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Commission on Water Resource Management

Effects of Surface-Water Diversions on Habitat Availability for Native Macrofauna, Northeast Maui, Hawaii

Scientific Investigations Report 2005-5213

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

EXHIBIT S-5

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Cover: Photograph of snorkeler observing habitat and native macrofauna during reconnaissance survey of Paakea Stream at about 1,400 ft altitude. The observed native opae or mountain shrimp (Atyoida bisulcata) were too numerous to count. (Photograph by Stephen B. Gingerich, U.S. Geological Survey)

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2005

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

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Conversion Factors and Datums

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

$$°F=(1.8\times°C)+32$$

Datums

Vertical coordinate information is referenced relative to local mean sea level.

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

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

Gaging station number and abbreviation.

The surface-water gaging stations mentioned in this report are numbered according to the USGS “downstream order” numbering system. Station numbers increase in a downstream direction along the main stream. All stations on a tributary entering upstream from a mainstream station have lower station numbers. A station on a tributary that enters between two mainstream stations is given a number between those two station numbers. In this report, the complete 8-digit downstream-order number for each gaging station has been abbreviated to the middle four digits, for example, 16518000 becomes 5180.

Effects of Surface-Water Diversions on Habitat Availability for Native Macrofauna, Northeast Maui, Hawaii

By Stephen B. Gingerich and Reuben H. Wolff

Abstract

Effects of surface-water diversions on habitat availability for native stream fauna (fish, shrimp, and snails) are described for 21 streams in northeast Maui, Hawaii. Five streams (Waikamoi, Honomanu, Wailuanui, Kopiliula, and Hanawi Streams) were chosen as representative streams for intensive study. On each of the five streams, three representative reaches were selected: (1) immediately upstream of major surface-water diversions, (2) midway to the coast, and (3) near the coast. This study focused on five amphidromous native aquatic species (alamoo, nopili, nakea, opae, and hihiwai) that are abundant in the study area.

The Physical Habitat Simulation (PHABSIM) System, which incorporates hydrology, stream morphology and microhabitat preferences to explore relations between streamflow and habitat availability, was used to simulate habitat/discharge relations for various species and life stages, and to provide quantitative habitat comparisons at different streamflows of interest. Hydrologic data, collected over a range of low-flow discharges, were used to calibrate hydraulic models of selected transects across the streams. The models were then used to predict water depth and velocity (expressed as a Froude number) over a range of discharges up to estimates of natural median streamflow. The biological importance of the stream hydraulic attributes was then assessed with the statistically derived suitability criteria for each native species and life stage that were developed as part of this study to produce a relation between discharge and habitat availability. The final output was expressed as a weighted habitat area of streambed for a representative stream reach.

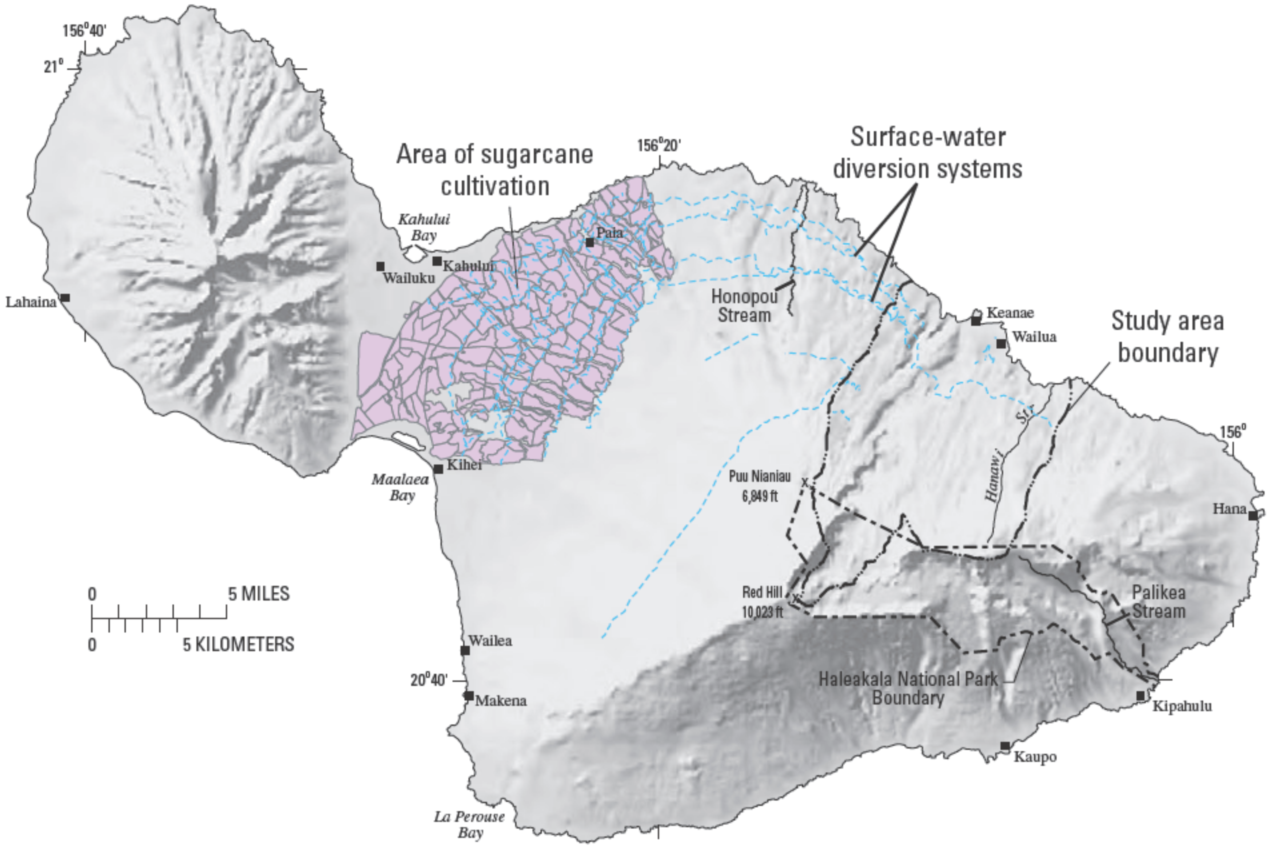
PHABSIM model results are presented to show the area of estimated usable bed habitat over a range of streamflows relative to natural conditions. In general, the models show a continuous decrease in habitat for all modeled species as streamflow is decreased from natural conditions.

