig. 1). The landscape of Oahu ranges from a broad coastal plain, surrounding much of the island, to steep interior mountains. Oahu can be divided into two primary physiographic zones, 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 while the leeward side has larger drainage basins, lower rainfall, and intermittent streamflow (Oki and Brasher, 2003).

The climate of Oahu is characterized by mild temperatures, which vary little between seasons. The small temperature difference between the warmest and coolest months is largely attributable to the influence of the surrounding ocean, the persistence of cool trade winds, and the small seasonal variation in solar radiation (Blumenstock and Price, 1967; Sanderson, 1993). Daylight hours also change little from season to season. The length of the longest day and the shortest day of the year vary only by a few hours. This lack of seasonality in temperature and day length is reflected in the reduction of seasonality in the invertebrate life cycles compared to temperate continental streams.

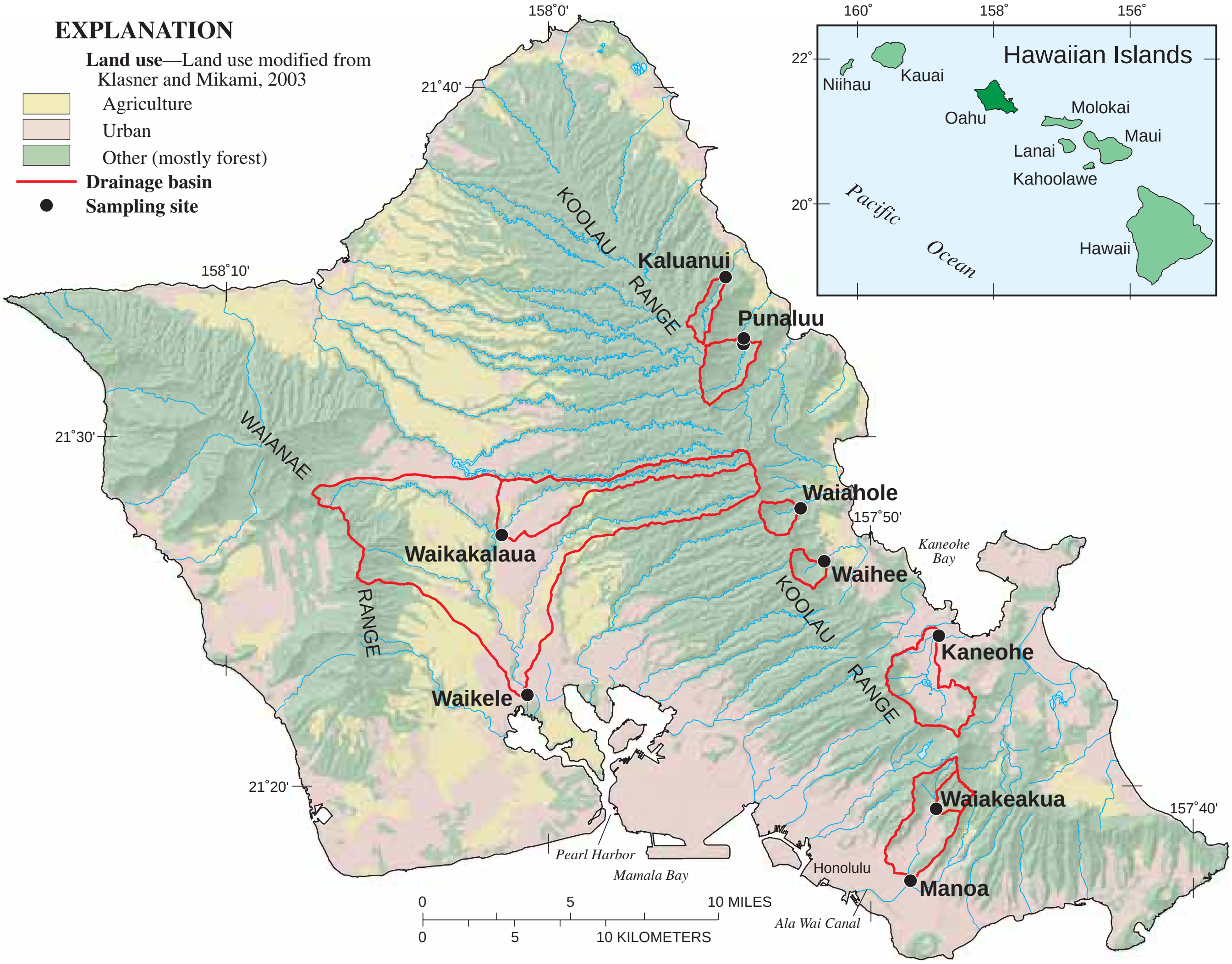


Figure 1. Land use and sampling sites on the island of Oahu, Hawaii.

A rainy season occurs on Oahu from October through April, and a dry season from May through September, however, high rains and storm flows can occur throughout the year (Blumenstock and Price, 1967; Sanderson, 1993). During heavy storms, 24-hour rainfall can exceed 10 in. over coastal areas and 20 in. over the mountainous interior of the Koolau Range (Giambelluca and others, 1984).

Drainage Basin and Streamflow Characteristics

Streams on Oahu originate in the steep mountainous interiors of the Waianae and Koolau Ranges and terminate at the coast. Some of these streams flow perennially throughout their entire course, others flow perennially over parts of their course, and the remainder flow intermittently throughout their entire course (Oki and Brasher, 2003). A total of 57 streams on Oahu have been classified as perennial in all or part of their courses (Hawaii Cooperative Park Service Study Unit, 1990).

Intermittent and perennial streams on Oahu may gain water along some reaches and lose water along other reaches depending on local geohydrologic conditions. Streams on Oahu flow perennially mainly because of ground-water discharge, although in the upper reaches of streams, persistent orographic rainfall may maintain streamflow during much of the year (Oki and Brasher, 2003). In some areas streams may be dry below the area of high rainfall because flow is lost to the streambed by infiltration.

Drainage basins on Oahu tend to be small compared to continental drainage basins, and the streams are flashy. However, streamflow characteristics are highly variable, both spatially and temporally. Streams on Oahu are flashy because of high-intensity rainfall, small drainage-basin size, steep basin and stream slopes, and little channel storage (Wong, 1994). Stream stage can rise and fall several feet over a few hours in response to rainfall. The bedload and suspended sediment load of a stream can be significant during periods of flood flows (Oki and Brasher, 2003). These naturally occurring scour events can profoundly affect algal and invertebrate communities. In addition to reducing overall abundances, scouring acts as a disturbance that can alter species composition (Wolff, 2000).

Seasonal streamflow patterns are also spatially variable. In some areas monthly streamflow is higher during the wet season than the dry season, while in other areas, particularly where base flow is significant, seasonal streamflow variations are less pronounced (Oki and Brasher, 2003). Discharge at a given site will vary from year to year depending mainly on rainfall (Oki and Brasher, 2003). Periods of less-than-average streamflow also can be caused by upstream surface-water diversions or nearby ground-water withdrawals that reduce base flow. During dry periods and ensuing low-flow conditions, the maintenance of streamflow may be dependent on ground-water inflow. Because streams in windward Oahu commonly receive significant ground-water inflow, discharge for streams in windward Oahu is generally less variable during low-flow conditions than for streams in leeward Oahu (Oki and Brasher, 2003).

Land Use

Current land-use patterns on Oahu reflect increases in population and decreases in large-scale agricultural operations during the 20th century (Klasner and Mikami, 2003). The last two sugarcane plantations on Oahu closed in the mid-1990s, and land that was once used for sugarcane is now lying fallow, used for diversified agriculture, or is being developed for urban use. Although two large pineapple plantations continue to operate in central Oahu, some of the land previously used for pineapple cultivation has also been converted to urban use (Oki and Brasher, 2003).

Lands on Oahu have been classified as either urban, agricultural, or other (primarily forested). As of 1998, about 26 percent of the land on Oahu was classified as urban, 16 percent was agricultural, and 58 percent was classified as other (Klasner and Mikami, 2003). No lands on Oahu were classified as rural. The resident population on Oahu increased from 58,500 in 1900 to 876,000 in 2000 (State of Hawaii, 2000). As the Oahu landscape continues to be developed for urban use, instream and riparian habitats are becoming more degraded. Physical changes including lower habitat heterogeneity and increased abiotic variability are compounded by the presence of a variety of organic and inorganic contaminants (Oki and Brasher, 2003).

Implications of Urbanization for Biota

The rapid population growth and increasing urbanization of Oahu has resulted in substantial stream habitat alteration. An extensive study, conducted in the 1970s, showed that 57 percent of the streams on the island of Oahu had been channelized, 58 percent had water exported from them, and all had roads crossing over them (Timbol and Maciolek, 1978). As is typical throughout the tropics (Pringle and Ramirez, 1998; Resh and others, 1992), modifications of the stream ecosystems have been most severe at the lower elevations where urban growth is greatest (Timbol and Maciolek, 1978).

Artificially straightened reaches with concrete-lined flat-bottomed channels and revetted (reinforced) banks are common in the urban areas of Oahu. Such modifications are commonly accompanied by removal of riparian vegetative cover, and a reduction in substrate complexity (removal of large boulders). The end result is a wide, shallow, unshaded, and generally homogenous stream reach; a stark contrast to the steep, heavily vegetated, boulder strewn reaches typical of the more pristine streams in forested areas of Hawaii (fig. 2).

Implications of channel modification for the benthic invertebrate communities are substantial. In areas where the stream channel has been straightened, flow velocities commonly increase. If the channel bottom has also been artificially widened and lined with cement, the resulting flow can be a thin, uniform sheet of water. In combination with a reduction of riparian vegetation, these changes to the stream channel can cause daytime water temperatures to rapidly rise. Channelized urban streams on Oahu typically have higher daily mean and maximum water temperatures, and greater daily fluctuations in water temperature than streams in more pristine forested areas of Hawaii. Additionally, in these urban streams increased solar radiation and elevated water temperature promote excessive algal growth, which in turn results in strong daily fluctuations in pH and dissolved oxygen (Norton and others, 1978).


Photograph by Mark Vinson.

Introduced clam (*Corbicula fluminea*)

Urban land use is also commonly associated with a variety of organochlorine, organophosphate, trace element, and metal contaminants in streams. These constituents are applied on land as pesticides, herbicides, or fertilizer, or may have industrial uses. Whether present in the water column or adhered to the sediment, they can have potentially negative effects on the benthic invertebrates that live in the streams (Oki and Brasher, 2003).

Invertebrates in Hawaiian Streams

The Hawaiian islands are the most isolated island archipelago in the world, located nearly 4,000 kilometers from the nearest continent. The native stream fauna of Hawaii 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 due to the limited dispersal mechanisms of most aquatic invertebrates. Most native stream species were probably derived from marine ancestors, although a few arrived by aerial dispersal or in various other ways, such as while attached to migratory birds. This isolation 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 larger native stream animals in Hawaii (fish, shrimp, and snails) are primarily amphidromous, evolved from marine organisms, and retain a marine larval life-stage. Adults lay eggs in the streams, the eggs hatch, and the larvae drift to the ocean where they spend 4 to 7 months as plankton before returning to a stream. There is no evidence that they return to the stream where they hatched. Distribution of these animals is largely controlled by their ability to migrate upstream unimpeded.

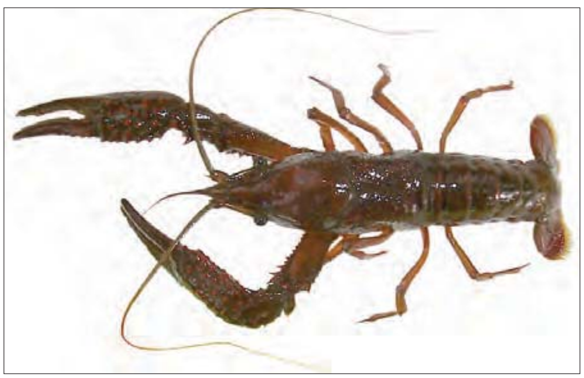
Since human colonization of the Hawaiian islands (1,400 years ago), many native species have been substantially affected by habitat alteration and the introduction of nonnative species. This process has been accelerated during the past 100 years of rapid urbanization. Native species are well adapted to the unique environment of Hawaiian streams and tend to be highly specialized. There is now a proliferation of introduced species that are generalists (able to adapt to a wide range of habitat conditions) and that are also far more tolerant of conditions in altered and degraded streams.

Nonnative macroinvertebrates arrived in Hawaii as a result of both intentional and accidental introductions. Some introductions were State sanctioned, such as the Tahitian prawn, *Macrobrachium lar (*Fabricius), while others, such as the Asiatic clam, *Corbicula fluminea* Müller, were not, although both were intentionally introduced for food purposes (Devick, 1991). The atyid shrimp, *Neocaridina denticulata sinensis*, was accidentally introduced from the aquarium trade (Englund and Cai, 1999) and a myriad of insect species were

Figure 2. Typical stream in (A) forested and (B) mixed land-use settings.

accidentally introduced aboard ships and planes and among 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; Rigby and others, 1997).

Species with univoltine life cycles (reproducing once per year) in temperate streams may switch to multivoltine life cycles (reproducing throughout the year) in Hawaiian streams, which lack the marked seasonality of temperate streams. This has recently been documented for the introduced caddisfly (Trichoptera) *Cheumatopsyche pettiti* (Banks) (Kondratieff and others, 1997; Wolff, 2000). Although seasons in Hawaii are considerably less variable than in those temperate regions, even minor seasonal variations in discharge, water temperature, and light regime can be important in the development of macroinvertebrate communities in Hawaiian streams (Wolff, 2000).



Photograph by Anne Brasher.

Introduced crayfish

Site Selection, Data Collection, and Analytical Methods

Site Selection

Sites were selected to represent the range of land-use and habitat characteristics present on the island of Oahu; including urban, agriculture, and forested drainage basins (fig. 1). Because the upper reaches of all drainage basins on Oahu are forested, a certain percentage of land cover upstream in the basin at every site is forest. For this study, sites were assigned land-use designations (urban, mixed urban and agriculture, and forest) based on dominant mapped land use (Klasner and Mikami, 2003) and personal observation of the surrounding area. Nine streams were selected for the study (table 1). A single sampling site was designated in each stream, with the exception of Punaluu Stream where two sites were selected, one directly above a water diversion and one directly below the diversion. Reaches were placed near USGS streamflow gages whenever possible.

Five additional samples were collected as part of the overall study. At Waikele Stream, an additional quantitative sample was collected from the deep, slow-moving section that made up most of the reach, but was not considered the “richest targeted habitat” required by the sampling design for quantitative sampling. At Waihee Stream, in addition to the samples collected in 1999, the site was resampled in 2000 and 2001, and in 2000 two adjacent reaches at Waihee Stream were also sampled. (Species lists from these additional samples are provided in appendix B, but these samples are not included in the data analysis for this report.)

Invertebrate Sampling

Quantitative and qualitative invertebrate samples were collected at each site following standard NAWQA protocols (Cuffney and others, 1993). All sampling was conducted during base-flow conditions. Quantitative samples were collected from the faunistically richest community (richest targeted habitat) of benthic invertebrates, which for Hawaiian streams is usually located in fast-flowing riffles (M.H. Kido, Hawaii Stream Research Center; R.A. Kinzie III, University of Hawaii; and G.W. Smith, U.S. Fish and Wildlife Service, oral commun., 1998). Quantitative samples provide estimates of organism relative abundances to allow comparison between sites. Qualitative multi-habitat samples were collected from all available habitats within the reach at each site, to provide a comprehensive species list.

Quantitative samples were collected using a modified Surber sampler (Slack sampler) with a 425-mm mesh net (Cuffney and others, 1993). All substrate within a 0.25-m^2 area in front of the net was gently dislodged and thoroughly scrubbed to remove all organisms, until bedrock was reached or nothing except extremely fine-grained substrate remained. Five quantitative samples were collected at each site, cleaned of extraneous mineral and organic material, and then composited to produce a single sample.

Table 1. Stream name, site code name, land use, and key physical and hydrological characteristics of the 10 sampling sites in 9 streams on the island of Oahu, Hawaii

[Discharge from water year October 1998 through September 1999 from U.S. Geological Survey streamflow-gaging station, except where otherwise noted; ft^3/s, cubic feet per second; na, not applicable; —, no data]

Stream	Code	USGS station	Land-use designation	Forest	Urban	Agriculture	Elevation (feet)	Drainage area (square miles)	Discharge (ft^3/s)				
				(percent)					annual mean daily	median daily mean	minimum daily	maximum daily	instan-taneous
Manoa	MANO	16242500	urban	61	38	1	38	6	[1]11.7	7.3	2.7	126.0	na
Kaneohe	KANE	16274100	urban	36	62	3	40	5	—	—	—	—	[2]6.33
Waikele	WKEL	16213000	mixed	47	28	25	1	47	31.7	22.0	15.0	289.0	
Waikakalaua	WKAK	16212700	mixed	52	40	7	540	7	—	—	—	—	[2]8.74
Waiakeakua	WKEA	16240500	mixed	96	0	4	295	1	4.2	3.3	1.9	27.0	na
Kaluanui	KALU	16304200	forest	100	0	0	110	1	3.2	1.6	0.15	32.0	na
Waihee	WHEE	16284200	forest	99	1	0	170	1	4.5	4.4	3.6	19.0	na
Waiahole	WHOL	212837157522001	forest	100	0	0	210	1	—	—	—	—	[2]22.2
Punaluu													
below diversion	PUNB	16303000	forest	100	0	0	212	3	8.8	6.9	0.17	83.0	na
above diversion	PUNA	16303003	forest	100	0	0	212	3	18.0	16.1	12.2	94.0	na

[1]Discharge statistic from 1/16/99-9/30/99
[2]Date: KANE 8/3/00
WKAK 7/15/99
WHOL 7/1/99

Qualitative samples were collected from all available habitats at each site using a D-frame kick net with a 210-mm mesh net. Samples were collected by dipping, kicking, and sweeping, as appropriate for the various habitats being sampled (Cuffney and others, 1993). The D-frame kick-net collections were supplemented by visual collection, which primarily included manually turning over large rocks and other substrates, and removing representative invertebrate taxa. Qualitative samples were cleaned of mineral and organic material and composited into a single sample at each site.

All samples were preserved in 10 percent formalin and sent to the USGS National Water Quality Laboratory Biological Unit in Denver, Colorado, for identification and enumeration. Verification of problematic taxa and routine quality-assurance checks on taxonomic identifications were done by nationally recognized experts. Data reported for the quantitative samples include both species occurrence and density using numeric (300 fixed-count) and time (total sorting time) criteria (Moulton and others, 2000). Qualitative samples were analyzed only for species occurrence, using a timed visual-sort method. A voucher collection of the invertebrates is maintained at the National Water Quality Laboratory, and specimens that are new records are also vouchered at Bishop Museum in Honolulu, Hawaii.

Habitat Characteristics

Habitat characteristics (table 2) were determined at multiple spatial scales: basin, segment, reach, transect, and point following standard NAWQA protocols (Fitzpatrick and others, 1998). Basin and segment characteristics (watershed-scale features) such as land use, drainage area, and gradient were determined using GIS and topographic maps. Reach, transect, and point measurements (table 3) were made at each site on the same day (or in some cases the following day) that the invertebrate samples were collected.

Reach length at each site was determined as the linear distance equal to 20 times the average wetted channel width, with a minimum length of 100 m. Streamflow and water-quality characteristics (such as temperature, discharge, and water chemistry) were measured at each reach during conditions representative of the invertebrate sampling period. Within each reach, 11 equally spaced transects were established across the stream perpendicular to the direction of flow. Physical measurements of bank and riparian features and instream characteristics were made at each transect (fig. 3). Bank and riparian features included measurements such as bank angle, erosion, and canopy cover. Instream habitat measurements included features such as aspect, wetted perimeter, depth, velocity, and substrate size. Point (microhabitat) measurements of depth and velocity were also made at each location where a quantitative invertebrate sample was collected.

Table 2. Habitat characteristics determined at four spatial scales: watershed (basin/segment), reach (study site), transect, and point (location of invertebrate samples)

Basin/Segment	Reach	Transect	Point
Drainage area	Discharge	Aspect	Depth
Land use/land cover	Reach length	Bank angle	Velocity
Mineralogy	Channel modifications	Bank height	
Gradient	Geomorphic channel units	Open canopy angle	
Curvilinear channel length	Riparian land use	Riparian canopy closure	
Sinuosity	Water temperature	Annual solar radiation	
Population density	Water quality	Wetted channel width	
		Bankfull channel width	
		Bank substrate	
		Bank vegetative cover	
		Erosion	
		Dominant substrate	
		Pebble count	
		Embeddedness	
		Silt	
		Water depth	
		Water velocity	

Table 3. Habitat characteristics measured at the reach and transect scales

[Additional detail provided by Fitzpatrick and others, 1998]

Bank

Riparian land use: dominant land use adjacent to the stream.
Bank angle: average slope of the stream bank adjacent to the water's edge.
Bank height: height of both banks from the thalweg.
Bank substrate: a categorical variable of the substrate type (see channel substrate) on the banks at each transect.
Bank vegetative cover: percent of the stream bank area at each transect that is covered by vegetation. This is a measure of the susceptibility of the banks to erosion.
Erosion: a categorical variable (yes/no).

Sunlight and Shading

Riparian canopy closure: the density of vegetation along the stream banks and overhanging the stream, thereby shading the stream, is measured with a densiometer.
Open canopy angle: amount of shading by stream bank objects (trees, buildings, etc.). The angle is measured with a clinometer from the middle of the stream to the tallest objects on the left and right banks.
Annual solar radiation: a solar pathfinder is used to estimate the monthly amount of solar radiation based on the amount of shading and the annual path of the sun.

Channel

Channel modifications: changes from the natural stream (dredged, stabilized, concrete lined, etc.).
Geomorphic channel units: linear measurement of the lengths of riffles, runs, and pools along the study reach.
- **Pools**: little flow or surface turbulence, usually deeper than the adjacent areas.
- **Riffles**: shallow, rocky, swiftly flowing sections with high surface turbulence and aerated 'white-water'.
- **Runs**: little or no surface turbulence with moderate depths and flows.

Wetted channel width: width of the stream measured to the water's edge.
Bankfull channel width: estimated width of the floodplain.
Aspect: direction of flow is measured (in degrees) with a clinometer.

Substrate

Pebble count: measure the length and width of streambed substrate across the stream (minimum 20 measurements) at three transects.
Embeddedness: the percent of the streambed substrate infilled by sediment.
Silt: a categorical variable (presence/absence).
Dominant substrate: a categorical variable of the substrate type at three point measurements at each transect.

1	Smooth bedrock/concrete/hardpan	6	Very coarse gravel
2	Silt/clay/marl/muck/organic detritus	7	Small cobble
3	Sand	8	Large cobble
4	Fine/medium gravel	9	Small boulder
5	Coarse gravel	10	Large boulder

Water Quality

Surface-water quality constituents including specific conductance, pH, water temperature, dissolved oxygen, major ions, nutrients, dissolved solids, and organic carbon (suspended and dissolved), were measured once at each reach for this study. The methods used for surface-water sample collection and analyses followed standard NAWQA protocols (Shelton and Capel, 1994; Mueller and others, 1997).

Water Temperature

Water temperature (°C) was continuously recorded at 30-minute intervals for approximately a 12-month period at each site using temperature loggers. The temperature loggers were attached to large boulders in the water, so that the probe was constantly submerged and out of direct sunlight. Temperature data were downloaded monthly and processed. A hand-held liquid-in-glass thermometer was used to verify calibration of the electronic loggers. At three of the sites (Waihee, Waikele, and Manoa), water temperature was continuously recorded

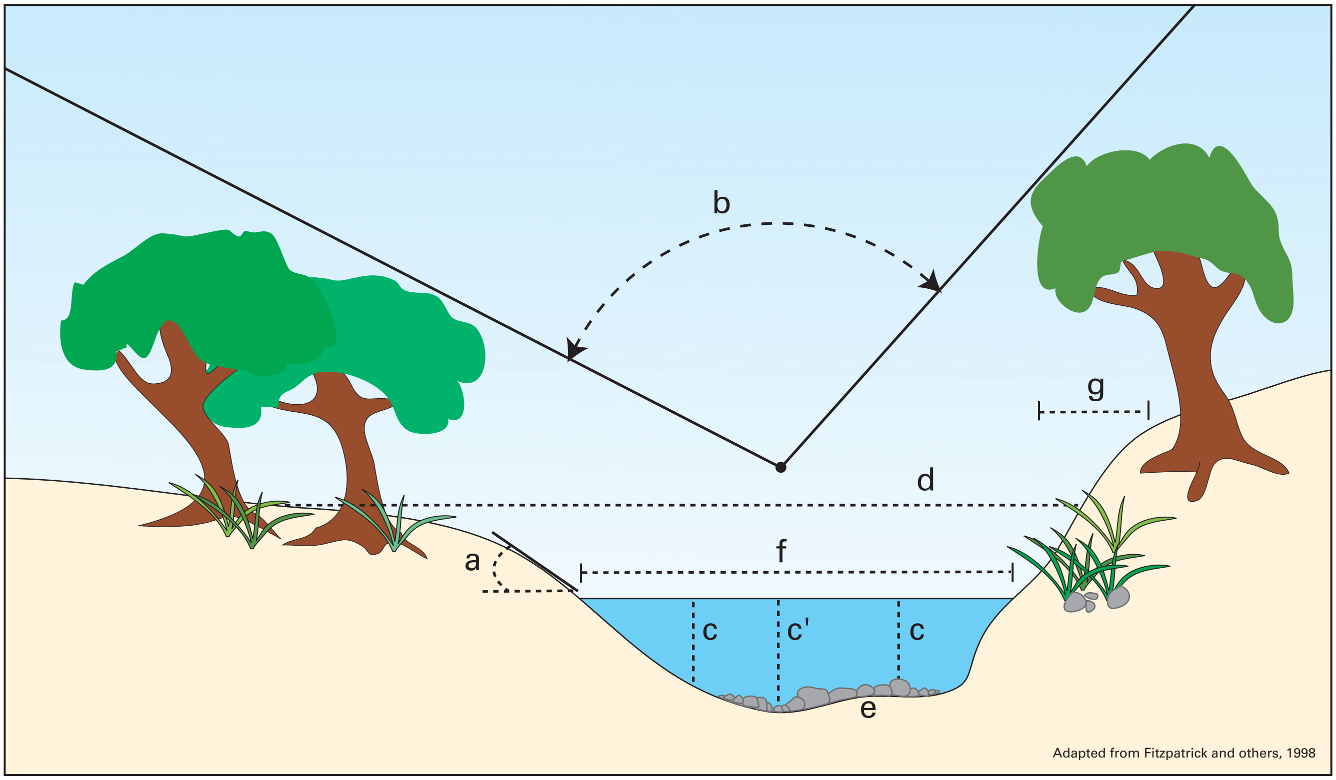


Figure 3. Diagram of selected habitat measurements made at each transect: (a) bank angle, (b) open canopy angle, (c) stream depth, (c') thalweg (deepest depth), (d) bankfull width, (e) substrate size, (f) wetted channel width, (g) riparian canopy closure.

at the USGS streamflow-gaging station as part of the NAWQA surface-water quality monitoring effort. Erroneous measurements generated by partial exposure of the logger during extreme low-flow conditions were edited from the final data. At some sites, data are missing for certain periods of time because of loss of or damage to the temperature loggers.

Statistical Analyses

Statistical analyses were performed on the quantitative invertebrate species abundance data. Before statistical analysis, the invertebrate data set was reviewed and edited to resolve for the occurrences of ambiguous taxa (Tom Cuffney, U.S. Geological Survey, oral commun., 1999). Ambiguous taxa are those taxa whose identifications cannot accurately be determined to the lowest common taxonomic level. For example, some individuals might be identified only to the family taxonomic level while others may be identified to a genus level within that family, and still others to a species level within that genus. These unresolved taxa are frequently the result of either damaged or immature individuals.

Multivariate analyses of habitat and invertebrate data were performed using the statistical packages PC-ORD (McCune and Mefford, 1999) and MVSP (Kovach, 1998). To explore the spatial variability among invertebrate communities, we used the multivariate statistical technique of Detrended Correspondence Analysis (DCA) using proportional relative abundance data from all 10 sites (Hill and Gauch, 1980). DCA is an ordination technique that simplifies the interpretation of complex multivariate data sets by indicating the primary and secondary axes of variation that can be plotted on a two-dimensional graph, thereby reducing the complexity of the data matrix and facilitating interpretation (Hill, 1979).

Principal Components Analysis (PCA) was performed on 60 environmental variables including habitat and water-quality measurements (Kovach, 1998). Percentage variables were arcsine-square root transformed and non-categorical variables were $ln\ (x+1)$ transformed prior to analysis. PCA is a multivariate technique that can reduce the individual effects of multiple variables into principal components (PC) that are linear combinations of the original variables. The first PC accounts for the greatest proportion of the total variance in the data set, and each successive PC accounts for a smaller proportion of the remaining variance. The contributions of individual variables to a PC are expressed as loadings, which can be interpreted to determine which variables explain the main portion of the variance for each PC. Redundant variables can be eliminated through an iterative process from subsequent analyses until surrogate variables are identified that best represent each portion of the variance within the group of correlated variables (Waite and Carpenter, 2000).

Spearman rank correlations (a nonparametric technique) (SAS Institute, 1993) were also used to examine relationships between environmental variables and invertebrate community structure. Results of the PCA and Spearman rank analysis were used to reduce the 60 environmental variables to 9 proxy variables, and patterns among these variables were then used to identify important habitat characteristics associated with the different land uses.

Diversity indices were calculated based on two distinct components: (1) richness (the total number of species) and (2) evenness (how abundance is distributed among the species) (Ludwig and Reynolds, 1988). Shannon's Index (based on the ability to predict what species an individual chosen at random from a collection of species will be) and Simpson's Index (the probability that two individuals drawn at random from a population belong to the same species) were used (McCune and Mefford, 1999).

$$D = 1 - \sum_{i}^{s} (p_i)^2$$

Simpson's Diversity Index *(D)*

$$H' = - \sum_{i}^{s} (p_i)\,(\ln p_i)$$

Shannon's Diversity Index *(H')*

p_i = proportion of individuals of species i in the community

s = number of species

Relations Among Habitat Characteristics, Water Temperature, and Land Use

Habitat characteristics varied greatly among land uses. Urban and mixed land-use sites had fewer riffles and more runs, while forested reaches had more riffles and fewer runs (fig. 4). Average instream substrate size was smaller (cobble and gravel dominated) in urban and mixed land-use sites, while forested sites had a larger proportion of boulder substrate. Embeddedness and siltation, which are partially a function of velocity (Gordon and others, 1992), tended to be higher at the urban and mixed land-use sites.

Adult Trichoptera (caddisfly)

Water-quality properties and constituents were measured once at each site during conditions representative of the invertebrate sampling period (appendix A). A general association of land use with certain constituents was observed. Ammonia, calcium, and magnesium concentrations were highest at urban and mixed land-use sites, and decreased with increasing percentage of forested land. Phosphorus concentrations showed a less clear pattern. The lowest concentration of total phosphorus occurred at forested Kaluanui (0.007 µg/L), and the highest at Waikele (0.184 µg/L) which is a mixed land-use site, but there was no apparent trend associated with land use. Elevated levels of phosphorus at Waikele Stream are likely an indication of the presence of agriculturally influenced ground water at that site (Tomlinson and Miller, in press). High levels of chloride (98.1 µg/L) and high specific conductivity (503 µS/cm) were also measured at Waikele Stream, indicative of the estuarine influence at that site.

Mean water temperature was positively correlated with urban land use (Spearman correlation coefficient $r = 0.78$; $p < 0.008$). Streams at urban sites, which tended to be shallow and have reduced riparian cover, had higher mean and maximum daily temperatures, and substantially greater diurnal temperature fluctuations than at the forested sites (fig. 5). Maximum water temperature at one urban site, Kaneohe, exceeded the upper lethal limit (34°C) for native atyid shrimp (Hathaway, 1978). The relative contribution of ground water during low-flow conditions also influenced the temperature profile. The

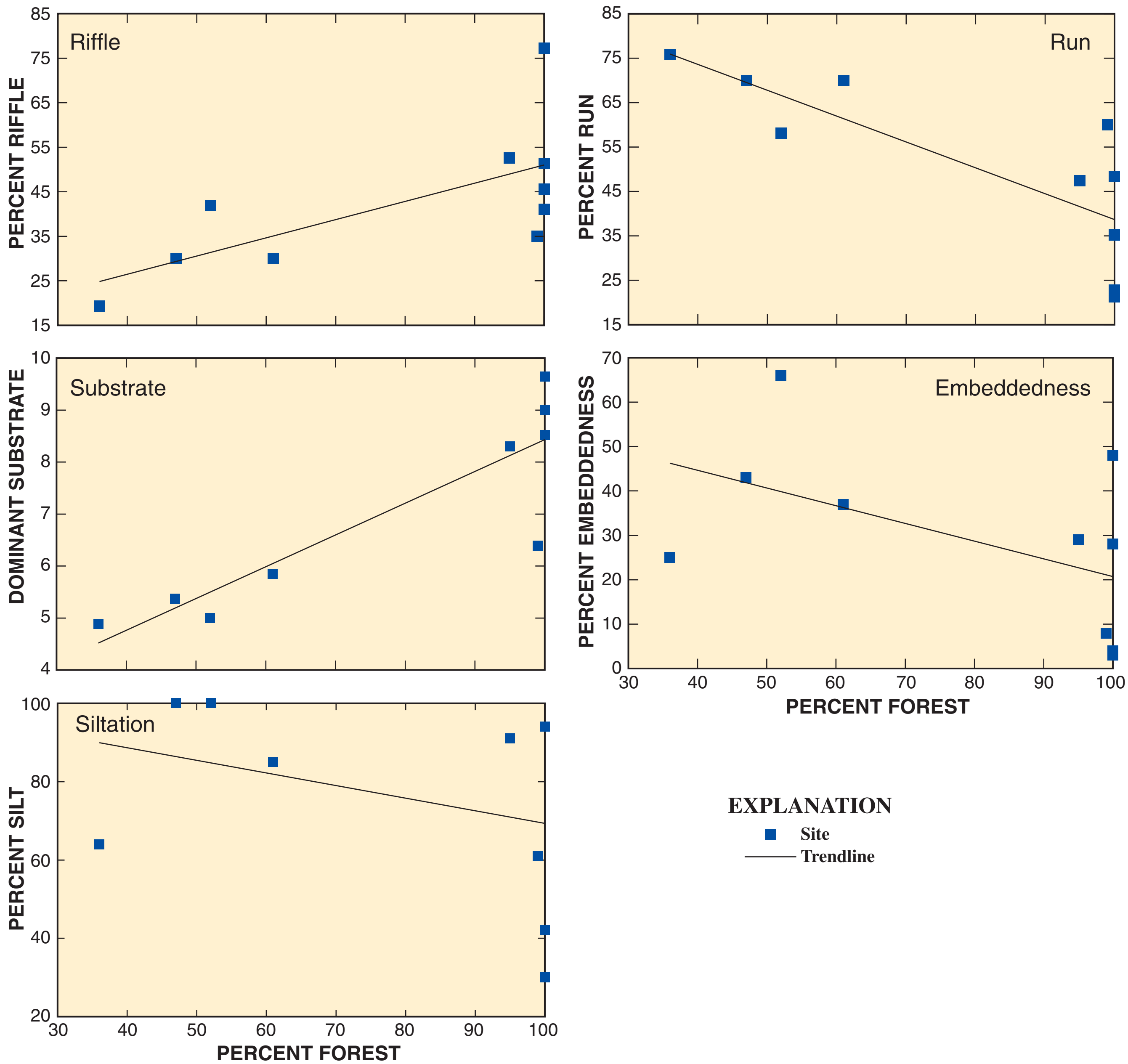


Figure 4. Relation between instream habitat characteristics and percent forested land.

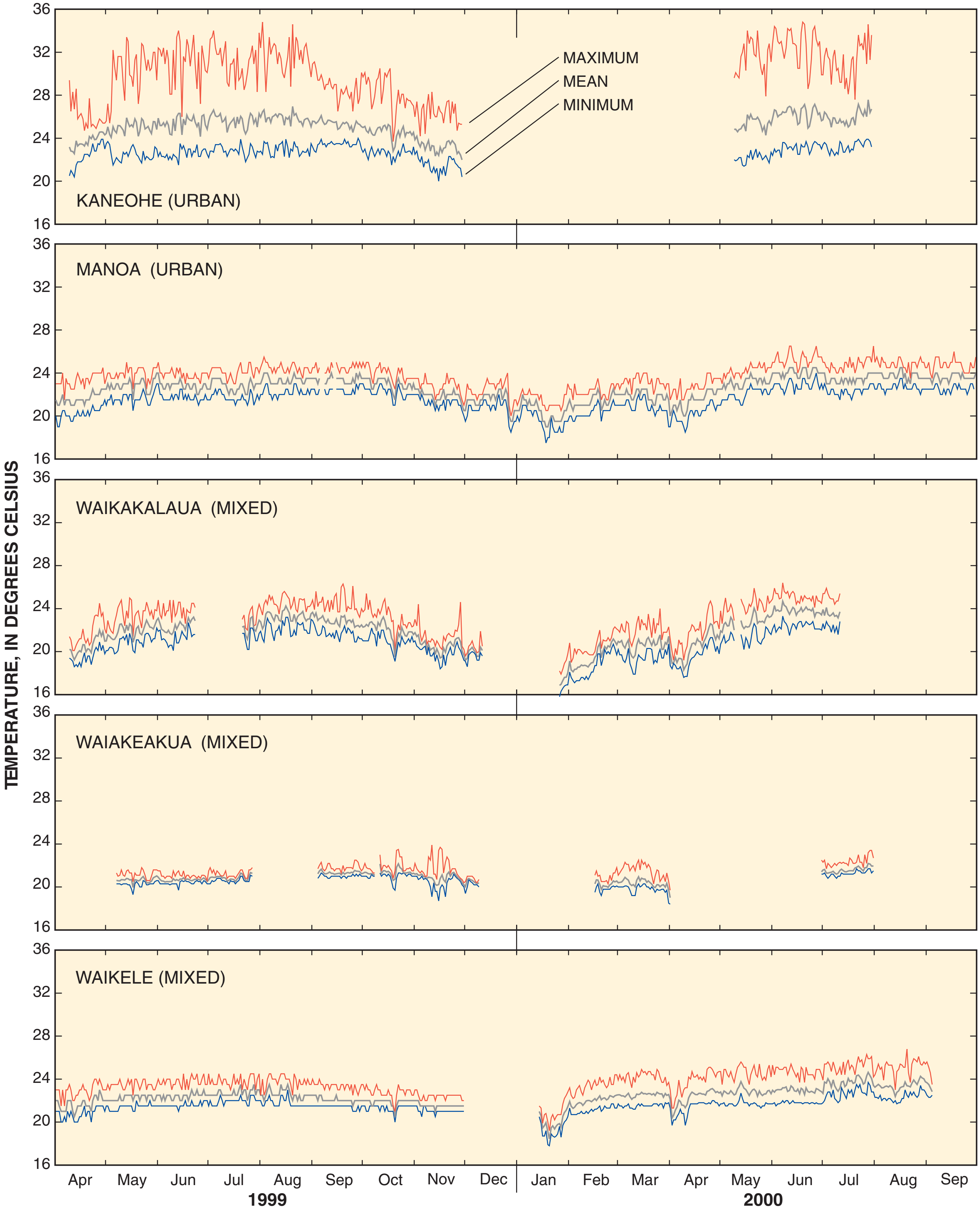


Figure 5. Mean, minimum, and maximum daily water temperature from continuous temperature monitoring at sampling sites.