The PHABSIM modeling results from the intensively studied streams were normalized to develop relations between the relative amount of diversion from a stream and the resulting relative change in habitat in the stream. These relations can be used to estimate changes in habitat for diverted streams in the study area that were not intensively studied. The relations indicate that the addition of even a small amount of water to a dry stream has a significant effect on the amount of habitat available. Equations relating stream base-flow changes to habitat changes can be used to provide an estimate of the relative habitat change in the study area streams for which estimates of diverted and natural median base flow have been determined but for which detailed habitat models were not developed.

Stream water temperatures, which could have an effect on stream ecology and taro cultivation, were measured in five streams in the study area. In general, the stream temperatures measured at any of the monitoring sites were not elevated enough, based on currently available information, to adversely effect the growth or mortality of native aquatic macrofauna or to cause wetland taro to be susceptible to fungi and associated rotting diseases.

Introduction

For more than a century, surface-water diversion systems have been used to transport water from the wet, northeastern part of Maui, Hawaii, to the drier, central part of the island, mainly for large-scale sugarcane cultivation (fig. 1). Since the 1930's, the Territory and then the State issued water permits to Alexander and Baldwin, Inc., Hawaiian Commercial and Sugar Co., and East Maui Irrigation Co., Ltd. (EMI), for the diversion of water from streams in northeast Maui. The collection system consists of 388 separate intakes, 24 mi of ditches, and 50 mi of tunnels, as well as numerous small dams, intakes, pipes, and flumes (Wilcox, 1996). With few exceptions, the diversions capture all of the base flow, which represents the ground-water contribution to total streamflow, and an unknown percentage of total streamflow at each stream crossing. During 1925–97, total flow in the diversion systems (measured crossing Honopou Stream, to the west of the study area [fig. 1] where records of total diversion-system flow are most complete) averaged about 163 Mgal/d (million gallons



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 2039'30' and 2057'30'', central meridian 15620'15''. Shaded relief from U.S. Geological Survey digital elevation models, 1:250,000

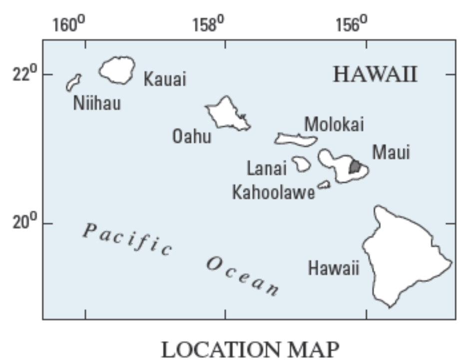


Figure 1. Location of study area and surface-water diversion systems, island of Maui, Hawaii.

per day) (Gingerich, 1999). The source of diverted water is a watershed with an area of about 56,000 acres, about two-thirds of which is owned by the State (Wilcox, 1996) and managed by the State Department of Land and Natural Resources.

The Hawaii State Water Code, enacted in 1987, mandates that the Commission on Water Resource Management (CWRM) establish a statewide instream-use protection program (Chapter 174C-71, Hawaii Revised Statutes). The principal mechanism that CWRM has for the protection of instream uses is establishing instream flow standards. “Each instream flow standard shall describe the flows necessary to protect the public interest in the particular stream. Flows shall be expressed in terms of variable flows of water necessary to protect adequately fishery, wildlife, recreational, aesthetic, scenic, or other beneficial instream uses in the stream in light of existing and potential water developments including the economic impact of restriction of such use” (Chapter 174C-71, Hawaii Revised Statutes). CWRM has recognized certain instream uses as beneficial, including: (1) maintenance of fish and wildlife habitat; (2) outdoor recreational activities; (3) maintenance of ecosystems such as estuaries, wetlands, and stream vegetation; (4) aesthetic values such as waterfalls and scenic waterways; (5) maintenance of water quality; (6) conveyance of irrigation and domestic water supplies to downstream points of diversion; and (7) protection of traditional and customary Hawaiian rights.