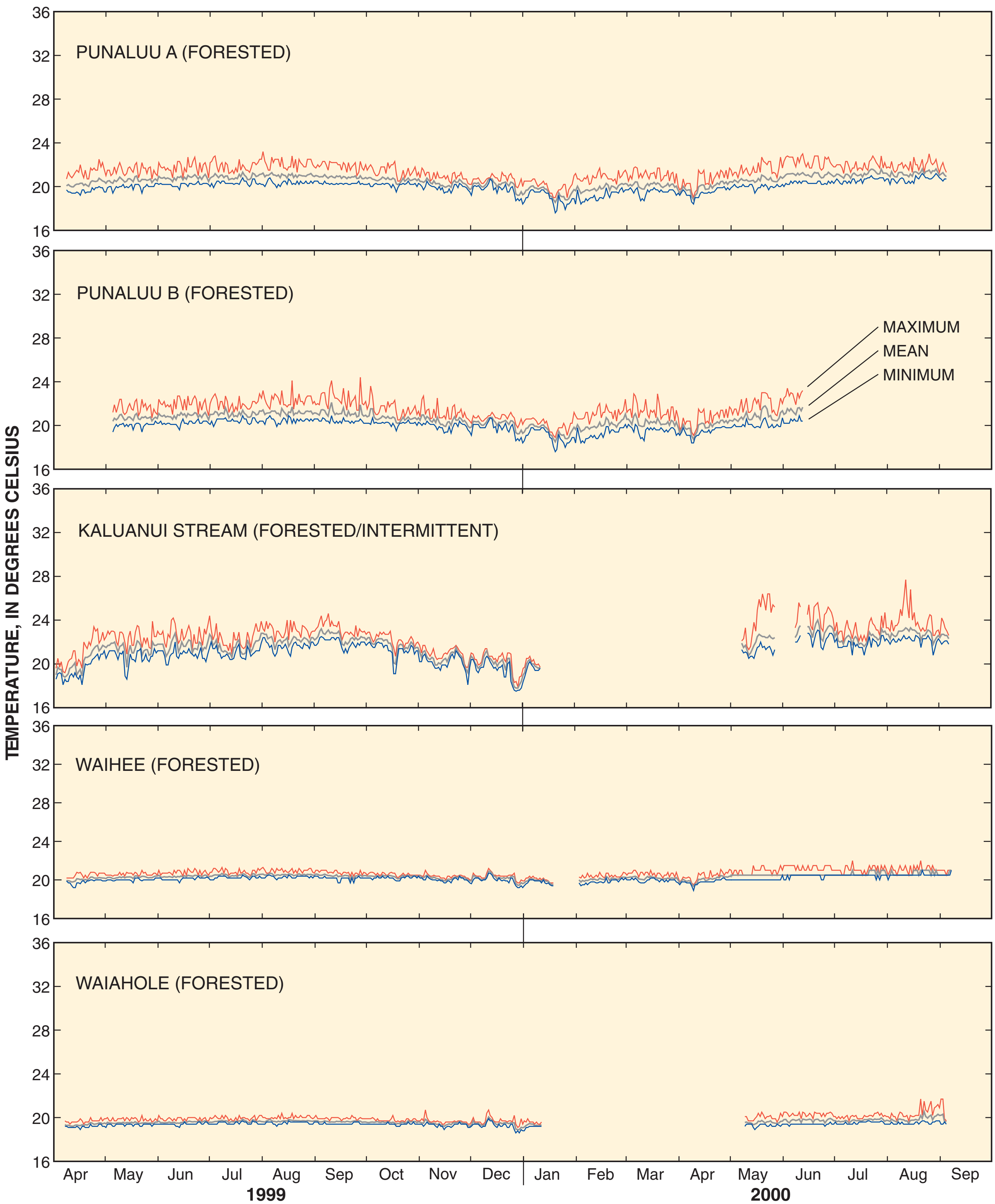


Figure 5. Mean, minimum, and maximum daily water temperature from continuous temperature monitoring at sampling sites—Continued.

two forested sites, Waihee and Waiahole, which are dominated by ground-water contribution had the smallest variation between maximum and minimum daily temperature, the least diurnal variation, and the coolest temperatures overall.

Sites with less than half of the watershed designated as forested typically had less than 55 percent canopy closure (riparian density, measured at stream edge), while those with nearly all of the watershed designated as forested had greater than 75 percent canopy closure. At urban and mixed land-use sites, canopy angles (measured mid-channel) were mostly open (greater than 60 degrees), while at forested sites, canopy angles were mostly closed (less than 30 degrees). Solar radiation (the amount of sunlight reaching the stream) was likewise high at urban and mixed land-use sites and low at forested sites. The mixed land-use site Waikakalaua was an exception to these patterns because it is a relatively narrow stream, and although the banks have sparse riparian vegetation, tall trees form a closed canopy shading the stream. Mean water temperature was strongly associated with riparian vegetation characteristics and was higher at urban and mixed land-use sites (21 – 25°C) than at forested sites (19.5 – 22°C) (fig. 6).

Multivariate techniques were used to examine associations among the habitat (physical and chemical) characteristics measured. Results of a Principal Components Analysis showed clear grouping of the sites (fig. 7) based on environmental characteristics. The first PCA axis accounted for 52 percent of the variance and was largely influenced by variables associated with land use (table 4). Sites plotted on the right side of the ordination were from forested watersheds, those on the left were urban and mixed land-use sites. Streams in the forested watersheds were predominated by riffles and had larger substrate, higher velocities, and closed canopies. Streams at the urban and mixed land-use sites tended to be channelized runs, with higher nutrient concentrations, smaller substrate, and higher temperatures.

Although Waiakeakua (WKEA) is designated as a mixed land-use site because houses line both banks and there is a large nursery upstream, it grouped with the forested sites reflecting the fact that 96 percent of its watershed is forested (fig. 7). Kaluanui (KALU), an intermittent stream, plotted lower than the other forested sites and closer to two mixed land-use sites, Waikakalaua (WKAK) (which also periodically goes dry) and Waikele (WKEL) on the second PCA axis (which accounted for an additional 19 percent of the variance). This separation reflects high levels of silt and embeddedness, and lower concentrations of dissolved oxygen at these three sites.

In general, the transect data at the forested sites showed wider ranges of velocity, depth, and width than at the urban or mixed land-use sites (fig. 8). Waikele Stream, which drains a substantially larger basin than any of the other study reaches, had the widest channel width, and on average was deeper than all but the most undisturbed forested site, Punaluu Stream above the diversion (PUNA). However, depths at Waikele Stream were likely underestimated due to inaccessibility in the deeper parts (>2 meters) of the stream channel.

Table 4. Eigenvalues and variable loadings for the Principal Components Analysis

[Values in bold had the highest contributions to the loading on a particular axis]

Eigenvalue		
	Axis 1	**Axis 2**
Eigenvalues	4.66	1.75
Percentage	51.81	19.44
Cumulative percentage	51.81	71.25
PCA variable loadings		
	Axis 1	**Axis 2**
Depth	0.083	-0.549
Velocity	0.251	0.109
Run	-0.404	0.058
Embeddedness	-0.306	-0.483
Substrate	0.407	-0.107
Forest	0.440	-0.011
Temperature	-0.381	0.223
Nitrogen	-0.386	0.149
Oxygen	0.140	0.605

Invertebrate Community Structure

For purposes of analysis, taxa were designated either as native, nonnative (introduced), or undetermined. The undetermined category consists of the invertebrate identifications that could not clearly be designated as either native or introduced. The invertebrate taxa observed in both the qualitative and quantitative samples consisted predominantly of introduced species. A total of 75 taxa were collected combining both the qualitative and quantitative samples from the 10 sampling sites (appendix B). Of these, 47 percent were introduced, 5 percent were native, and the remaining 48 percent were undetermined (table 5).

A total of 54 taxa were collected from all sites combined as part of the quantitative sampling. Forty-three percent were designated as introduced, 6 percent were native,

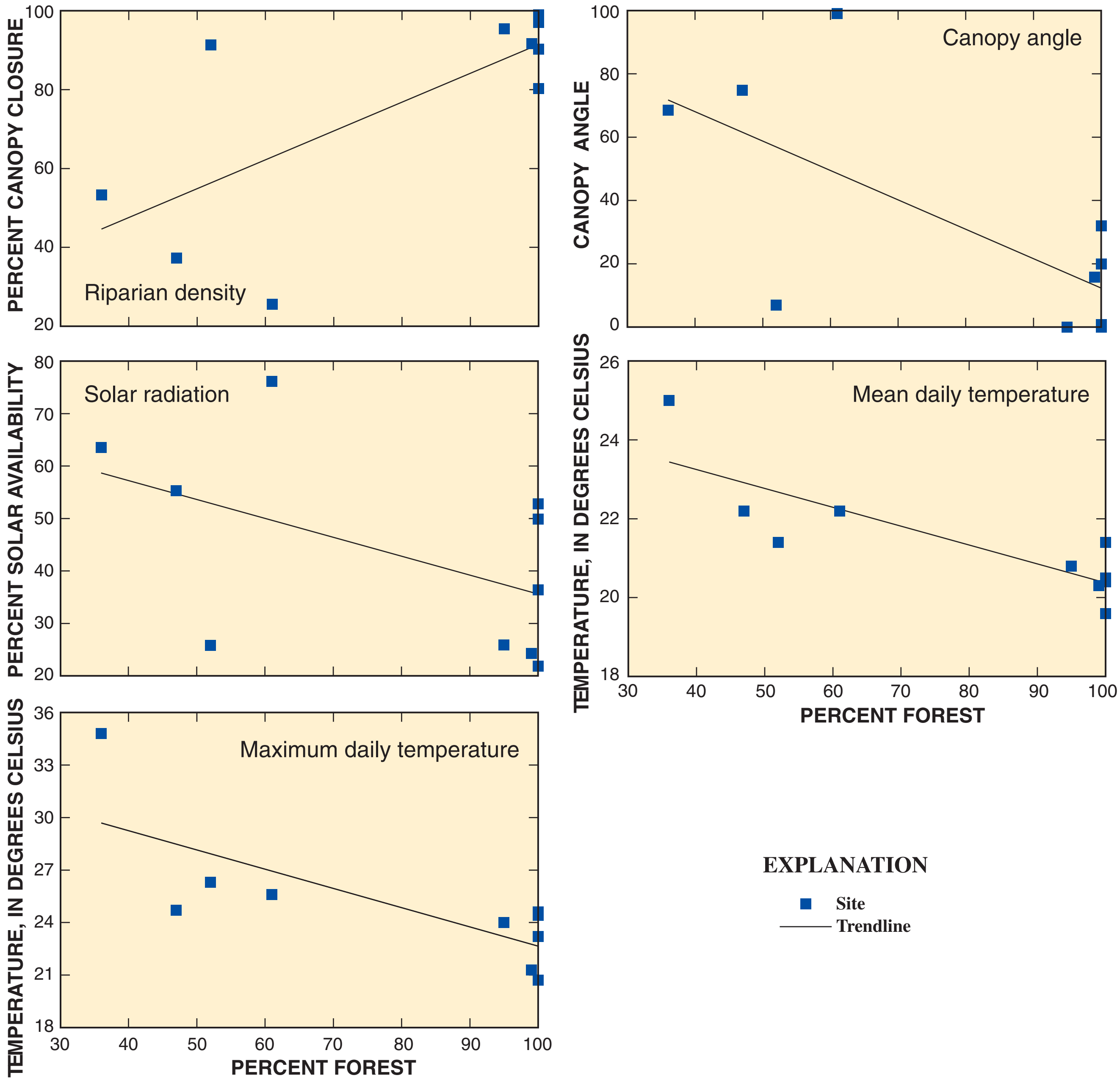


Figure 6. Relation between riparian characteristics, water temperature, and percent forested land.

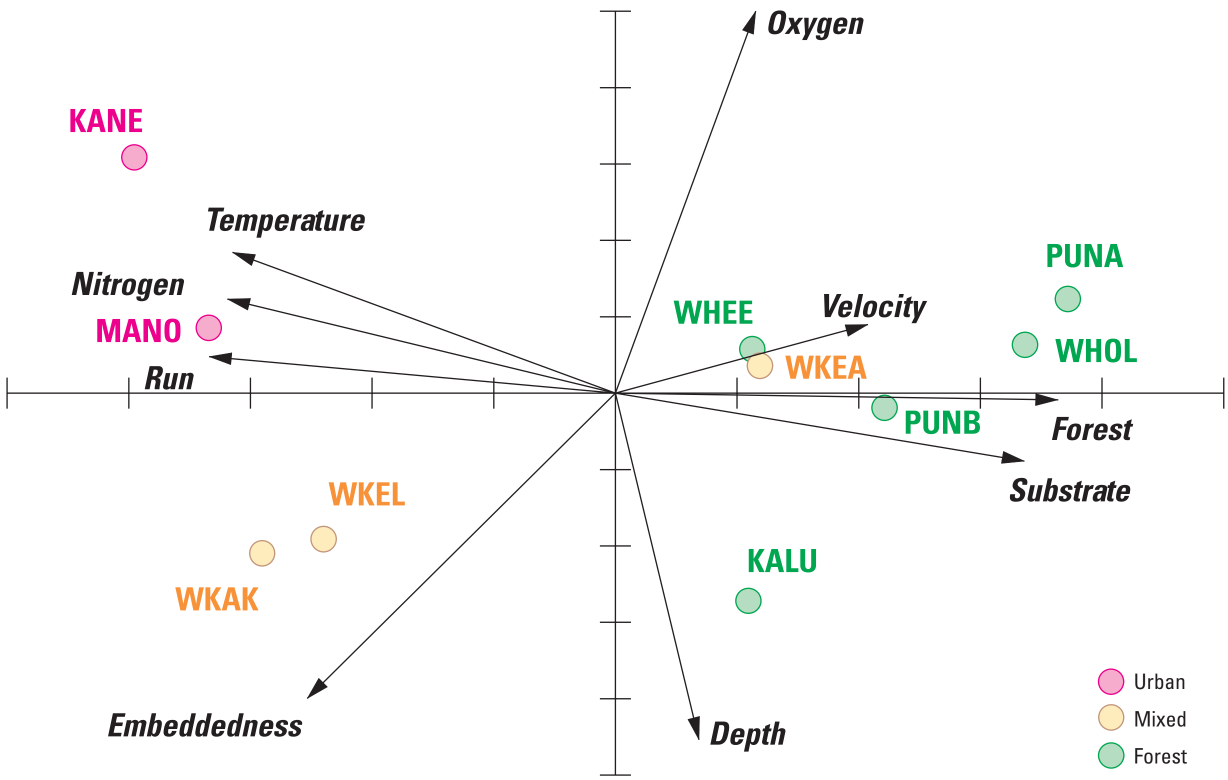


Figure 7. Principal Components Analysis of habitat variables at sampling sites.

and 52 percent were undetermined. Sixty-four taxa were collected from all sites combined as part of the qualitative sample. Forty-eight percent were designated as introduced, 3 percent were native, and 48 percent were undetermined. The phyla Nematoda (roundworms), Nemertea (proboscis worms), Platyhelminthes (flatworms), and Porifera (sponges) were entirely designated as undetermined.

Larval Trichoptera (caddisfly)

Table 5. Status (native, introduced, or undetermined) of invertebrates at sampling sites, Oahu, Hawaii

[n, number of taxa identifications to lowest possible determination]

Site	Total n	Percent native (n)	Percent introduced (n)	Percent undetermined (n)
MANO	20	5 (1)	50 (10)	45 (9)
KANE	41	2 (1)	51 (21)	46 (19)
WKEL	19	5 (1)	42 (8)	53 (10)
WKAK	38	5 (2)	40 (15)	55 (21)
WKEA	22	9 (2)	18 (4)	73 (16)
KALU	20	5 (1)	30 (6)	65 (13)
WHEE	18	6 (1)	56 (10)	39 (7)
WHOL	19	5 (1)	47 (9)	47 (9)
PUNB	23	0 (0)	35 (8)	65 (15)
PUNA	22	0 (0)	55 (12)	46 (10)
Total	75	5 (4)	47 (35)	48 (21)

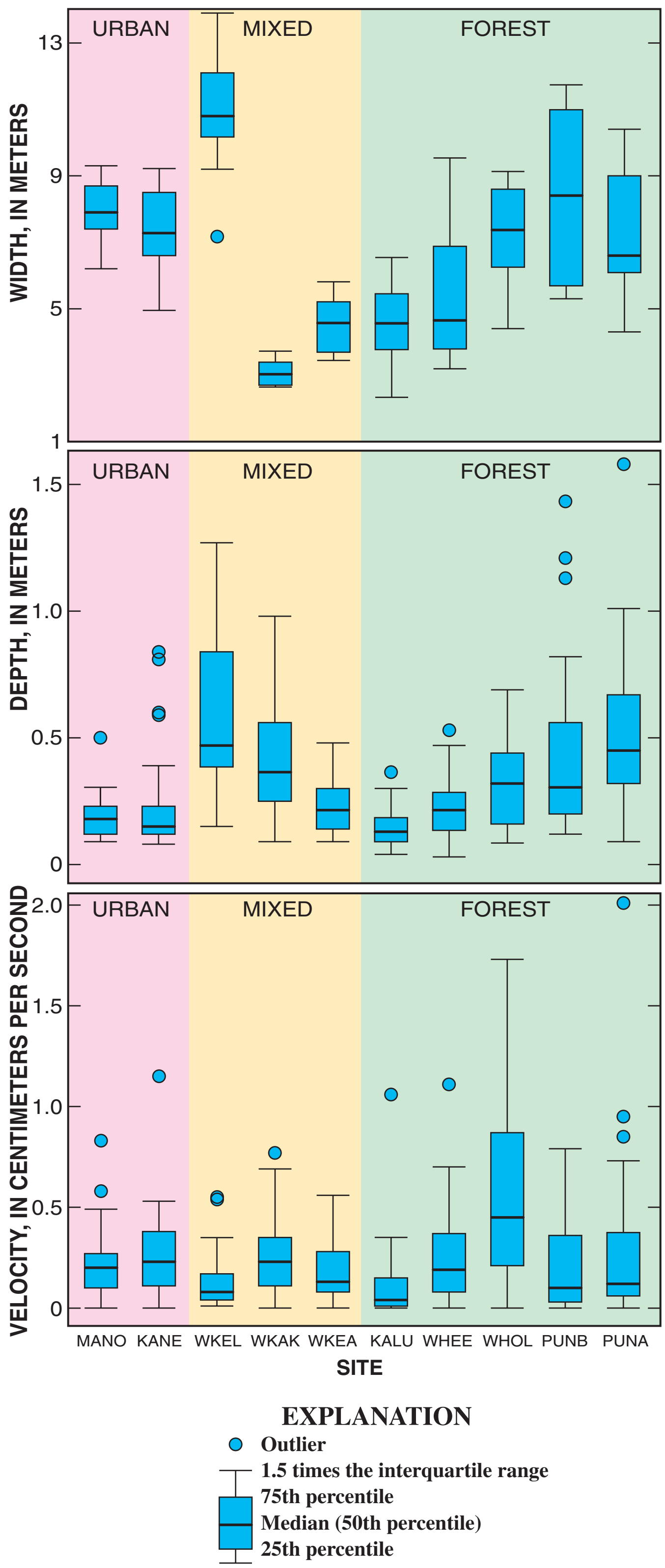


Figure 8. Selected stream characteristics at transects.

At each site there were 11 transects, except for Waikele (WKEL), where there were 9 transects. Across each transect 3 measurements were made of depth and velocity.

For all sites except Punaluu above the diversion (PUNA), quantitative samples included more (mean of 79 percent including PUNA) of the total number of taxa collected than the qualitative samples (mean of 61 percent, including PUNA) at a given site (table 6). Likewise, at all sites except PUNA, quantitative samples contained more species (mean of 39 percent including PUNA) not found in the qualitative sample than vice-versa (mean of 21 percent including PUNA). At all sites combined, out of the total number of taxa collected (75), there were 11 taxa unique to the quantitative samples and 21 taxa unique to the qualitative samples.

Table 6. Comparison of qualitative and quantitative samples, percent of the total species at a given site, and of the number of species collected with one sampling method but not the other (percent unique)

[n, number of taxa]

Site	Total n	Percent qualitative (n)	Percent quantitative (n)	Percent qualitative unique (n)	Percent quantitative unique (n)
MANO	20	60 (12)	85 (17)	15 (3)	40 (8)
KANE	41	63 (26)	68 (28)	32 (13)	37 (15)
WKEL	19	37 (7)	95 (18)	5 (1)	63 (12)
WKAK	38	71 (27)	76 (29)	24 (9)	29 (11)
WKEA	22	46 (10)	82 (18)	18 (4)	55 (12)
KALU	20	55 (11)	85 (17)	15 (3)	45 (9)
WHEE	18	67 (12)	78 (14)	22 (4)	33 (6)
WHOL	19	68 (13)	79 (15)	21 (4)	32 (6)
PUNB	23	52 (12)	87 (20)	13 (3)	48 (11)
PUNA	22	91 (20)	55 (12)	46 (10)	9 (2)
Mean	24	61 (15)	79 (19)	21 (5)	39 (9)
Total	75	85 (64)	72 (54)	28 (21)	15 (11)

Two orders of insects, Diptera and Trichoptera, were the dominant insect groups collected during invertebrate sampling. None of the dipterans nor trichopterans were identified as native. Seven new State records of introduced stream insects were reported (at the genus level) during this study. Six of the new records were in the dipteran family Chironomidae (Wolff and others, 2002). Chironomids are non-biting midges that resemble mosquitoes in appearance. There are as many as 15,000 species of Chironomidae worldwide (Merritt and Cummins, 1984). One new State record was in the insect order Trichoptera (caddisflies), in the family Hydroptilidae. There are about 170 species of Hydroptilidae in North America (Merritt and Cummins, 1984).

Although a number of native molluscs occur in Hawaii (including neritid limpets and lymnaeid snails), they tend to inhabit the more pristine streams, and none were collected during this study. The most abundant molluscs collected were pan-tropical thiarid snails, the introduced clam *Corbicula fluminea*, and the limpet *Ferrissia* *sharpi* (Sykes) whose origin is currently uncertain (R.H. Cowie, University of Hawaii, oral commun., 2003).

Two native and four introduced species of Crustacea were collected during our surveys. Both of the native species (*Atyoida bisulcata* Randall and *Macrobrachium grandimanus*) and one of the introduced species, *Macrobrachium lar* (Fabricius), are amphidromous and spend their larval life-stage in the ocean.

Manoa Stream

The Manoa Stream sampling site (fig. 9) is located in the Honolulu area of Oahu at an altitude of about 38 ft and has a drainage area of about 6 mi^2. The upper 61 percent of the drainage is largely forested land and the lower is 38 percent urban and 1 percent agriculture (table 1). A continuous record of streamflow has been collected at this site since January 1999. This site was also part of the NAWQA surface-water network for water-column studies during the period March 1999 through February 2001.

Manoa Stream drains the largely residential community of Manoa Valley (which includes the University of Hawaii) and discharges into the Ala Wai Canal. Upstream of the site, the University diverts water for ornamental fishponds and experimental taro patches. Downstream of the site, the stream channel is highly modified for flood control. Five water-development tunnels were excavated in the valley of Waiakeakua Stream, the easternmost tributary of Manoa Stream, in the 1920s (Stearns and Vaksvik, 1935) and several additional tunnels have been excavated elsewhere in the Manoa watershed. Currently, one water-development tunnel in Waiakeakua Valley is in operation.

The Manoa Stream site is typical of an urban Oahu stream. The stream channel is artificially widened and stabilized with concrete and stone with sparse riparian vegetation scattered along the cemented banks. The water is very shallow (mean depth at the site of 0.19 m) with small substrate and high levels of silt (silt was present at 85 percent of the instream habitat measurement locations) and embeddedness.

Insects accounted for half of the total invertebrate abundance at Manoa Stream. Dipterans (55 percent) and trichopterans (45 percent) were the only insects collected. Nonnative thiarid snails are commonly found in urban Oahu streams, and contributed 33 percent of the total invertebrate abundance at Manoa. The introduced amphipod *Hyalella* sp. made up another 7 percent of the total invertebrate abundance.

Kaneohe Stream

The Kaneohe Stream sampling site (fig. 10) is in an urban area of windward Oahu at an altitude of about 40 ft and has a drainage area of about 5 mi^2. The upper 36 percent of the drainage is largely forested and the lower is 62 percent urban and 3 percent agriculture (table 1). The sampling site is near the terminal reach of Kaneohe Stream which flows through the town of Kaneohe. Upstream, the channel is concrete lined and the typical flow consists of a thin sheet of water. Mean water depth at the site was only 0.24 m. Downstream of the site the waterway meanders, deepens, and empties into Kaneohe Bay. Flow into Kaneohe Stream is regulated by a flood control reservoir, Waimaluhia, which was built in response to heavy flooding in Kaneohe during the 1960s (Wong, 2001).

The stream channel at this site on Kaneohe Stream has been modified, with mounds of rocks and concrete debris along most of the banks. The streambed substrate is predominantly gravel. Macrophyte beds of the introduced aquarium plant *Elodea* are scattered throughout the reach. Density of riparian vegetation is sparse to moderate and the canopy over the stream channel is completely open. High densities of introduced fish were observed at this site during field work for this study.

Molluscs were the most numerous invertebrates collected, accounting for 41 percent of the total invertebrate abundance. Insects accounted for an additional 35 percent of the total invertebrate abundance, with trichopterans composing 55 percent and dipterans 41 percent of the total insect abundance. An introduced freshwater sponge (Porifera) was found on the underside of many of the rocks at this site. The mayfly (Ephemeroptera) *Caenodes nigropunctatum* (Klapálek) was also collected at this site. This introduced mayfly species has recently been found at other windward Oahu locations including Waimanalo Stream (Smith, 2000) and Kawainui Marsh (Brasher and Wolff, personal observation).

Waikele Stream

Waikele Stream (altitude of about 1 ft) in central Oahu (fig. 11) has the largest drainage area (about 47 mi^2) of the sampling sites. The upper 47 percent of the drainage is largely forested land. The lower 53 percent of the drainage consists of agricultural (25 percent) and urban (28 percent) land use (table 1). A continuous record of streamflow has been collected at this site since 1960. This site was also part of the NAWQA surface-water network for water-column studies during the period

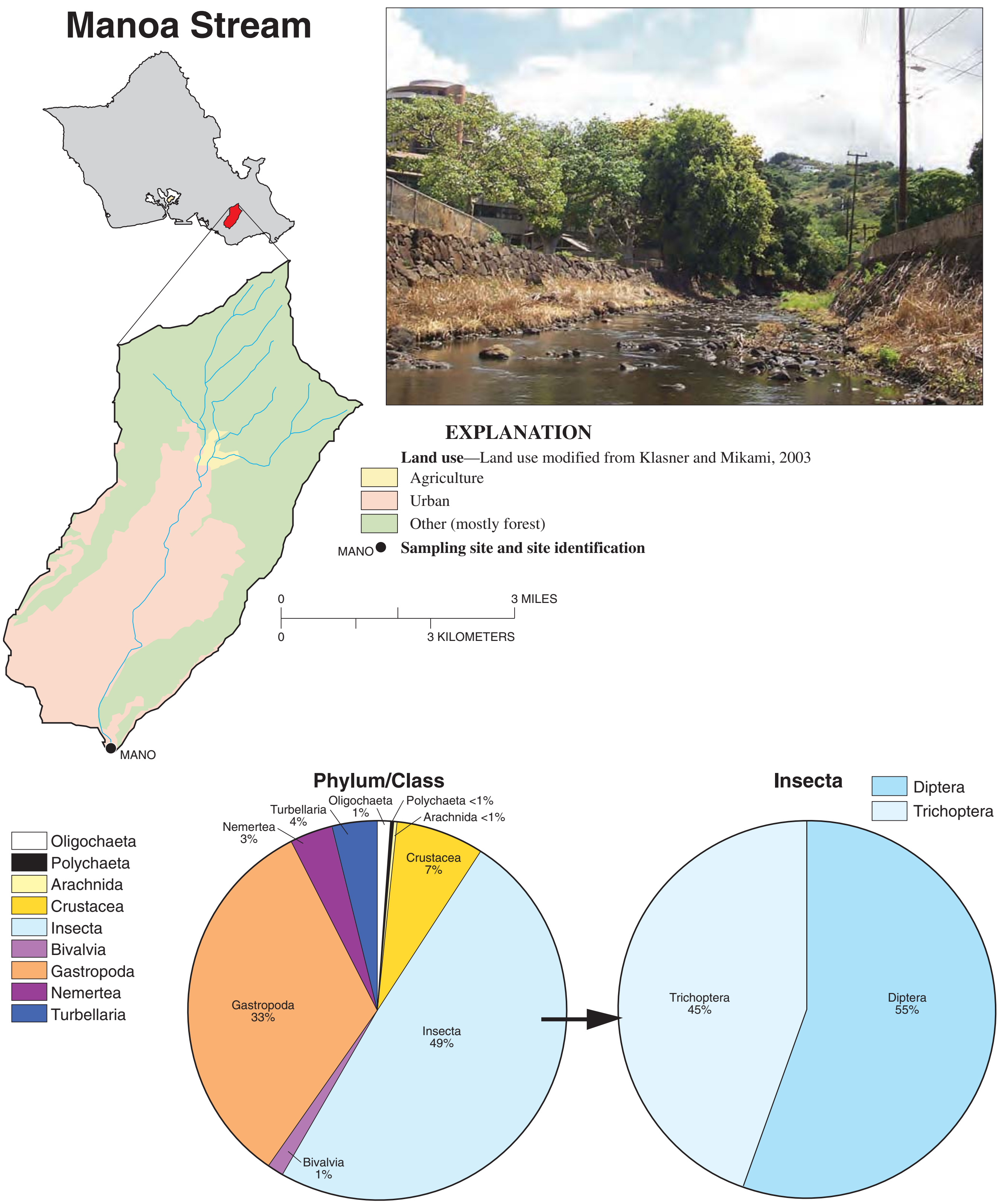


Figure 9. Manoa Stream and relative abundances of key invertebrates.

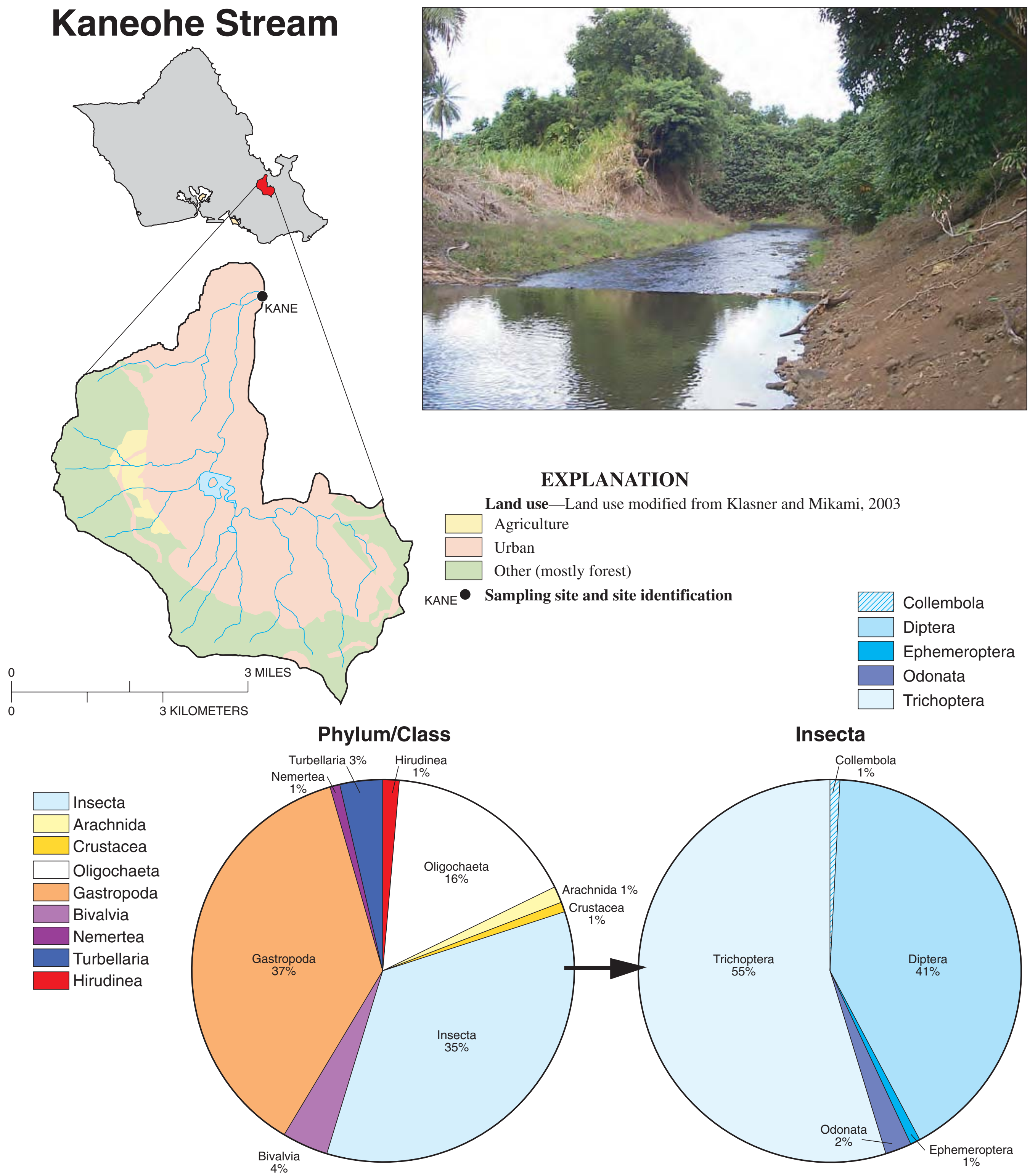


Figure 10. Kaneohe Stream and relative abundances of key invertebrates.

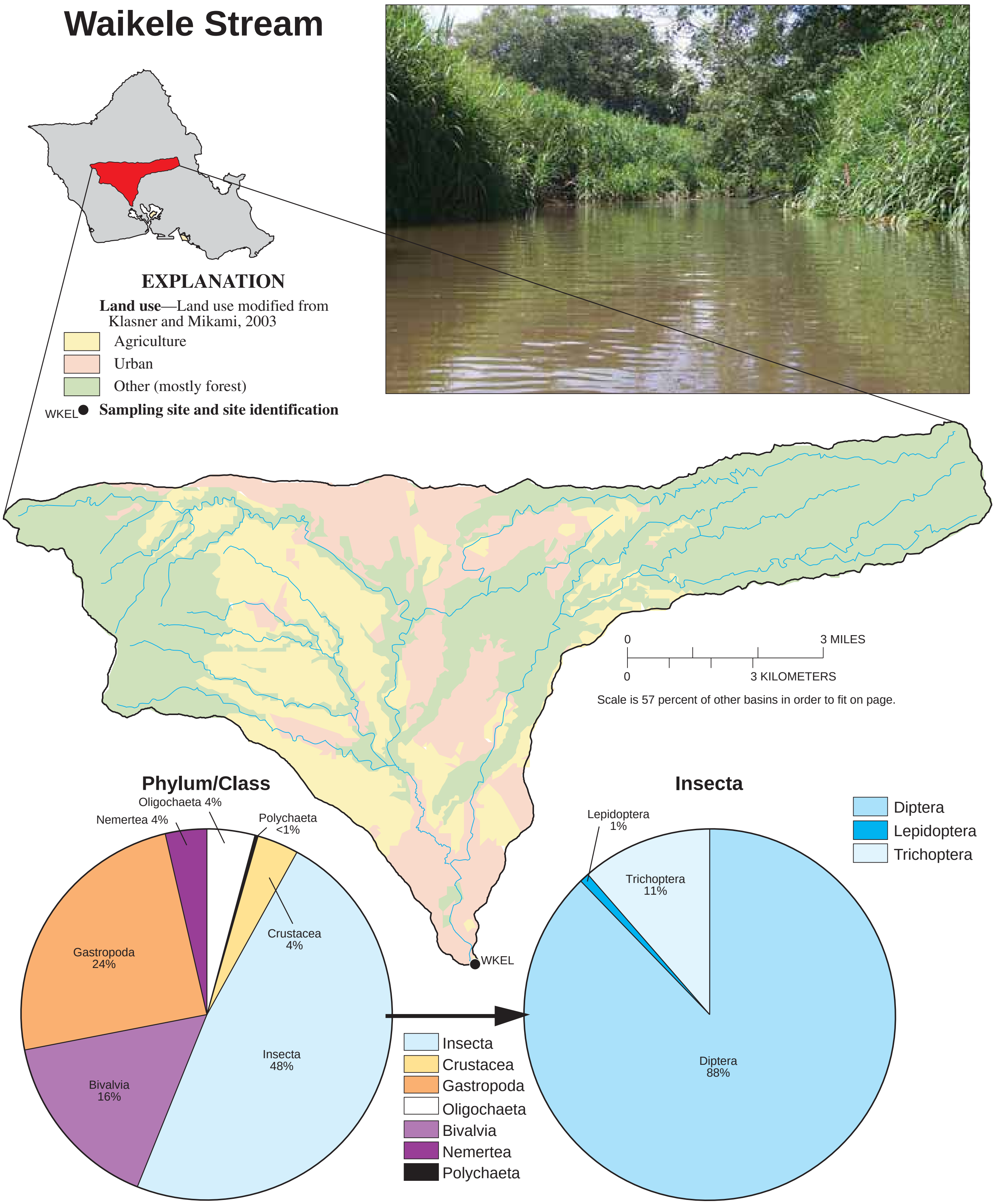


Figure 11. Waikele Stream and relative abundances of key invertebrates.

March 1999 through February 2001. Several large springs that discharge ground water upstream of the Waikele sampling site provide most of the base flow in the lower reaches.

The Waikele sampling site is located near the mouth of Waikele Stream, and is influenced by oceanic tides immediately downstream of the site. This site had the largest estuarine influence among the sampling sites. In the past, water was diverted from Waikele Stream upstream of the site and from a pool adjacent to the site for sugarcane irrigation and sugar mill operations. Wastewater from the mill was then returned to the stream about 1 mi upstream of the sampling site until the mid-1990's. Effluent from a wastewater treatment plant was discharged into Kipapa Stream, a tributary to Waikele, until 1984 (Tomlinson and Miller, in press).

The drainage basin upstream of the sampling site is a mixture of residential, commercial, agricultural, and military land uses. Land use within the Waikele basin has changed dramatically over the past 25 years, with agricultural land decreasing from 41 percent to 25 percent, while urban land use increased from 14 percent to 28 percent (Klasner and Mikami, 2003). Directly downstream of the site, the stream channel is lined with concrete supporting the Farrington Highway Bridge. The channel then meanders through a labyrinth of mangrove (*Rhizophora mangle*), and drains into the West Loch of Pearl Harbor. Habitat conditions at this reach are characterized by open canopy, relatively deep water (mean depth at the site of 0.57 m), small substrate size, and high levels of silt (silt was present at 100 percent of the instream habitat measurement locations). Dense stands of invasive California grass (*Brachiaria mutica*) line the banks.

Insects, primarily dipterans (88 percent of the insect abundance), accounted for 48 percent of the invertebrate abundance at Waikele Stream. Molluscs accounted for an additional 40 percent of the invertebrate abundance. Thirty-nine percent of the molluscs were the introduced clam *Corbicula fluminea*, 59 percent were thiarid snails, and the remainder were the limpet *Ferrissia sharpi*. Earthworms (oligochaetes), flatworms (Nemertea) and crustaceans each accounted for 4 percent of the total invertebrate abundance.

Waikakalaua Stream

This site on Waikakalaua Stream (fig. 12) is located in central Oahu at an altitude of about 540 ft and has a drainage area of about 7 mi^2. The lower 40 percent of the drainage is urban, and includes military land. The upper 59 percent includes agricultural (7 percent) and forested (52 percent) land (table 1). Annual maximum discharge has been measured at this site since 1958. Waikakalaua Stream is a tributary of Waikele Stream. Streamflow is perennial at the study reach but intermittent at lower elevations before the confluence with Waikele Stream.

At the study reach, which is bordered by a highway on one side and a military base on the other, the stream channel has been dredged and widened. Although trees along the banks create a closed canopy (mean canopy closure 92 percent), the stream banks were highly eroded with sparse vegetative cover. The streambed substrate consisted primarily of silt and clay with a few embedded boulders.

Invertebrate diversity was high in Waikakalaua Stream. Insects accounted for 46 percent of the invertebrate abundance, and 70 percent of the insects were dipterans. Introduced gastropods (snails) accounted for 29 percent, and oligochaetes (earthworms) for another 18 percent of the total invertebrate abundance. Mites (Arachnida), polychaete worms, and flatworms (Nemertea) each accounted for 2 percent of the total invertebrate abundance.

Waiakeakua Stream

The Waiakeakua Stream site (fig. 13) is located in the Honolulu area of Oahu at an altitude of about 295 ft and has a drainage area of about 1 mi^2. The upper 96 percent of the drainage is largely forested and the lower is 4 percent agriculture (nursery farming) (table 1). This 4 percent non-forested land use in the lower basin resulted in Waiakeakua being designated as a mixed land-use site. A continuous record of streamflow has been collected at this site from May 1913 to January 1921, and August 1925 to present. Waiakeakua Stream is a tributary of Manoa Stream and is part of the Ala Wai Canal watershed.