The U.S Geological Survey (USGS), in cooperation with CWRM and in collaboration with the Maui Department of Water Supply, the Hawaii State Board of Land and Natural Resources, and East Maui Irrigation Co., Ltd., undertook an investigation to assist in determining equitable, reasonable, and beneficial instream and off-stream uses of the surface-water resources in northeast Maui. The overall objectives of the 3-year study (2002-05) are to (1) assess the effects of existing surface-water diversions on flow characteristics for perennial streams in northeast Maui, (2) characterize the effects of diversions on instream temperature variations, and (3) estimate the effects that streamflow restoration (full or partial) would have on the availability of habitat for native stream fauna (fish, shrimp, and snails) in northeast Maui. Scientific information generated by the overall study will support the CWRM in its efforts to document water rights and uses associated with northeast Maui streams and to analyze the social and economic effects of curtailing existing uses on the streams, and to then establish technically defensible instream flow standards for those streams. Results of an assessment of the effects of existing surface-water diversions on flow characteristics, objective 1, were addressed in Gingerich (2005).

Purpose and Scope

This report addresses objectives 2 and 3 described above for selected streams in northeast Maui, Hawaii. This report presents information on stream macrofauna habitat availability and utilization collected at 15 sites on 5 streams over a 20-month period from July 2002 to April 2004. Stream temperature data are also presented. The methods used to collect habitat information are described and the habitat data are presented. Froude number and stream substrate habitat suitability criteria for five native aquatic species are presented along with the method used to create the criteria. Aquatic species habitat estimates are provided for diverted and natural (undiverted) stream conditions in the study area.