Habitat characteristics at Waiakeakua Stream are typical of a forested Oahu stream. There is dense riparian vegetation and closed canopy (mean canopy closure 95 percent), a boulder and cobble substrate, and moderately cool water temperatures (mean daily temperature 20.8°C). However, houses line both sides of the bank, and the county regularly clears the riparian vegetation at the site. Waiakeakua had low invertebrate abundance (total number of individuals) and relatively low diversity. Insects made up 93 percent of the total invertebrate abundance, and 94 percent of the insects were trichopterans. Only one or two individuals were collected in five different classes of invertebrates: Polychaeta (two), Arachnida

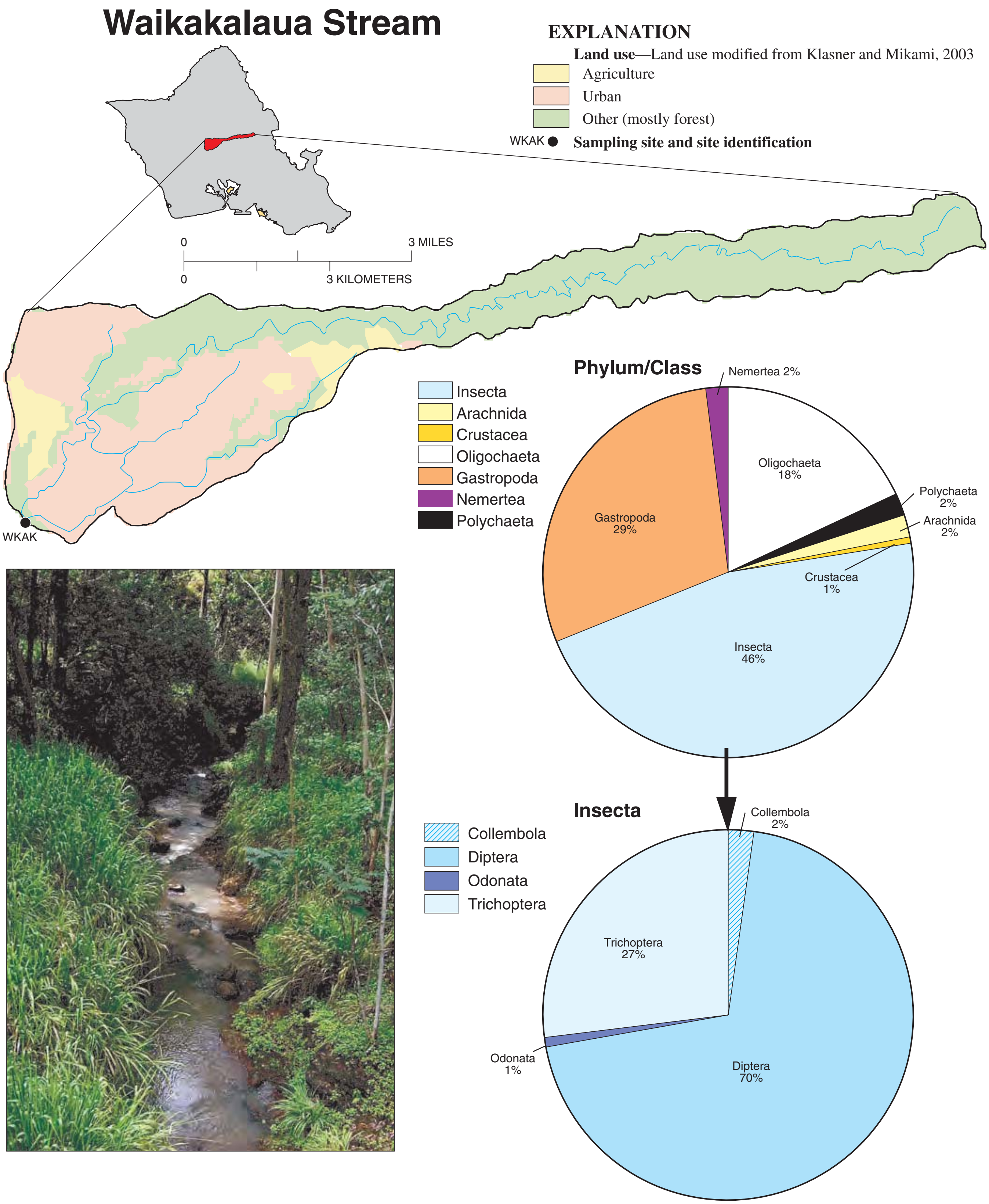


Figure 12. Waikakalaua Stream and relative abundances of key invertebrates.

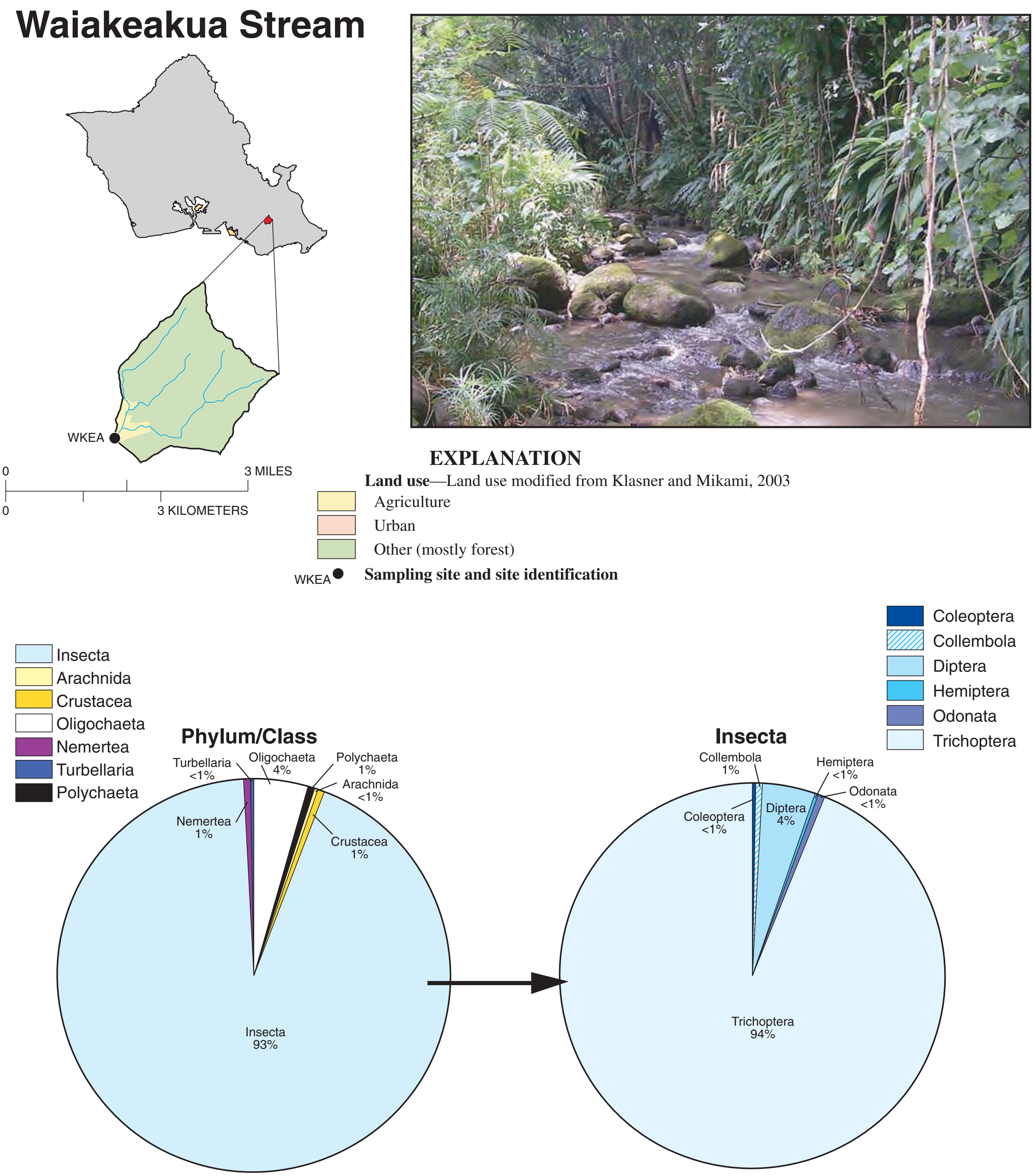


Figure 13. Waiakeakua Stream and relative abundances of key invertebrates.

(one), Crustacea (two), Nemertea (two) and Turbellaria (one).

Kaluanui Stream

The Kaluanui Stream site (fig. 14) is located in windward Oahu at an altitude of about 110 ft and has a drainage area of about 1 mi^2, which is classified as 100 percent forested (table 1). A continuous record of streamflow has been collected at this site since 1967. This site has intermittent flow, and the reach is known to occasionally dry out completely. Because of this, the site at Kaluanui had certain habitat characteristics such as high siltation (silt was present at 94 percent of the instream habitat measurement locations) that were more similar to the urban and mixed land-use sites than to the other forested sites. Kaluanui also had the lowest mean depth (0.15 m vs. 0.35 m at all of the other sites combined) and velocity (0.12 cm/sec vs. the mean at all the other sites of 0.27 cm/sec) of any of the sites sampled.

As do the other forested sites on Oahu, Kaluanui has dense riparian vegetation. The canopy is closed by interweaving branches of hau (*Hibiscus tiliaceus*). Thick mats of macro-algae cover the boulders and cobbles of the streambed. Oligochaetes (earthworms) of the family Naididae were the predominant invertebrates collected at Kaluanui, accounting for 77 percent of the overall invertebrate abundance. Insects accounted for an additional 22 percent. Eighty-two percent of the insects were dipterans.

Waihee Stream

The site on Waihee Stream (fig. 15) in windward Oahu is located at an altitude of about 170 ft and has a drainage area of about 1 mi^2, of which 99 percent is forested land and 1 percent is classified as urban (table 1). Land use downstream of the site is a mixture of rural residential and small-scale agricultural. A continuous record of streamflow has been collected at this site since 1974. This site was also part of the NAWQA surface-water network for water-column studies during the period March 1999 through February 2001. Surface-water flow at this site is dominated by ground-water input. A water-development tunnel was installed in 1955 at the headwaters to provide water for domestic supply. Because ground-water withdrawals affect surface-water quantity in the basin, the water withdrawn from the tunnel and wells is regulated to maintain an instream flow of 4.2 ft^3/s [Charles F. Reppun vs. Board of Water Supply, City and County of Honolulu, 65 Haw. 531 (1982): p. 531–565].

Waihee Stream is a typical forested Oahu stream. Riparian vegetation lines the stream bank and tree limbs form closed canopies that reduce the amount of sunlight reaching the stream. Reduced sunlight and the predominant ground-water input result in cool water temperatures with comparatively little diurnal water temperature variation (a mean difference of 3.4°C between daily minimum and maximum temperatures vs. mean difference of 7.3°C for all of the other sites combined). The unmodified stream channel has a substrate of mainly boulders and large cobbles, with moderate water velocity and moderate siltation (silt was present at 61 percent of the instream habitat measurement locations) and embeddedness.

Insects accounted for 88 percent of the total invertebrate abundance at Waihee Stream. Turbellaria (flatworms) made up an additional 8 percent and Oligochaeta (earthworms) 4 percent of the total invertebrate abundance. Trichopterans accounted for 72 percent of the insects and dipterans for 28 percent.

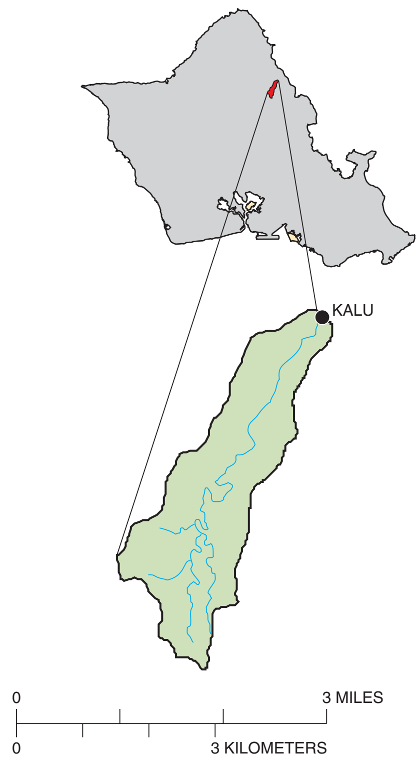
Waiahole Stream

The Waiahole Stream site (fig. 16) is located in windward Oahu at an altitude of about 210 ft and has a drainage area of about 1 mi^2. The drainage is 100 percent forested (table 1). Waiahole Stream has been diverted since construction of the Waiahole Ditch and Tunnel System that began in 1913. Surface water and dike-impounded ground water are diverted from the windward side to the leeward side of the island for agricultural irrigation.

In April 2001, the Hawaii State Commission on Water Resource Management (CWRM) adopted an Interim Instream Flow Standard for Waiahole Stream that added 4.8 Mgal/d to the existing base flow (following diversion) of 3.9 Mgal/d for a total of 8.7 Mgal/d (Miike, L.H., 2001[Minute order number 85]). To mitigate for variability of streamflow and off-stream demand on the leeward side, the CWRM amended the instream flow standard to allow the further diversion of 2.1 Mgal/d (for 5 non-consecutive days of each month).

Since an initial return of water to Waiahole Stream in 1995, the streamflow has increased, but is also extremely variable because of fluctuations in the release of water to accommodate the off-stream demand on the leeward side (R.A. Fontaine, U.S. Geological Survey, oral commun., 2002). Human controlled variability of instream flow does not necessarily replicate the natural variability of streamflow. Together, the relatively recent return of flow and the non-natural variability of the streamflow

Kaluanui Stream



EXPLANATION

Land use—Land use modified from Klasner and Mikami, 2003
- Agriculture
- Urban
- Other (mostly forest)

KALU ● **Sampling site and site identification**

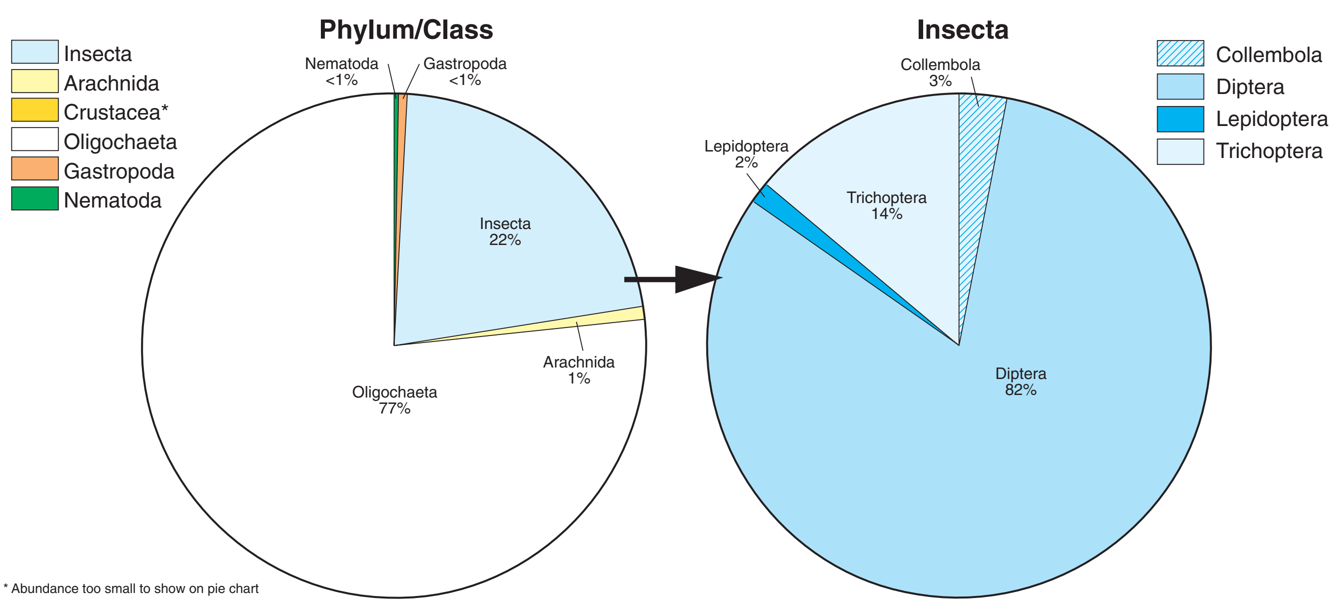


Figure 14. Kaluanui Stream and relative abundances of key invertebrates.

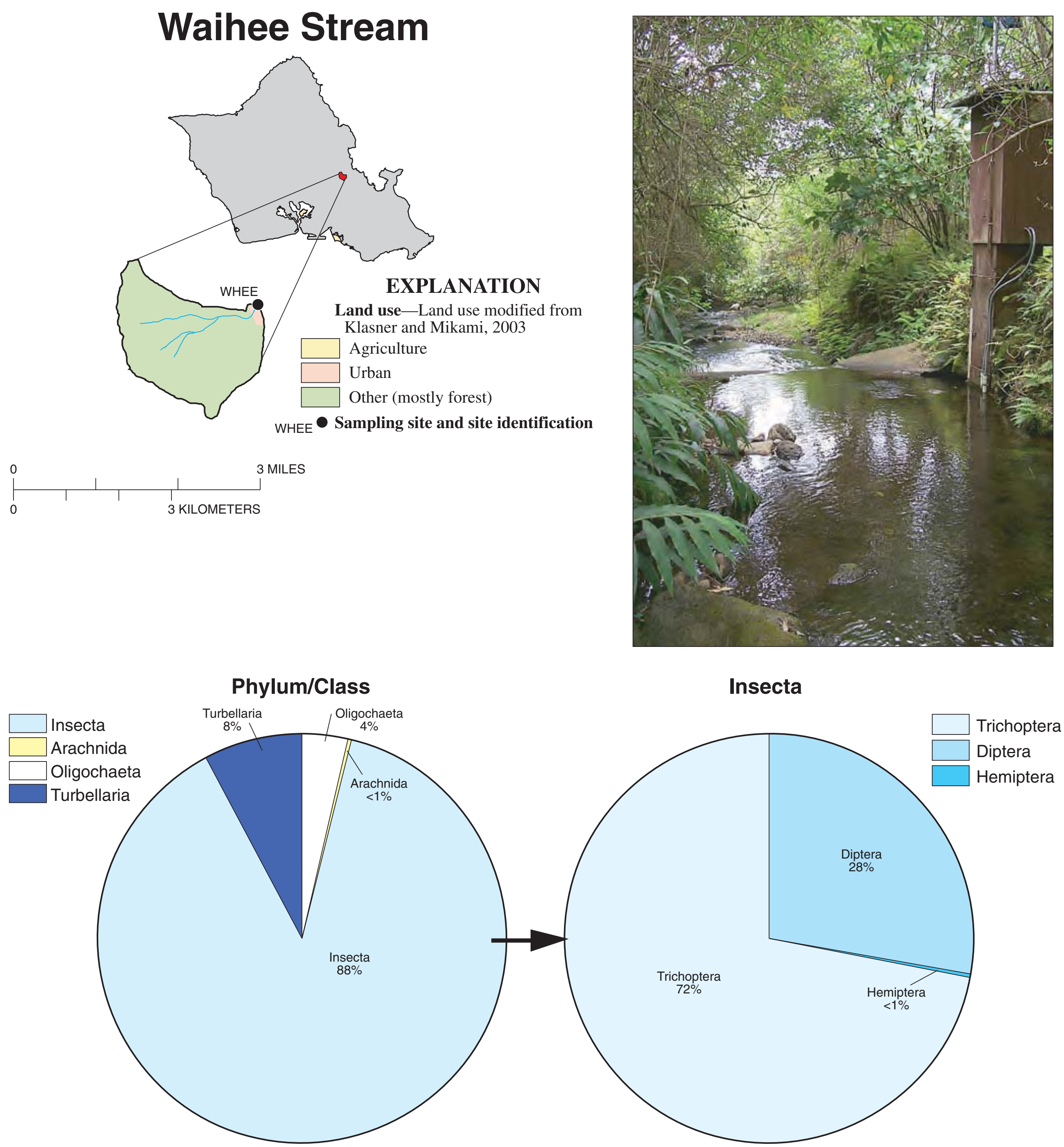


Figure 15. Waihee Stream and relative abundances of key invertebrates.