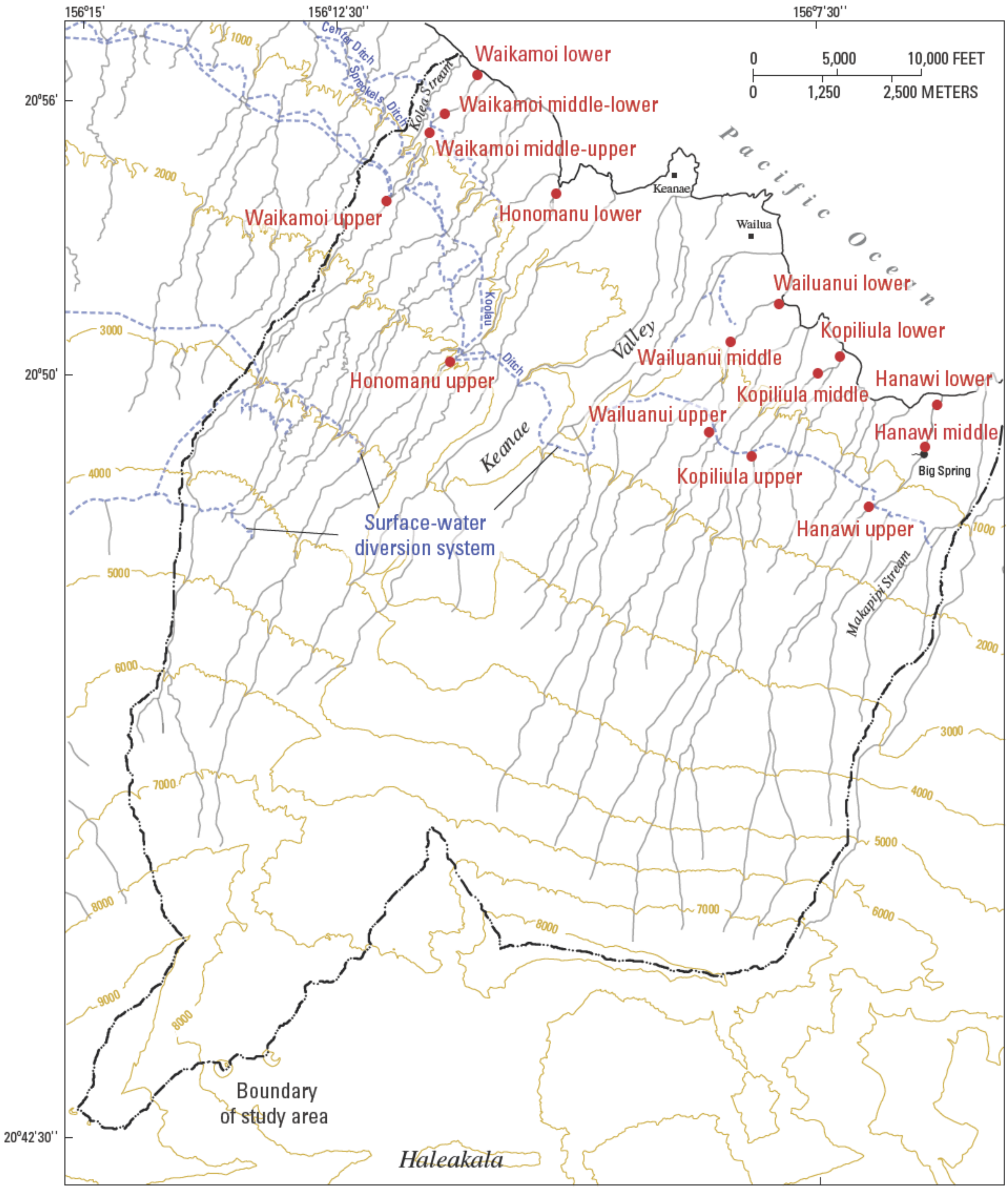
Description of Study Area

The study area is on the northern flank of the East Maui Volcano (Haleakala), which forms the eastern part of the island of Maui, the second-largest island in the Hawaiian archipelago (fig. 1). The study area, covering about 67 mi^2, is bounded to the north by about 11 mi of coastline and lies between (and includes) the drainage basins of Kolea Stream to the west and Makapipi Stream to the east (fig. 2). Land-surface altitudes range from sea level to 10,000 ft at the summit of Haleakala. The topography is gently sloping except for the steep sides of gulches and valleys that have been eroded by the numerous streams. The largest valley is Keanae Valley, which extends from the coast to Haleakala Crater, where the valley walls are nearly 1,000 ft high. Most of the study area is made up of forest reserves; at intermediate altitudes, rain forests densely cover the slopes to about 7,000 ft. Grasses and shrubs cover the upper slopes to the north wall of Haleakala Crater. Two small villages (Keanae and Wailua) are at low altitudes along the coast at the mouth of Keanae Valley. Land use around the villages is mainly small-scale agriculture including wetland taro cultivation. At higher altitudes, most of the land is forested State conservation land.

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

Intensively Studied Streams

Of the 21 named streams that reach the coast in the study area, 5 were chosen as representative streams for intensive study on the basis of several factors, including the amount of flow downstream of major surface-water diversions, type of stream terminus (estuary or waterfall), impact from human activities, availability of existing hydrologic and biologic data, geographic location and drainage area, and access. The five streams (from west to east) are Waikamoi, Honomanu, Wailuanui, Kopiliula, and Hanawi Streams (fig. 2). These five streams represent most of the range of hydrologic



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Transverse Mercator projection, zone 4, central meridian -159°, North American Datum 1983

Figure 2. Northeast Maui study area and location of intensively studied stream sites, island of Maui, Hawaii.

conditions encountered in the study area, including streams with the highest (Hanawi Stream) and lowest (Honomanu and Waikamoi Streams) flows remaining below the diversions; streams with estuaries (Honomanu Stream) and terminal waterfalls (Waikamoi Stream); streams with gaining (Hanawi and Kopiliula Streams) and losing (Honomanu and Waikamoi Streams) lower reaches, and streams with taro diversions and return flows (Wailuanui Stream). These five streams have similar drainage areas (3.2 to 5.4 mi^2), slopes (1,650 to 2,115 ft/mi), and substrates (mainly cobbles, boulders, and bedrock), all of which are representative of most the streams in the study area. Strong consideration was given to including Waiokomilo or Palauhulu Stream in this group because of the significance of these streams for taro cultivation and gathering practices to the area residents. These streams were excluded from intensive study, however, owing to several factors, including complex geology in Keanae Valley, numerous taro and domestic diversions, and the presence of introduced alien aquatic species.

On each of the five selected streams, representative reaches were in turn selected directly upstream of the major diversion at about 1,400–1,700 ft altitude, midway to the coast at about 500–600 ft altitude, and near the coast at 10–40 ft altitude. An additional study reach was selected on Waikamoi Stream because of a second major diversion at about 700 ft altitude. A middle reach was not studied on Honomanu Stream, however, because of poor accessibility. Overall, 15 representative reaches in the study area were studied intensively.

The middle and lower sites on Hanawi Stream, downstream of Big Spring (fig. 2), were considered reference sites with healthy, undisturbed native aquatic species populations because of the steady and considerable input from ground-water discharge. Because no streams in the study area maintained continuous flow from the upper study sites at about 1,400 ft altitude to the coast, an upper study site was chosen for an aquatic survey on Palikea Stream on the southeast flank of Haleakala near Kipahulu in Haleakala National Park (fig. 1) to provide background data from a relatively undisturbed higher altitude location. During the study, however, streamflow in Palikea Stream was very low and all the native species were observed clustered in one large pool. Therefore, data from Palikea Stream was not considered applicable to background higher altitude conditions.