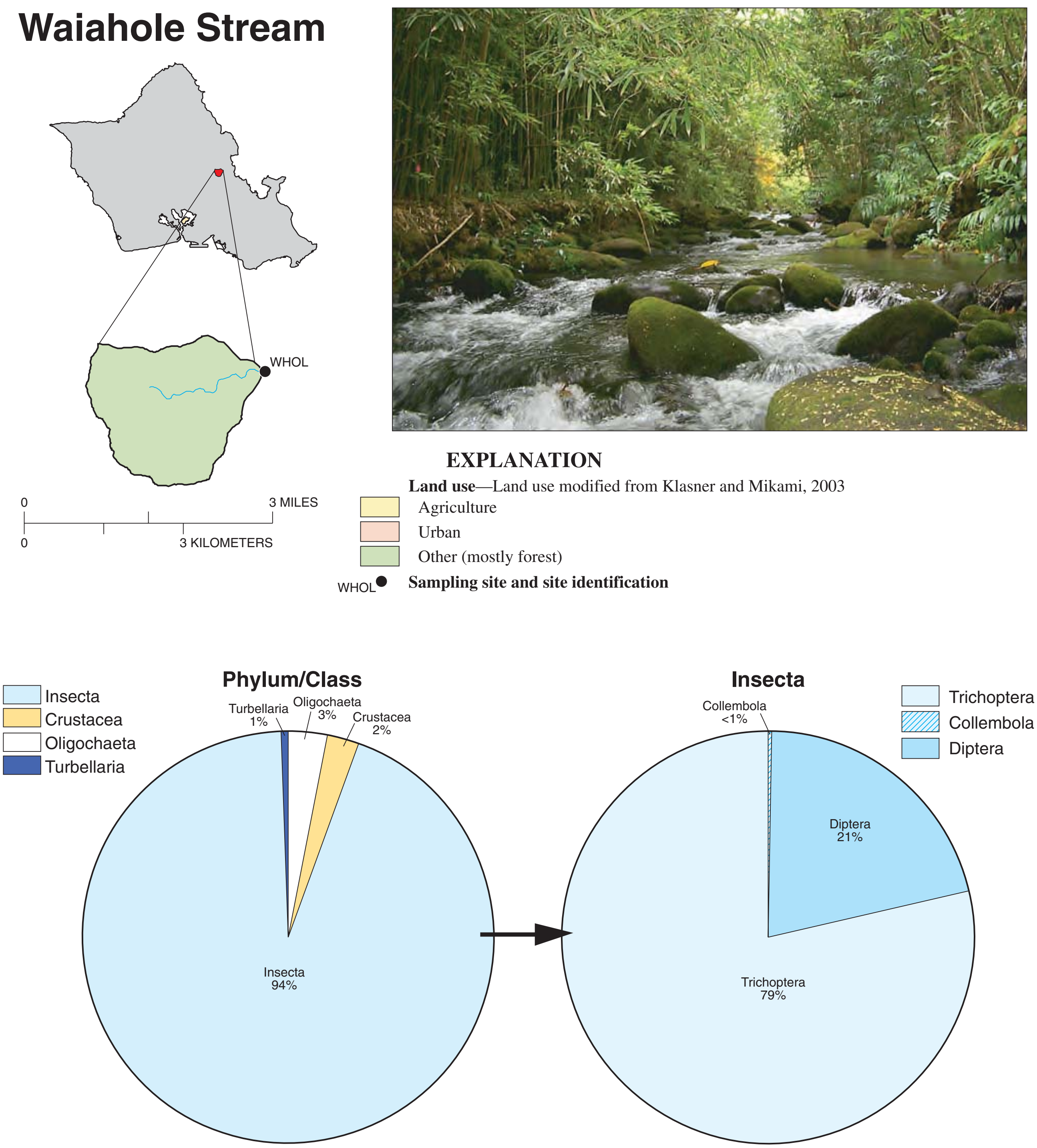


Figure 16. Waiahole Stream and relative abundances of key invertebrates.

may result in conditions unlike those that occur in more natural situations. Invertebrate sampling in 1999 occurred during the period when the invertebrate community may have been changing from one more adapted to the pre-water-return conditions.

Waiahole Stream is characteristic of a forested Hawaiian stream. Large boulders are the dominant stream substrate and silt and embeddedness are low (silt was present at 42 percent of the instream habitat measurement locations). Riparian vegetation is dense, with a mainly closed canopy (97 percent canopy closure). Water temperatures are cool with the least (mean of 2.1°C difference between the minimum and maximum daily temperature) diurnal variation measured at any of the sampling sites (also reflective of the large ground-water input). Insects accounted for 94 percent of the overall invertebrate abundance at Waiahole Stream. Oligochaetes and the native atyid shrimp *Atyoida bisulcata* accounted for an additional 3 percent and 2 percent, respectively. Seventy-nine percent of the insects were trichopterans and 21 percent were dipterans.

Punaluu Stream

The Punaluu Stream site (figs. 17 and 18) is located in windward Oahu at an altitude of about 212 ft and has a drainage area of about 3 mi^2. The drainage is 100 percent forested (table 1). Water is diverted from Punaluu Stream through a ditch system for irrigation of agricultural land downstream. Two sampling sites were located at Punaluu: one above the diversion (PUNA) and one below (PUNB). A USGS streamflow gage and weir is located near the diversion intake. During water year 1999, an average of 5.95 Mgal/d was diverted (Hill and others, 2000). An average of 5.26 Mgal/d has been diverted since 1953 (Hill and others, 2000). Potentially all of the flow in this stream reach can be diverted by the ditch, leaving little or no water flowing over the weir. Water does flow over the weir during times of higher flow (such as during spates), or when debris has clogged the grated intake.

Habitat at both sites on Punaluu Stream is typical of a forested stream: large boulders are the dominant substrate, riparian vegetation is thick, providing a closed canopy, and water temperatures are cool. The site above the diversion (PUNA) had twice the mean annual discharge (18.0 ft^3/s) as the site below the weir (PUNB) (8.80 ft^3/s) during the water year 1999. Furthermore, the minimum discharge for the same time period was 12.2 ft^3/s above the weir and 0.17 ft^3/s below the diversion. This difference in flow regimes affects the instream habitat characteristics, and consequently the invertebrate communities, of the two stream reaches. For example, at PUNA silt was present at only 30 percent of the instream habitat measurement locations whereas at PUNB silt was present at 94 percent of the measurement locations.

Insects were the most abundant invertebrates at both sites on Punaluu Stream, accounting for 96 percent of the total abundance above the diversion (PUNA) and 89 percent below (PUNB). Oligochaetes (earthworms) accounted for an additional 3 percent of the total invertebrate abundance above the diversion and 8 percent below the diversion. Turbellaria (flatworms) accounted for an additional 1 percent above the diversion, and 3 percent below.

Invertebrate Community Structure, Habitat Characteristics, and Land Use

Detrended Correspondence Analysis (DCA) was used to determine groupings of sites based on the macroinvertebrate communities from the quantitative samples. Sites with large proportions of urban land use, Manoa (MANO), Kaneohe (KANE), and Waikele (WKEL), grouped separately from the forested sites, Waihee (WHEE), Waiahole (WHOL), and both Punaluu (PUNA and PUNB) sites (fig. 19). Waiakeakua (WKEA), a mixed land use site with 95 percent of its drainage basin forested, grouped close to the forested sites. Two sites plotted alone: Waikakalaua (WKAK), an especially degraded mixed land-use site, and Kaluanui (KALU), an intermittent stream in a forested watershed.

Photograph by Eric Nishibayashi.

Native *Megalagrion* damselfly

The urban sites were characterized by molluscs such as thiarid snails and the clam *Corbicula fluminea*, decapod crustaceans (*Macrobrachium* sp.), and dipteran insects such as *Cricotopus* sp. Forested sites were characterized by native species such as the mountain shrimp

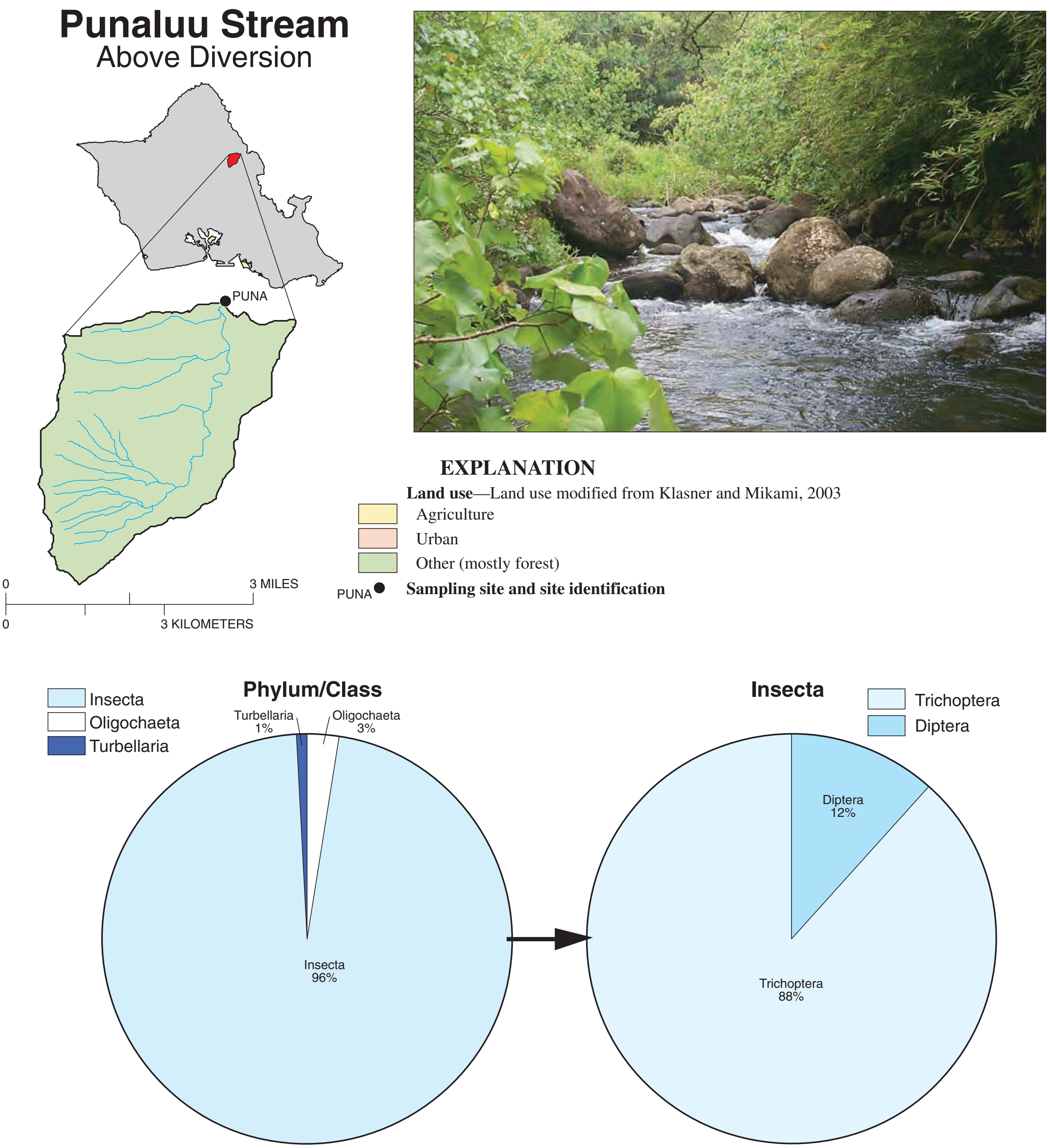


Figure 17. Punaluu Stream above diversion and relative abundances of key invertebrates.

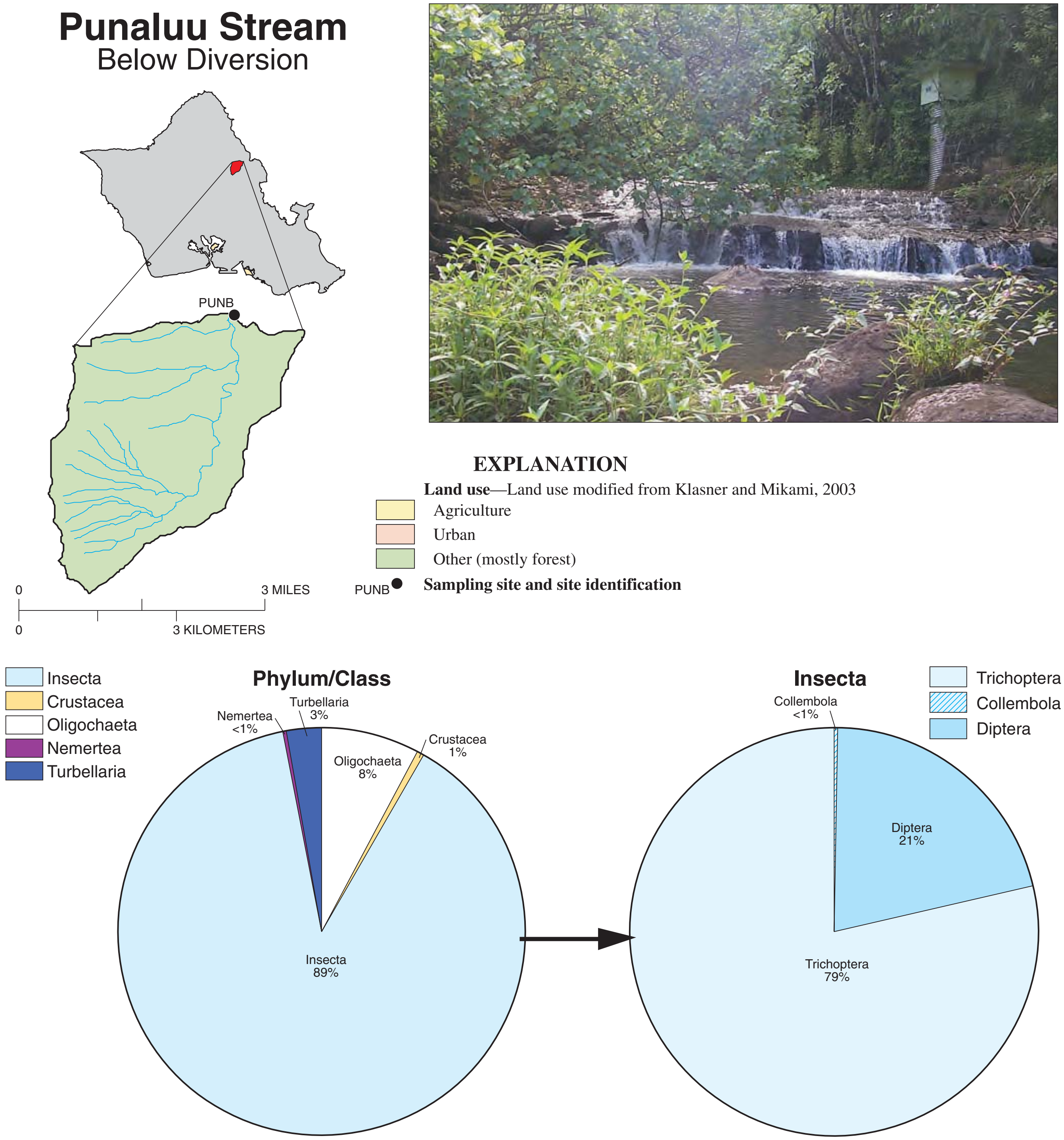


Figure 18. Punaluu Stream below diversion and relative abundances of key invertebrates.

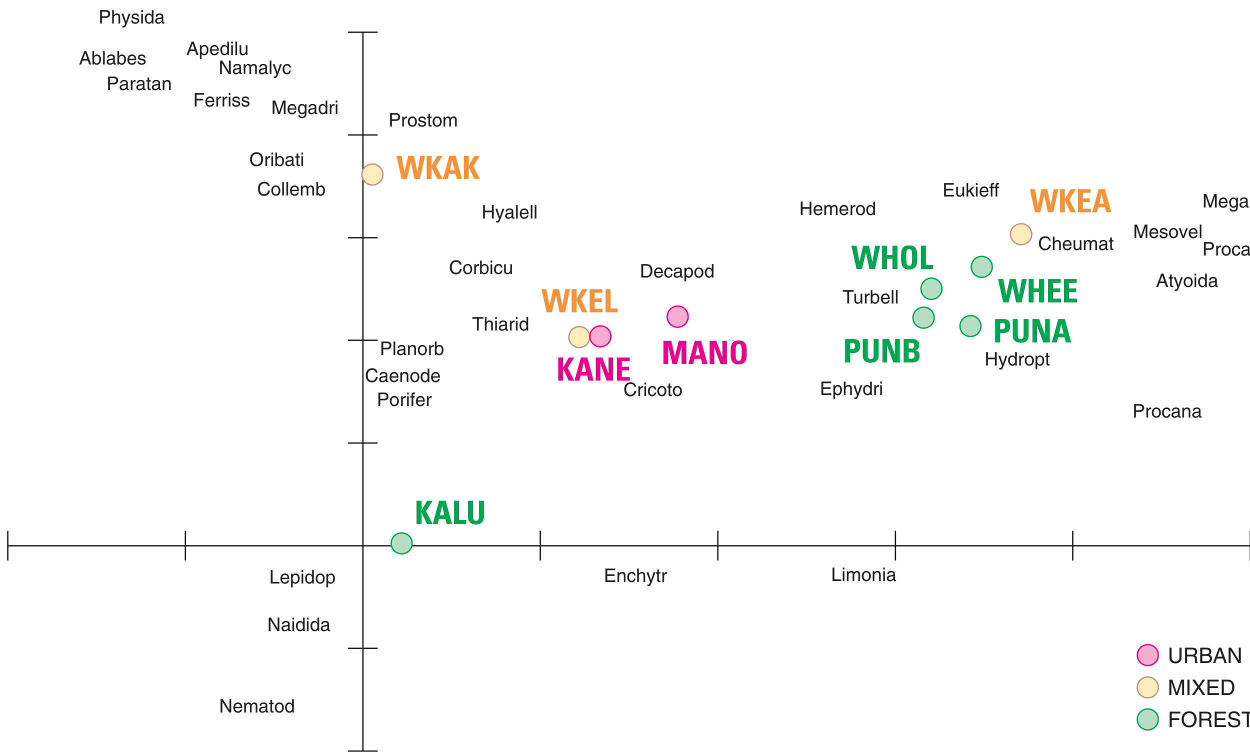


Figure 19. Detrended Correspondence Analysis of relative invertebrate abundance at sampling sites.

Table of species names

Abbreviated name	Taxa	Abbreviated name	Taxa
Ablabes	*Ablabesmyia* sp.	Megadri	Megadrile
Apedilu	*Apedilum* sp.	Megalag	*Megalagrion nigrohamatum*
Atyoida	*Atyoida bisulcata*	Mesovel	*Mesovelia amoena*
Brachyc	Brachycera	Microve	*Microvelia vagans*
Caenode	*Caenodes nigropunctata*	Naidida	Naididae
Ceratop	Ceratopogonidae	Namalyc	*Namalycastis abiuma*
Cheumat	*Cheumatopsyche pettiti*	Nematod	Nematoda
Coenagr	Coenagrionidae	Oribati	Oribatida
Collemb	Collembola	Parakie	*Parakiefferiella* sp.
Corbicu	*Corbicula* sp.	Paratan	*Paratanytarsus* sp.
Cricoto	*Cricotopus* sp.	Physida	Physidae
Curculi	Curculionidae	Planorb	Planorbidae
Decapod	Decapoda	Polyped	*Polypedilum* sp.
Enchytr	Enchytraeidae	Porifer	Porifera
Ephydri	Ephydridae	Procamb	*Procambarus clarkii*
Eukieff	*Eukiefferiella* sp.	Procana	*Procanace* sp.
Ferriss	*Ferrissia sharpi*	Prostom	*Prostoma* sp.
Gastrop	Gastropoda	Psychod	Psychodidae
Glossip	Glossiphoniidae	Tanytar	*Tanytarsus* sp.
Hemerod	*Hemerodromia stellaris*	Thiarid	Thiaridae
Hyalell	*Hyalella* sp.	Trichoc	*Trichocorixa reticulata*
Hydropt	*Hydroptila* sp.	Tubific	Tubificidae
Lepidop	Lepidoptera	Turbell	Turbellaria
Limonia	*Limonia* sp.		