Aquatic Species of Interest

This study focused on some of the native fish, snails, and shrimp species found in Hawaiian streams. Three of the five native fish species, collectively referred to as oopu, were observed in sufficient abundance for consideration in the study. These fishes are all in the family Gobiidae, collectively referred to as gobies. The three fish species considered were the endemic (found only in Hawaii) gobies alamoo (*Lentipes concolor* (Gill)) and nopili (*Sicyopterus stimpsoni* (Gill)), and the indigenous (native to Hawaii and elsewhere) goby nakea (*Awaous guamensis* (Valenciennes)). Alamoo was considered a category 1 candidate for listing in the National Register for Endangered Species (Devick and others, 1995) but has since been reclassified as a Species of Concern (U.S. Fish and Wildlife Service, 1996; 1999). The eleotrid (family: Eleotridae) akupa (*Eleotris sandwicensis* Vaillant and Sauvage) was not observed frequently enough to consider, and the teardrop goby naniha (*Stenogobius hawaiiensis* Watson) was not encountered at all during this study. The abundance of one of the endemic freshwater snail species, *Neritina granosa* (Sowerby), commonly referred to as hihiwai, and the abundance of the endemic mountain shrimp, *Atyoida bisulcata* (Randall), commonly referred to as opae kalaole or mountain opae, were sufficient for consideration in the study.

Several life history characteristics factor into habitat selection by the native fauna in Hawaiian streams. Having evolved from marine ancestors, the species of interest for this study are all amphidromous, having retained a marine larval stage (Ford and Kinzie, 1982). Amphidromy is a type of diadromy in which individuals migrate between a freshwater stream and the saltwater ocean and return once in their lifetime. Females deposit their eggs in the streams, the eggs hatch, and the larvae are carried downstream to the ocean where they live as plankton for a time until they develop into post-larvae. The post-larvae then make their way back to the freshwater streams where they eventually mature into adults and live the remainder of their lives (Ego, 1956; Tomihama, 1972; Ford and Kinzie, 1982; Kinzie and Ford, 1982).

Another relevant life history characteristic is the upstream migratory ability of the different species. Four of the five oopu, alamoo, nakea, nopili, and naniha are true gobies and have a fused pelvic fin. The fused pelvic fin forms a suction disk that enables these fishes to attach themselves to the stream substrate and to climb cascades and waterfalls (Kinzie and Ford, 1982). Differences in climbing abilities have allowed the fish species to segregate along a longitudinal gradient. Although there is considerable overlap, especially in streams with high waterfalls or in dewatered streams, the fish species tend to inhabit stream reaches according to their climbing abilities. Akupa is not a true goby and lacks the fused pelvic fin and therefore is restricted to the lowest stream reaches, stream mouths, and estuaries. Naniha has the weakest climbing ability and is also confined to the lower stream reaches, stream mouths, and estuaries. Nakea, the largest of the fish species, is a moderate climber and is commonly found in lower and middle stream reaches. Nopili often inhabits the middle stream reaches, whereas alamoo, the best climber, is typically found in middle and upper stream reaches (Nishimoto and Fitzsimons, 1986; Fitzsimons and Nishimoto, 1990a; Kinzie, 1990). The mountain opae have exceptional climbing ability and most often inhabit the upper stream reaches (Couret, 1976; Kinzie, 1990). Hihiwai are commonly found in lower stream reaches but can be found in reaches up until the first large waterfall (Ford, 1979; Kinzie, 1990). Segregation along elevational and longitudinal gradients reduces the amount of competition among the species for resources and shelter.

Another factor in habitat selection involves territoriality. Mature alamoo males have been observed to be very territorial, aggressively defending territories against male conspecifics (males of the same species) while females tend to move freely about the stream (Nishimoto and Fitzsimons, 1986; Fitzsimons and Nishimoto, 1990a; Lau, 1973; Maciolek, 1977). Similarly, male nopili aggressively defend territories with larger fish defending larger territories (Fitzsimons and Nishimoto, 1990b; Fitzsimons and others, 1993). The normally docile nakea exhibits aggressive territoriality toward conspecifics as well as other species during the fall spawning season (Fitzsimons and Nishimoto, 1990b).

The dietary preferences of the stream fauna also can influence habitat selection. The heterogeneous nature of streams may make it possible for species to occupy the same stream macrohabitats because microhabitats commonly have different dietary resources. Species-specific morphological adaptations of the fishes may have functionally served to reduce interspecific competition for resources and allow the fish species to coexist (Kido, 1996; Kido, 1997a; Kido, 1997b). Because flow in Hawaiian streams is flashy, the resultant heterogeneous algal and invertebrate assemblages that comprise the diet of the native species provide a diversity of resources for the various fish species and age classes to utilize.

Acknowledgments

Many people provided assistance with logistics and fieldwork during this study. Foremost, the authors would like to thank Gladys Kanoa for all of her help and knowledge of the study area to allow us to work efficiently and comfortably in northeast Maui. Much field assistance was also provided by Skippy Hau (State of Hawaii, Depatment of Land and Natural Resources, Division of Aquatic Resources [DAR]); Gordon Smith (U.S. Fish and Wildlife Service); Awapuhi Carmichael and Ed Wendt (Na Moku Aupuni O Koolau Hui); Alex Michaelidis, Kat Lui, Clinton Fukushima, and Jon Ciacci (East Maui Watershed Partnership); Katina Henderson (State of Hawaii, Department of Health, Environmental Planning Office), Robert Kinzie III (University of Hawaii [UH]), John Ford (SWCA Environmental Consultants), Robert Hobdy (State of Hawaii, Depatment of Land and Natural Resources, Division of Forestry and Wildlife) and volunteers Holly Rebert and Danielle Pattison. Others who helped greatly with the project include east Maui residents and landowners Alan Bradbury, Neola Caveny, Lucienne De Naie, Isaac Kanoa, Christine Shaw, Jake Waxman, Gene and Lajon Weaver, and Elaine Wender. Mark Vaught and Garret Hew at East Maui Irrigation Co., Ltd. provided cooperation and assistance in accessing the study area.

We would also like to acknowledge the many parties that attended the East Maui Streamflow Stakeholders and Aquatic Biology Working Group meetings for providing feedback and direction throughout the study. Those attending the Stakeholders meetings (Dec. 3, 2002; May 29 and Nov. 3, 2003; Feb. 4, and July 30, 2004) included representatives from the CWRM, EMI, Ltd., DAR, Alexander and Baldwin, Inc., Native Hawaiian Legal Corporation, Na Moku Aupuni O Koolau Hui, Maui Tomorrow, and the Maui County Department of Water Supply. Members attending the Aquatic Biology Working Group meetings (Oct. 20 and Dec. 15, 2003; June 14, 2004; Mar 3, 2005) include Robert Kinzie III, Allison Sherwood and Tara Sim (UH); Ronald Englund (Bishop Museum); John Ford (SWCA); Skippy Hau, Glenn Higashi, and Robert Nishimoto (DAR); James Parham (The University of Nebraska-Lincoln); Charles Ice, Ernest Lau, Dean Nakano, Edwin Sakoda, and Dean Uyeno (CWRM); Stephen Anthony, Anne Brasher, Stephen Gingerich, Gordon Tribble, and Reuben Wolff (USGS).

USGS employees that provided valuable field assistance in completing this project include Nathaniel Adams, Don Arnold, Gregory Berman, Anne Brasher, Henry Carter, Eden Feirstein, Richard Fontaine, Heather Jeppesen, Todd Presley, Nick Simon, Gordon Tribble, and Chiu Yeung. Anne Brasher also provided much of the design and organization of the biological data collection efforts.

The effects of surface-water diversions on habitat availability for native stream macrofauna were evaluated using models that relate the hydrology of the streams to the biology of the macrofauna that inhabit the streams. Various habitat data were collected for a subset of the streams in the study area and models were developed to incorporate these data. A relation between flow in the stream and habitat availability was then developed for the native species of interest. This relation was then applied to the rest of the streams in the study area to estimate habitat availability for diverted and natural conditions in each stream.

Habitat Selection Models

To address growing national concerns associated with the environment, the National Environmental Policy Act (NEPA) was enacted in 1969, (Sec. 2 [42 USC § 4321]):

> To declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man; to enrich the understanding of the ecological systems and natural resources important to the Nation; and to establish a Council on Environmental Quality.

This national policy for the environment was the motivation behind the design of new methods to quantify the effects of incremental changes in streamflow associated with an array of developmental alternatives (Stalnaker and others, 1995). The Instream Flow Incremental Methodology

(IFIM), a tool used to quantify the effects of incremental changes in streamflow, was developed to assess instream flow problems and assist in water management decision-making (Bovee, 1982). The development of many small hydropower projects and expanding urban development encroaching on and affecting river and stream systems in the 1970's and 1980's led to the design and refinement of tools that could be used to evaluate instream habitat quality and predict how the populations and communities inhabiting the streams and rivers would be changed by these effects. Many discussions about the IFIM approach have been published, and discussions of the pros and cons of this approach can be found in the literature (for example see Estes and Orsborn, 1986; Scott and Shirvell, 1987; Karim and others, 1995).

A number of these tools are referred to as habitat selection models, preference models, or habitat index models. The Physical Habitat Simulation System (PHABSIM) (Bovee, 1986; Bovee, 1997; Bovee and others, 1998) is an example of a habitat selection model for stream organisms and has been used in many studies that have assisted in many management decisions (Railsback and others, 2003). The basic mechanism behind habitat selection modeling involves combining the biological component with the hydrological component of a stream. Elements of the biological component usually include quantifying the frequency of microhabitat utilization of a target species. This is often compared with a measurement of microhabitat availability with the ratio of utilization to availability defined as preference criteria or habitat suitability criteria. The 'preferred' microhabitat is assumed the most advantageous for a specific activity and life stage of the target species. The hydrological component includes the determination of base-flow conditions and the stream geomorphology. Computer models like PHABSIM are used to merge these components to determine estimates of how much 'preferred' microhabitat area will be available for the target species with incremental changes in the amount of streamflow. Water-management decision makers can then use this information to mitigate the possible impacts on the stream biota (Railsback and others, 2003).