Atyoida bisulcata (opae kalaole) and *Megalagrion* damselflies. Insects at the forested sites were typically trichopterans such as *Cheumatopsyche pettiti* and *Hydroptila sp*. The intermittent forested stream, Kaluanui (KALU), was noteworthy in that 77 percent of the invertebrates at that site were an oligochaete (earthworm), Naididae.

Streams at forested sites were found to have higher abundances (total number of individuals based on quantitative sampling at targeted habitats) than urban and mixed sites (fig. 20). In contrast, species richness (the total number of different taxa collected at a site) showed the opposite pattern. Forested sites were found to have fewer taxa while urban and mixed sites had more taxa. Quantitative samples had higher species richness than qualitative samples, except at Punaluu Stream above the diversion (PUNA), the most undisturbed forested site we sampled (fig. 21).

Forested sites were found to have lower levels of diversity than urban and mixed sites (table 7). The indices showed Kaneohe and Waikakalaua, both highly degraded sites, to have the highest diversity, and Waiakeakua and Kaluanui to have the lowest. Kaluanui is an intermittent stream, which would be expected to have different

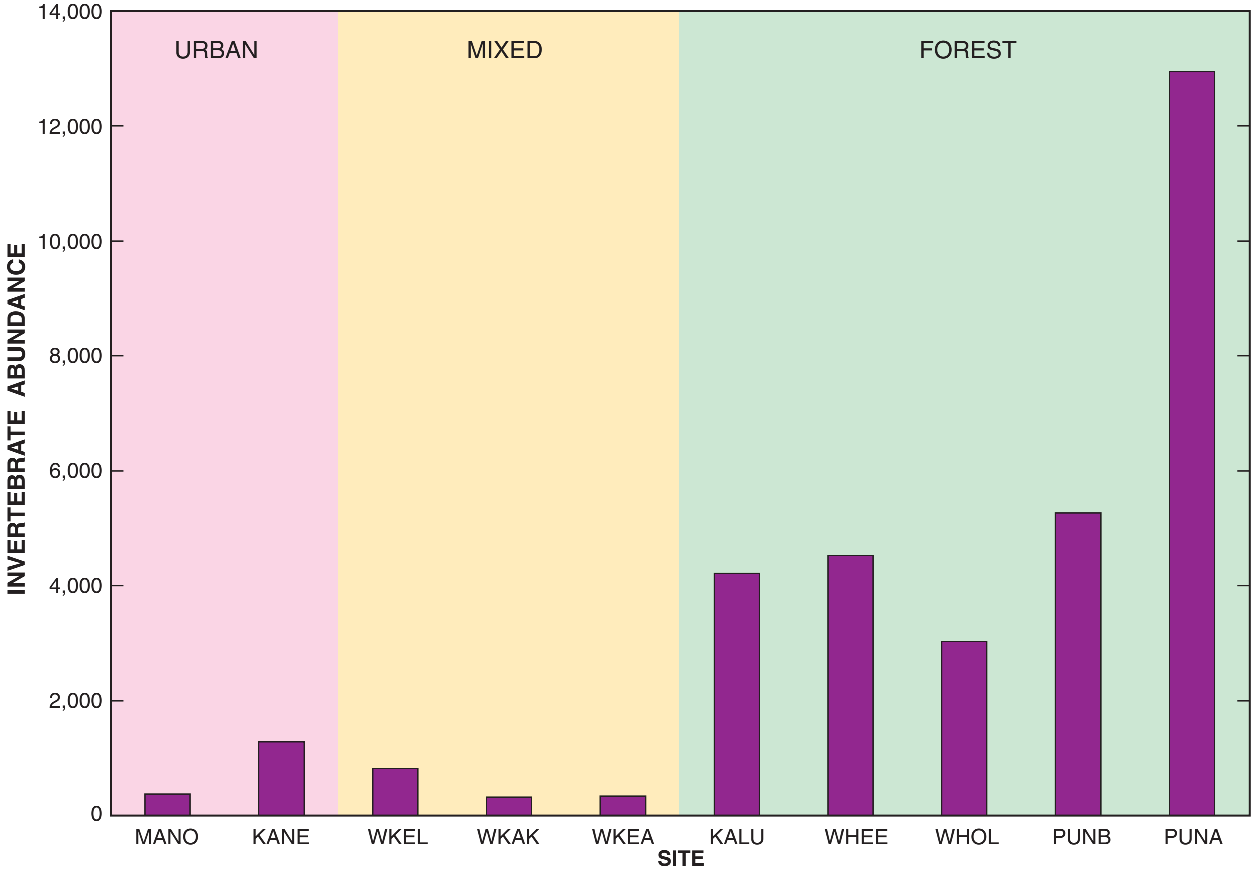


Figure 20. Total number of individuals (abundance) collected in quantitative samples at each site, in relation to percent forested land.

Table 7. Measures of community structure and abundance

[The highest values for each measure are in bold; S, richness (number of taxa present in the sample); H', Shannon's diversity index; E, evenness (H'/logS); D, Simpson's diversity index]

Site	Land use	S (richness)	E (evenness)	H′ (diversity)	D (diversity)
MANO	urban	13	**0.661**	**1.697**	**0.7677**
KANE	urban	**21**	**0.693**	**2.110**	**0.8130**
WKEL	mixed	13	**0.652**	**1.672**	**0.7357**
WKAK	mixed	**24**	**0.827**	**2.628**	**0.9015**
WKEA	mixed	17	0.230	0.653	0.2288
KALU	forest	16	0.310	0.859	0.3899
WHEE	forest	12	0.557	1.383	0.6640
WHOL	forest	12	0.511	1.270	0.5710
PUNB	forest	15	0.609	**1.650**	**0.7354**
PUNA	forest	10	0.494	1.136	0.5402

community characteristics than a perennial stream (Thorp and Covich, 1991) as different species would be better adapted to the periodic conditions of substantially reduced flow or complete drying of the reach. Punaluu below the diversion (PUNB), a forested site with reduced flow, had higher diversity, similar to the urban and mixed land-use sites, while Punaluu above the diversion (PUNA) had lower diversity scores, similar to the other forested sites.

The ratio of dipteran abundance to trichopteran abundance was found to vary with urbanization (fig. 22). Forested sites were dominated by Trichoptera whereas urban and mixed land-use sites tend to be dominated by Diptera. The particular species composition of Diptera and Trichoptera (DT) differed among sites, and did not appear to be clearly associated with land use. For example, in the

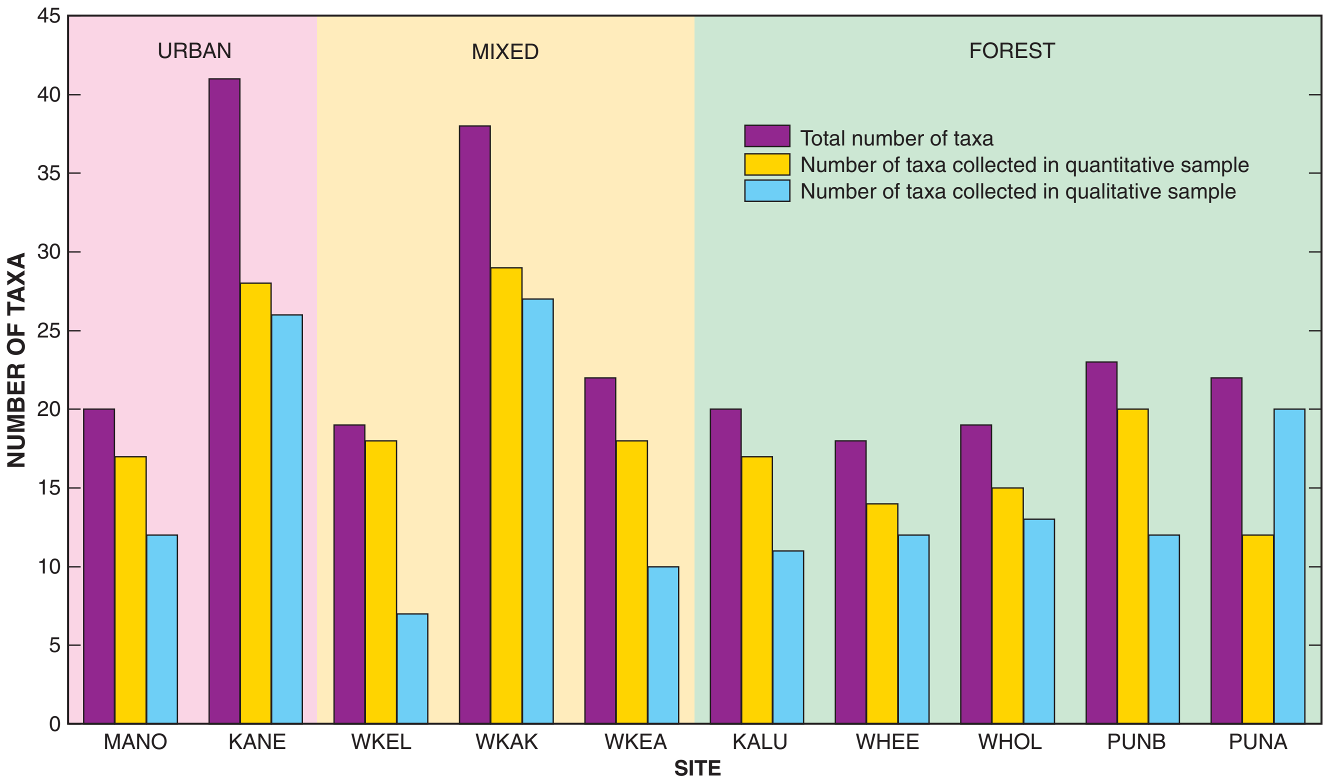


Figure 21. Total number of taxa (richness) collected in quantitative and qualitative samples at each site.

dipteran family Chironomidae, *Cricotopus* made up 89 percent of the DT abundance at Waikele, a mixed land-use site, and only 18 percent at Waikakalaua, also a mixed land-use site. *Cricotopus* also accounted for 53 percent of the DT abundance at Manoa, an urban site. Six genera, other than *Cricotopus,* in the family Chironomidae accounted for 42 percent of the DT abundance at Waikakalaua (mixed land use) but none of these were collected at Waikele (also mixed land use).


Photograph by Eric Benbow.

Larval Diptera (*Chironomidae*)

Overall, the trichopteran *Cheumatopsyche pettiti* (Banks) was the most abundant of the DT species, accounting for 33 percent of the individuals in all of the samples combined. At specific sites, the percentage of *C. pettiti* ranged from zero at Manoa to 96 percent at Waiakeakua. *C. pettiti* was the most abundant DT species at two forested sites, Waihee and Waiahole, and at the predominantly forested mixed land-use site Waiakeakua. The trichopteran *Hydroptila* was the most abundant genus at both of the other forested sites (on Punaluu Stream), accounting for 67 percent above the diversion and 41 percent below the diversion. *Hydroptila* also accounted for 45 percent of the DT abundance at Manoa Stream, an urban site.

No native molluscs were collected during this study. The most abundant molluscs were pan-tropical thiarid snails, the introduced clam *Corbicula fluminea* Müller, and the limpet *Ferrissia sharpi* (Sykes). No molluscs were present in the quantitative samples from the forested sites except at Kaluanui, the intermittent stream (fig. 23). *C. fluminea* was most abundant at the mixed land-use site Waikele where 124 individuals were collected. Thiarid snails were most abundant in urban Kaneohe Stream where 448 individuals were collected.

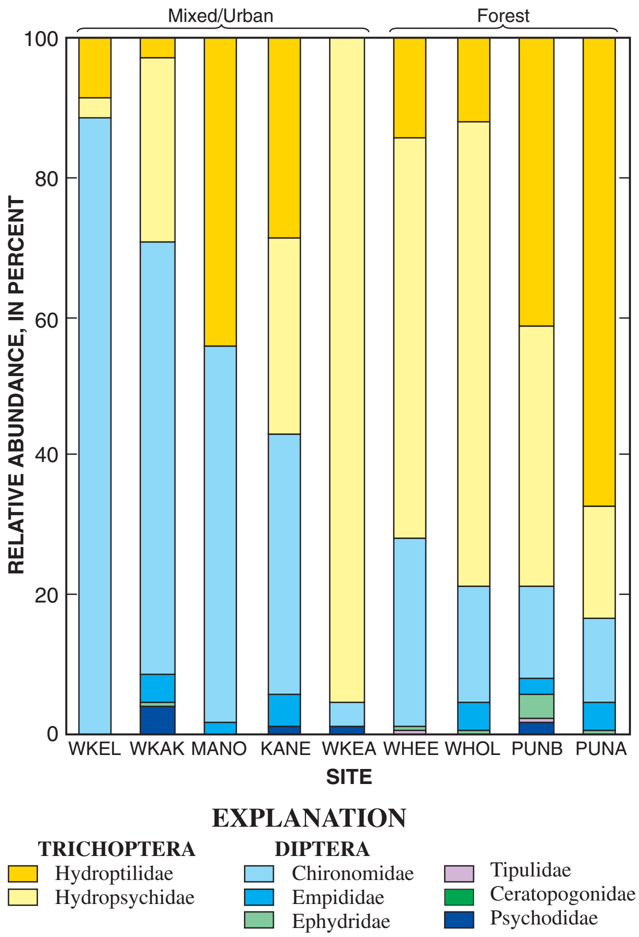


Figure 22. Ratio of Diptera to Trichoptera at sampling sites (perennial streams only) in relation to percent forested land.

Sites with less than 100 percent forest were sorted by basin size.

Two native and four introduced species of Crustacea were found during benthic collection and electrofishing surveys. Two amphidromous species, the native atyid shrimp *Atyoida bisulcata* Randall and the introduced Tahitian prawn *Macrobrachium lar (*Fabricius) occurred primarily at forested sites (fig. 24). The other native amphidromous crustacean, *Macrobrachium grandimanus*, is an estuarine and lower stream-reach species, and was only collected at Kaneohe and Waikele, both sites located near stream mouths. The three other nonnative crustaceans, a recently introduced shrimp *Neocaridina denticulata sinensis*, an amphipod *Hyalella* sp., and a crayfish *Procambarus clarkii (*Girard), were collected primarily at the urban and mixed land-use sites (fig. 24). The native shrimp, *Atyoida bisulcata (*opae kalaole) was most abundant at Waiahole Stream where 407 individuals were collected. The introduced shrimp, *Neocaridina denticulata sinensis*, which looks similar to the native shrimp, was most abundant at the mixed land-use site Waiakeakua where 564 individuals were collected.

Although this study was not designed to specifically assess the effects of flow regime on invertebrate community structure, some associations were noted. For example, species composition was different above and below the diversion at Punaluu Stream. Caddisflies (Trichoptera) were far more abundant above the diversion (10,422 individuals) than below the diversion (3,615 individuals). Conversely, earthworms (oligochaetes) and flatworms (Turbellaria) accounted for 4 percent of the invertebrate abundance above the diversion and 12 percent below. Similar results were found in a study conducted on the island of Maui at sites above and below a major water diversion, with several invertebrate species that utilize fast-flowing torrential habitats present above the diversion structure but absent below the diversion (McIntosh and others, 2002).

The association of flow regime with community structure was also demonstrated by the two separate invertebrate samples collected at Waikele Stream. One was collected in a riffle and the other from a deep slow-moving run. A number of taxa were unique to each sample, indicating habitat preference of different species. Taxa collected in the run sample that were not present in the riffle sample included a dipteran (Brachycera), a corixid (water boatman), oribatid mites, and tubificid worms. Aquatic moths (Lepidoptera), the limpet *Ferrissia sharpi*, the trichopteran *Cheumatopsyche pettiti*, and the proboscis worm *Prostoma*, were collected only in the riffle sample and not in the run sample.

Siltation and dissolved oxygen concentration are both affected by water velocity. Annelids (class Polychaeta) in Hawaiian streams have been shown to occur primarily in slow-flow depositional areas with high levels of silt and low concentrations of dissolved oxygen (Benbow and others, 2001). Annelids were more abundant below the diversion (8 percent of all invertebrates collected) where siltation levels were high (silt was present at 94 percent of the instream habitat measurement locations) than above the diversion at Punaluu (3 percent of all invertebrates collected) where siltation levels were low (silt was present at 30 percent of the measurements). At Kaluanui Stream where 77 percent of all invertebrates were annelids (class Oligochaeta), silt was present at 94 percent of the instream habitat measurement locations.

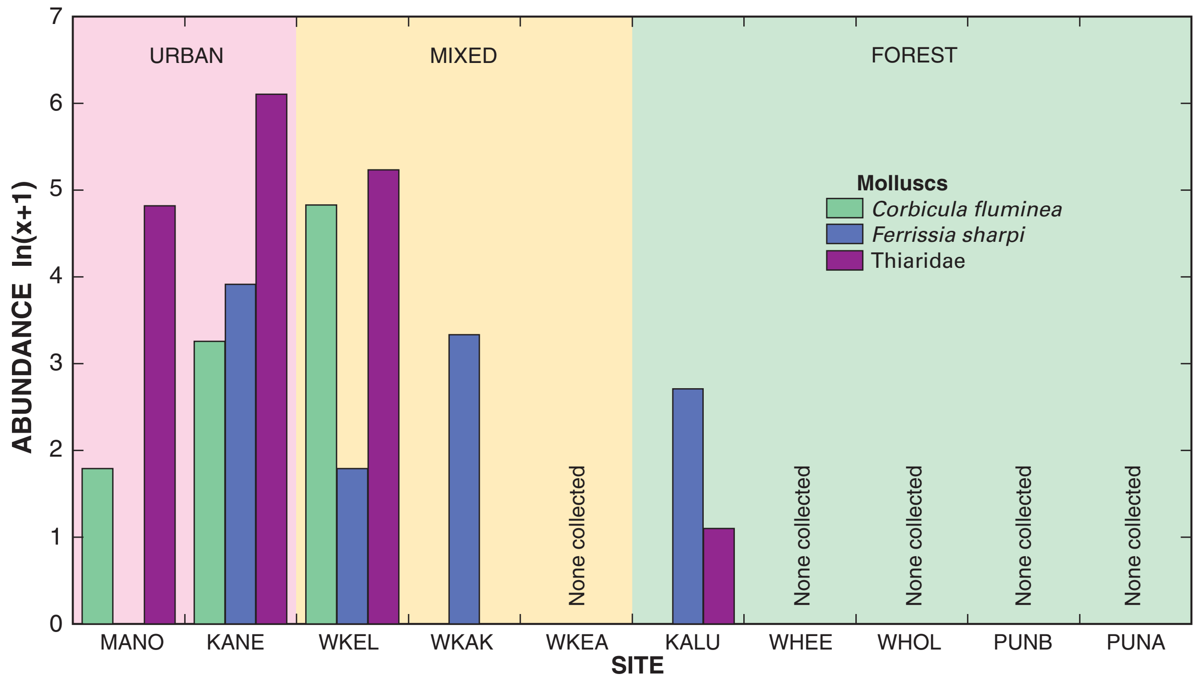


Figure 23. Relative abundance of molluscs at sampling sites.