Definitions of Terms Used in this Report (modified from Bovee and others, 1998)

Macrohabitat: the set of conditions that control the longitudinal distribution of organisms along one of several environmental gradients: hydrology, geomorphology, temperature, water quality, or energy source.

Microhabitat: a subset of conditions defining the spatial attributes (for example, depth, velocity, and substrate) of physical locations within a stream.

Habitat availability: the proportion of microhabitat conditions present at a site regardless of the presence or absence of any macrofauna.

Habitat utilization (utilization criteria)*:* the proportion of microhabitat conditions occupied by the target species.

Utilization curve: a univariate habitat suitability index curve derived from observations and measurements of locations occupied by the target species. No correction of adjustment for habitat availability is made for a utilization curve.

*Habitat suitability criteri*a: graphical or statistical models that depict the relative utility of increments or classes of macro- or microhabitat variables to a life stage of a target species.

Utilization criteria: (Category II criteria): habitat suitability criteria developed by observing microhabitat conditions occupied by a target organism engaged in an activity (for example, spawning, resting, feeding) not accounting for habitat availability.

Nonparametric tolerance limits: technique used to determine a range of an independent variable within which a certain percentage of the population will be found.

Preference criteria (Category III criteria; electivity criteria): habitat suitability criteria developed by incorporating utilized *and* available microhabitat conditions for a target organism. The determination of habitat preference criteria requires habitat utilization to be a function of habitat availability and not simply a random function. The operational theory behind habitat preference assumes that fish will occupy or prefer certain areas (combinations of habitat parameters) available within the stream to other, less desirable available areas. If the preferred habitats are available within the stream, the fish will differentially occupy these areas. If the preferred habitats are not available within the stream, the fish will differentially occupy the next most favorable of the less desirable habitats and so on. An alternative to habitat preference is the random dispersal of the fish throughout the stream, occupying the available habitats proportionally to the percent the habitats are represented in the stream.

Representative reach: an intensively studied section of a stream selected to include a "typical" assemblage of flow regimes (riffles, runs, pools) in proportion to those regimes found along the entire stream section of interest.

Stream segment: a length of stream that is classified as being relatively homogenous with respect to flow reductions due to surface-water diversion.

Transferability: in order to apply the PHABSIM model to stream reaches where fish were not counted or not present, it must be shown that the habitat suitability criteria are transferable to other streams. In other words, the habitat suitability criteria developed in one stream should be able to predict accurately the habitat utilization in other streams based exclusively on habitat availability.

Previous Instream Flow Studies in Hawaii

A number of earlier studies have been conducted to determine habitat preferences of native benthic macrofauna in Hawaii. The U.S. Fish and Wildlife Service conducted the most extensive of these studies in collaboration with the UH and DAR during 1983–88 (Kinzie and others, 1984; Kinzie and others, 1986; Kinzie, 1988; Kinzie and Ford, 1988). The first part of their study focused on the development of habitat utilization curves for nakea, nopili, and alamoo (adults and juveniles) (Kinzie and others, 1984). Habitat utilization curves, based on observing the habitat ranges occupied by the fishes, were determined for the habitat parameters: mean water column velocity, depth, and substratum (streambed type). Observations were made at several sites on four Hawaii streams: Hanawi and Puaaluu Streams on Maui, and Wainiha and Hanakapiai Streams on Kauai. Study results indicated that adult nopili utilized faster flowing water than the other fish species, while adult nakea utilized deeper water and comparatively smaller substrate than the other species. The second part of their study integrated habitat utilization with habitat availability to determine habitat preference in an evaluation of the IFIM for Hawaiian streams (Kinzie and others, 1986). The third part of their study was to determine the transferability of the habitat preference curves to other streams (Kinzie and Ford, 1988). They concluded that their curves, developed for depth, velocity, and substrate independently, were not transferable between streams in their study area. However, they did not rule out the possibility that curves could be developed by using a different approach.

Thomas R. Payne and Associates (TRPA) conducted a series of instream flow studies in Hawaii during 1986–88 for various proposed hydroelectric projects (Thomas R. Payne and Associates, 1987; 1988a; 1988b). As part of an analysis of instream flow requirements, TRPA developed habitat utilization curves in Lumahai River on Kauai for nakea, nopili, opae, and hihiwai. TRPA also assessed instream flow for opae in undiverted sections of streams in the study area, East and West Wailuaiki and Kopiliula Streams. In this study, species criteria curves were developed from observations in East Wailuaiki Stream and used in PHABSIM models for sites on all three streams.