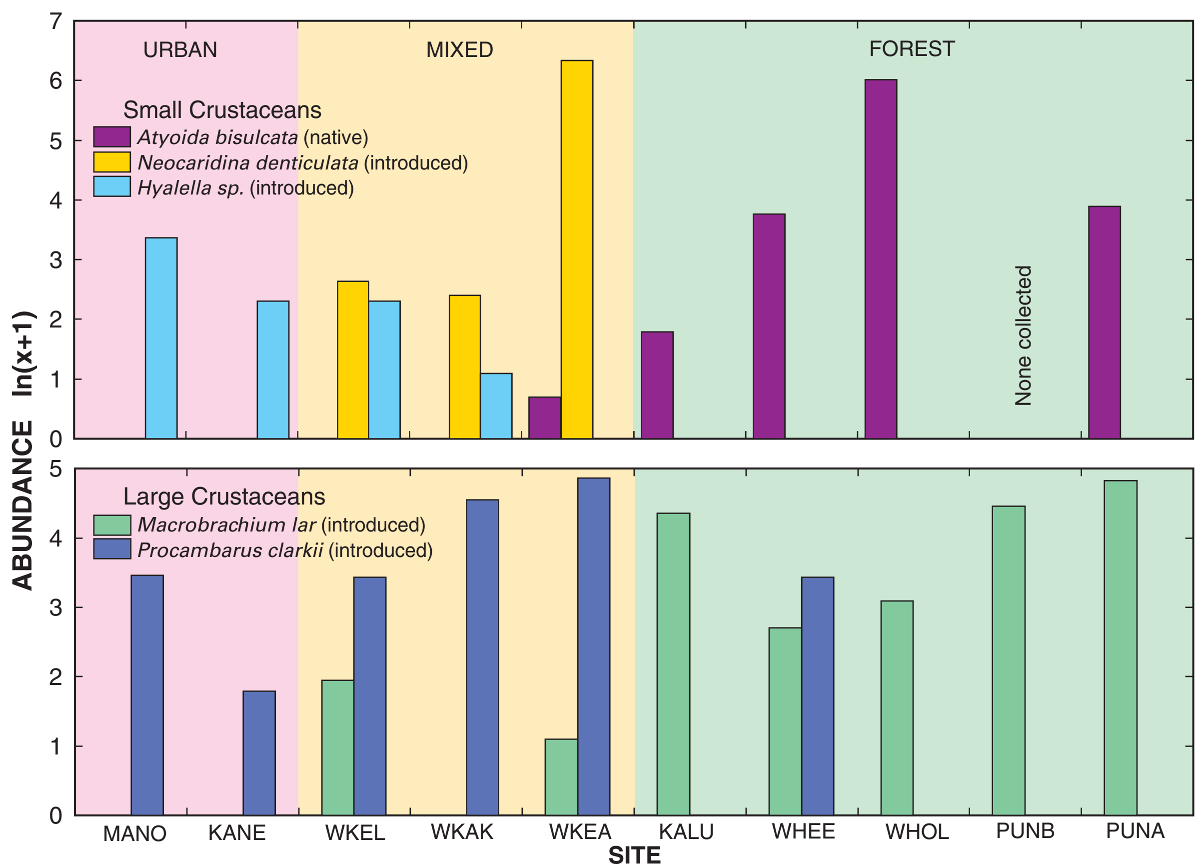


Figure 24. Relative abundance of crustaceans at sampling sites during benthic surveys and electrofishing.

Summary and Implications for Stream-Quality Assessments and Management

Associations among land use, habitat characteristics (physical and chemical), and benthic invertebrate community structure at 10 sites in 9 streams on the island of Oahu were examined. Sites were selected to represent the range of land use and habitat characteristics present on the island of Oahu; including urban, mixed (agriculture and urban), and forested watersheds. Qualitative and quantitative samples of invertebrates were collected at each site, and habitat characteristics were determined at multiple spatial scales.

The purpose of this study was to describe the associations among land use, habitat characteristics, and invertebrate community structure and abundance. Results of this study indicate that urban and mixed land-use sites (most of which had channelized streambeds) tended to have less riparian vegetation, higher water temperatures, smaller substrate, and higher levels of embeddedness and siltation than forested sites. Invertebrate community structure appeared to be characteristic of specific land-use type, and consequently may be useful as a tool for evaluating habitat impairment.

Invertebrate abundance (total number of individuals) was lower at urban and mixed land-use sites than at forested sites. In contrast, species richness (the number of different taxa) was higher at urban and mixed land-use sites. Urban and mixed land-use sites had many more taxa than forested land-use sites. Most invertebrates identified during this study were nonnative. Diversity would be naturally low in a pristine Hawaiian stream, but the introduced generalists are abundant in the more degraded Oahu streams.

Multivariate analyses showed species composition of invertebrate communities to be similar at sites with similar land use. Sites with large amounts of urban land use in the watershed (Manoa, Kaneohe, and Waikele) grouped closely together based on the invertebrates present at those sites, as did the forested sites (Waihee, Waiahole, and both Punaluu sites). Molluscs occurred primarily at urban and mixed land-use sites. The most abundant molluscs were pan-tropical thiarid snails, the introduced clam *Corbicula fluminea*, and the limpet *Ferrissia sharpi.* As has been reported in Japan (Karr and Chu, 1997), on Oahu the most common freshwater molluscs are nonnative and indicators of degraded conditions. Likewise for crustaceans, the native atyid shrimp was collected only at sites with greater than 95 percent forested land use, while the introduced amphipod *Hyalella* sp. was collected only at urban and mixed land-use sites.

There is a growing interest across the Nation in incorporating invertebrates as part of stream-quality assessments, and a number of metrics have been developed for this purpose. However, invertebrate metrics developed for streams in continental settings may not be appropriate for Hawaii. For example, the commonly used EPT (Ephemeroptera, Plecoptera, Trichoptera) metric is inappropriate for Hawaii because only a few individuals of one introduced species of Ephemeroptera have been reported for Hawaii, and Plecoptera have never been reported. However, two orders of insects dominated the Oahu invertebrate samples, Diptera and Trichoptera. The ratio of dipteran abundance to trichopteran abundance varied with the degree of urbanization. Forested sites were dominated by Trichoptera, and urban and mixed land-use sites tend to be dominated by Diptera.

This study identified habitat characteristics associated with degraded sites that can potentially be used in making decisions regarding stream restoration projects. For example, high levels of siltation and warm water temperatures were strongly associated with urban and mixed land-use sites. An important factor affecting the level of siltation is flow velocity, which can potentially be regulated by management activity. Likewise, water temperature has been shown to be greatly affected by the amount of riparian vegetation along the stream bank, suggesting that stream restoration focusing on improving riparian conditions could potentially have an effect on stream-water temperature, and consequently, on stream quality.

Photograph by Mark Vinson.

Larval Diptera (Tipulidae, cranefly)

This study provides information needed for an integrated assessment of stream quality and the development of appropriate monitoring and management strategies. To further evaluate the effectiveness of using invertebrates as indicators of stream quality in Hawaii, a wider range of stream conditions than included in the Oahu NAWQA study would need to be sampled. Also, whereas this study focused on habitat, the relation between contaminants in surface water and streambed sediment and invertebrate communities needs to be examined. In addition, to examine interisland variability, reference and degraded sites on the other Hawaiian islands would need to be sampled to determine if differences exist among the islands.

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For Further Information...

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APPENDICES

Appendix A. Water-quality properties and constituents and data from the invertebrate sampling sites, Oahu, Hawaii

[Site code, see table 1 and fig. 1, WKAK was sampled in 2001 because of flooding conditions immediately following the invertebrate sampling; all other sites sampled in 1999; *two sites at Punaluu Stream (PUNA and PUNB) are represented by one water-quality sample. All values are in milligrams per liter unless otherwise denoted; ft^3/s, cubic feet per second; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mm, millimeters; Hg, mercury; µg/L, micrograms per liter; <, actual value is less than the value shown; E, estimated value; N/A, not available; pH values are from filtered samples except for the WKAK sample which was unfiltered. Instantaneous discharge measurements may be an interpolation between two discharge measurements within a 15-minute period]

Site code:	MANO	KANE	WKEL	WKAK	WKEA	KALU	WHEE	WHOL	PUN (A&B)*
Sample date:	10-Jun-99	3-Aug-99	8-Jun-99	20-Jun-01	17-Jun-99	12-Aug-99	15-Jun-99	24-Jun-99	22-Jun-99
Sample time:	11:20	11:20	10:30	12:00	10:10	11:00	11:20	11:20	12:20
Discharge (measurement) (ft^3/s)	N/A	6.3	N/A	0.4	N/A	N/A	N/A	25	N/A
Discharge (instantaneous) (ft^3/s)	4.2	no gage	16	no gage	2.5	3.3	4.4	no gage	8.2
Gage height (ft)	9	no gage	1.97	no gage	0.33	5.11	2.7	no gage	2.32
Air temperature (degrees Celsius)	27	28	27	24	23	25.5	22.5	23	25
Water temperature (degrees Celsius)	23	29	22.5	23.5	21	22.5	20.5	20	21.5
Oxygen, dissolved	8	9.5	7.9	7.6	8.9	6.5	8.9	N/A	9.4
Oxygen, dissolved (percent saturation)	93	124	91	91	101	75	99	N/A	107
Specific conductance (µS/cm)	186	199	503	65	129	54	155	114	123
Barometric pressure (mm of Hg)	761	762	762	751	756	759	760	756	757
pH	8.3	9.4	7.4	7	8.2	7.5	8.2	8	8.3
Alkalinity	51	56	59	12	45	4	44	36	37
Bicarbonate	62	44	72	14	55	5	54	44	45
Calcium dissolved	9.04	9.83	13.6	2.44	7.53	0.94	8.23	6.16	6.18
Chloride dissolved	20	20.2	98.1	10.4	12.3	11.1	15.1	10.9	12.4
Fluoride dissolved	<0.1	<0.1	0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Iron dissolved (µg/L)	149	57	E7	158	13	131	<10	<10	45
Magnesium dissolved	8.02	7.47	12.5	1.82	5.9	1.4	5.03	4.32	4.89
Manganese dissolved (µg/L)	12.5	7.9	44.8	36.9	3.5	<3	<3	<3	3
Potassium dissolved	1.14	0.9	2.4	0.77	0.6	0.4	0.9	0.6	0.7
Residue	120	121	336	51	97	35	122	81	90
Silica dissolved	17.4	22.9	55.5	5.7	20.7	4.05	27.9	26.7	27.7
Sodium dissolved	14.2	15.9	58	6.63	10.6	6.58	12.5	9.01	10.1
Sulfate dissolved	5.8	5.5	19	2.4	1.9	1.3	2	1.5	1.5
Nitrogen, ammonia	0.02	<0.02	0.06	<0.04	<0.02	<0.02	<0.02	<0.02	<0.02
Nitrogen, nitrite	0.017	<0.01	<0.01	<0.006	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrogen, nitrite plus nitrate	0.13	0.1	1.61	E0.03	<0.05	<0.05	0.12	0.11	<0.05
Nitrogen, ammonia and organic	0.2	0.21	E0.07	0.2	<0.1	<0.1	<0.1	E0.07	<0.1
Nitrogen, ammonia and organic total	0.29	0.47	<0.1	0.21	0.13	0.2	E0.05	E0.08	0.11
Phosphorus ortho	0.03	0.02	0.19	<0.02	0.02	<0.01	0.03	0.03	0.03
Phosphorus dissolved	0.024	0.019	0.17	<0.006	0.014	0.004	0.031	0.034	0.041
Phosphorus total	0.049	0.043	0.184	0.023	0.025	0.007	0.033	0.038	0.024
Carbon organic dissolved	3	N/A	0.4	2.6	0.7	3.9	0.3	0.3	0.5
Carbon organic suspended total	0.8	N/A	0.3	0.5	0.5	0.2	0.2	0.2	0.2
Sediment suspended	9	15	3	12	6	4	2	2	3

Appendix B. Oahu NAWQA invertebrate list

[**Status**: E, Endemic, native to Hawaii only; N, Indigenous, native to Hawaii and elsewhere; I, Introduced, nonnative to Hawaii; R, New Record, new state record of introduced species; U, Undetermined, status of species currently unknown; **Site code:** WKEL2 and WHEE A-00, B-00, C-00, and B-01 are additional sampling sites where data were collected during this study, but not included in the statistical analyses of this report]

Phylum	Class	Order	Family	Genus, species, author, or lowest taxonomic designation	Status	Site Code (see table 1 and fig. 1)														
						KALU	KANE	MANO	PUNA	PUNB	WHEE B-99	WHEE A-00	WHEE B-00	WHEE C-00	WHEE B-01	WHOL	WKAK	WKEA	WKEL	WKEL2
Porifera																				
	Porifera			**Porifera**	U		X		X											
Platyhelminthes																				
	Turbellaria			**Turbellaria**	U		X	X	X	X	X	X	X	X		X		X		
Nemertea																				
	Nemertea			***Prostoma* sp.**	U		X	X	X	X							X	X	X	
Nematoda																				
	Nematoda			**Nematoda**	U	X														
Mollusca																				
	Bivalvia			**Bivalvia**	I		X	X											X	X
			Corbiculidae	***Corbicula* sp.**[1]	I		X	X											X	X
	Gastropoda																			
				Gastropoda	U						X				X		X	X	X	
			Ancylidae	***Ferrissia sharpi* (Sykes)**	U	X	X	X									X		X	
			Lymnaeidae	***Pseudosuccinea columella* (Say)**	I		X													
			Physidae	**Physidae**	I												X			
				***Physella* sp.**	I												X			
			Planorbidae	**Planorbidae**	I		X													
				***Planorbella* sp.**	I		X									X				
			Thiaridae	**Thiaridae**	I	X	X	X	X		X								X	X
Annelida																				
	Hirudinea																			
			Erpobdellidae	**Erpobdellidae**	U				X					X						
			Glossiphonidae	**Glossiphoniidae**	I		X													
	Oligochaeta																			
				Megadrile	U				X	X	X	X	X	X	X	X	X	X		
			Enchytraeidae	**Enchytraeidae**	U	X				X					X			X	X	X
			Naididae	**Naididae**	U	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
			Tubificidae	**Tubificidae**	U					X				X			X	X		X
				***Branchiura sowerbyi* Beddard**	U			X											X	
	Polychaeta																			
			Nereididae	***Namalycastis abiuma* (Müller)**	N	X	X	X			X	X			X		X	X	X	X
Arthropoda																				
	Insecta																			
		Coleoptera																		
			Curculionidae	**Curculionidae**	U		X											X		
			Hydrophilidae	**Hydrophilidae**	U							X								
			Staphylinidae	**Staphylinidae**	U												X			
		Collembola		**Collembola**	U	X	X			X		X				X	X	X		

Appendix B. Oahu NAWQA invertebrate list—Continued

Phylum / Class / Order / Family	*Genus, species,* author, or lowest taxonomic designation	Status	Site Code (see table 1 and fig. 1)														
			KALU	KANE	MANO	PUNA	PUNB	WHEE B-99	WHEE A-00	WHEE B-00	WHEE C-00	WHEE B-01	WHOL	WKAK	WKEA	WKEL	WKEL2
Arthropoda—Continued																	
Insecta—Continued																	
Diptera																	
Brachycera (suborder)	**Brachycera**	U											X	X	X		X
Canacidae	***Procanace* sp.**	U				X											
Empididae	**Empididae**	U					X										
	***Hemerodromia stellaris* Melander**	I	X	X	X	X	X	X	X	X	X	X	X	X			
Ephydridae	**Ephydridae**	U	X				X	X				X		X	X		
Stratiomyidae	**Stratiomyidae**	I		X													
Nematocera (suborder)																	
Ceratopogonidae	**Ceratopogonidae**	U	X	X			X							X			
	***Forcipomyia* sp.**	U												X			
Chironomidae	**Chironomidae**	U		X			X		X	X	X	X	X	X	X		X
	Chironominae	U							X					X			
	***Apedilum* sp.**	R		X					X					X			
	***Chironomus* sp.**	U		X													
	***Goeldichironomus* sp.**	I												X			
	***Polypedilum* sp.**	I												X			
	***Micropsectra /Tanytarsus* sp.**	U		X													
	***Paratanytarsus* sp.**	R			X			X		X		X		X			
	***Stempellinella* sp.**	R												X			
	***Tanytarsus* sp.**	U		X	X									X			
	Orthocladiinae	U	X	X	X	X	X	X	X	X	X	X	X	X		X	
	***Cricotopus/Orthocladius* sp.**	U	X				X		X	X	X	X		X			X
	***Cricotopus* sp.**	I	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	***Cricotopus bicinctus* group**	I		X	X									X		X	X
	***Eukiefferiella* sp.**	R	X			X	X	X				X	X	X			
	***Ablabesmyia* sp.**	R												X			
Dixidae	***Dixa longistyla* Takahashi**	I							X	X	X		X				
Psychodidae	**Psychodidae**	U													X		
Tipulidae	**Tipulidae**	U													X		
	***Limonia* sp.**	U	X	X		X	X			X		X	X				
Ephemeroptera																	
Caenidae	***Caenodes nigropunctata* (Klapálek)**	I		X													
Hemiptera																	
Corixidae	***Trichocorixa reticulata* (Guérin-Méneville)**	I				X											X
Mesoveliidae	***Mesovelia amoena* Uhler**	I					X	X		X		X			X		
	***Mesovelia mulsanti* White**	I		X		X											
Veliidae	***Microvelia vagans* White**	E										X					
Lepidoptera																	
	Lepidoptera	U	X	X					X	X						X	

Appendix B. Oahu NAWQA invertebrate list—Continued

Phylum	Class	Order	Family	*Genus, species,* author, or lowest taxonomic designation	Status	Site Code (see table 1 and fig. 1)														
						KALU	KANE	MANO	PUNA	PUNB	WHEE B-99	WHEE A-00	WHEE B-00	WHEE C-00	WHEE B-01	WHOL	WKAK	WKEA	WKEL	WKEL2
Arthropoda—Continued																				
	Insecta—Continued																			
		Odonata																		
		Anisoptera (suborder)																		
			Libellulidae	***Pantala flavescens* (Fabricius)**	N												X			
		Zygoptera (suborder)																		
			Coenagrionidae	**Coenagrionidae**	U		X										X			
				***Enallagma civile* (Hagen)**	I		X													
				***Ischnura* sp.**	I		X													
				***Megalagrion nigrohamatum* (Blackburn)**	E													X		
		Trichoptera																		
			Hydropsychidae	***Cheumatopsyche pettiti* (Banks)**	I	X	X		X	X	X	X	X	X	X	X	X	X	X	
			Hydroptilidae	***Hydroptila* sp.**	I	X	X	X	X	X	X	X	X	X	X	X	X		X	X
				***Hydroptila arctia* Ross[2]**	I		X		X	X	X	X	X	X		X				
				***Hydroptila icona* Mosely**	R		X	X	X	X		X							X	
				***Oxyethira maya* Denning**	I				X				X							
	Arachnida																			
		Oribatida		**Oribatida**	U	X	X	X			X	X	X	X	X		X	X		X
	Crustacea																			
		Amphipoda	Hyalellidae	***Hyalella* sp.[3]**	U		X	X									X		X	
		Decapoda[4]																		
				Decapoda	U	X	X		X	X		X	X		X	X	X	X	X	
			Atyidae	***Atyoida bisulcata* Randall**	E	X			X		X	X	X	X	X	X		X		
				***Neocaridina denticulata sinensis* (de Haan)**	I										X		X	X	X	X
			Cambaridae	***Procambarus clarkii* (Girard)**	I		X	X			X	X	X	X	X		X	X	X	X
			Palaemonidae	***Macrobrachium grandimanus* (Randall)**	E		X												X	X
				***Macrobrachium lar* (Fabricius)**	I	X			X	X	X	X	X	X	X	X		X	X	X

[1]*Corbicula fluminea* is currently the only known *Corbicula sp*. from Hawaii (Burch, 1995)

[2]*Hydroptila arctia* Ross pending identification as *Hydroptila potosina* Bueno

[3]*Hyalella sp*. identified by Les Watley, University of Maine.

[4]Some Decapoda listed were collected using electrofishing.

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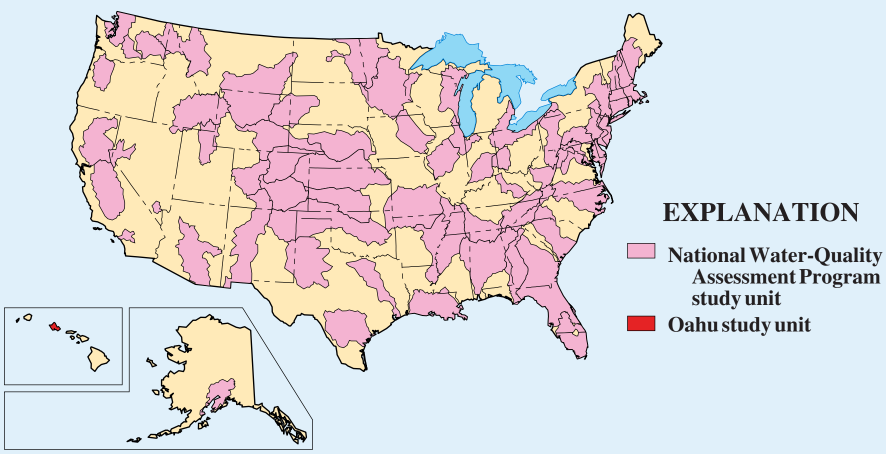

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