Studies conducted for the National Park Service investigated and compared the distributions, abundances, and habitat use of nakea, nopili, alamoo, hihiwai, and opae in Pelekunu and Waikolu Streams on Molokai (Brasher, 1996, 1997a, 1997b). Comparisons were made, along an elevational gradient, between the species assemblages and abundances in the undiverted Pelekunu Stream and the assemblages and abundances in the notably diverted Waikolu Stream. Brasher (1997b) determined that the reduced flow in Waikolu Stream resulted in a narrower range of habitat availability and greater species overlap in Waikolu than in the undiverted Pelekunu Stream. Her study showed that nakea utilized slow flowing, deeper habitats while nopili used mainly shallow habitats. Fishes in Pelekunu Stream utilized habitats that were not available in Waikolu Stream.

A series of geographic information system (GIS) spatially based models were created by Parham (2002) to address a statewide need for the conservation of native Hawaiian stream fishes. These models integrated major geomorphologic features to determine the distribution of fish habitat within stream reaches. Habitat suitability criteria were developed and integrated with an assessment of the migratory abilities of the fishes and used to quantify available habitat. A stream classification scheme, based on the stream's major morphological characteristics, was developed, and the available habitat was quantified for each stream type. Lastly, the distribution of these stream types and the amount of fish habitat were determined for each island.

A study conducted in the terminal reach of Wailoa Stream on the north shore of the island of Hawaii investigated microhabitat use by a variety of native and non-native fish species (McRae, 2001). Observations of adult and juvenile fishes were made at randomly selected quadrats in either a riffle or run habitat, and habitat parameters, including depth, substrate, velocity at the fish snout, bottom velocity, surface velocity, mean water column velocity, channel position, percent algae, and percent vegetation, were recorded at each fish location within each quadrat. Available habitat was determined by randomly selecting three locations within each quadrat and recording the same habitat parameters listed previously. McRae determined that microhabitat utilization differed between the gobies in the riffle habitat; nopili preferentially selected deeper, faster flows and larger substrates than were randomly available, whereas nakea displayed a moderate preference for shallower depths and slower velocities with a strong preference for sand substrate. The native fishes nakea, akupa, and naniha, in the run habitat, were determined to have much more overlap in microhabitat utilization, but coexistence in the run habitat was attributed to differences in foraging behaviors and feeding morphologies.

Stream Habitat and Macrofauna Data Collection

Stream habitat and macrofauna data must be collected in order to determine habitat availability under existing conditions and to provide information that is used in the development and application of the linked hydrologic/biologic models. Detailed observations were made in the intensively studied streams and reconnaissance level observations (including snorkel survey and substrate classification) were made in the remaining streams in the study area.

Intensively Studied Streams

A 300- to 500-ft length of the channel was investigated at each of the intensively studied reaches on Waikamoi, Honomanu, Wailuanui, Kopiliula, and Hanawi Streams to collect data that could be used for habitat modeling of the stream reaches. The upstream and downstream boundaries were resolved so that the reach (1) was representative of the larger stream segment in terms of flow regimes (riffles, runs, and pools) and substrate; (2) did not include any inputs or withdrawals from tributaries or diversions; and (3) did not include any problematic features such as waterfalls. Two study reaches (Honomanu and Waikamoi lower) included dry segments at low-flow conditions.

Stream habitat and macrofauna data collected as part of the intensive surveys are available to download via the Internet at the U.S. Geological Survey Pacific Islands Water Science Center Website at http://hi.water.usgs.gov/projects/project_emaui_data.htm. The website includes hand drawn maps of each study reach, plots of each transect location, and spreadsheets containing information such as water depth and velocity, substrate, species type, and species size.

Transects

Transect locations within each study reach were determined using a stratified random design. The study reach was stratified at the level of three habitat types: riffle, run, and pool. Riffles were defined as stream sections with high gradient, and shallow, fast-moving turbulent water; runs were defined as stream sections with moderate to fast-flowing water with minimal turbulence; and pools were defined as low gradient, deeper stream sections with negligible flow. Within the study reach, the length and location of each discrete riffle, run, and pool were determined. The individual lengths were summed by habitat type and the proportion of each habitat type within the study reach was calculated. Seven to ten transects were located within each study reach (except at the Honomanu lower site). The number of transects per habitat type was calculated on the basis of the proportion of the habitat type within the study reach. Once it was determined how many transects per habitat category were to be established, the locations of the discrete habitat type to be surveyed and the downstream distance within the habitat type were determined using random numbers from a computer-generated random numbers table. Brightly colored vinyl flagging tape was labeled and placed on the stream bank to mark each location.

Stream morphology at each transect was determined using turning point leveling. Relative streambed and water-surface altitudes were measured at 1-ft intervals across each transect and all transects in an individual reach were surveyed to a common datum to provide a vertical and horizontal representation of each intensively studied reach. Measuring points for determining stage-discharge relations in individual pools and runs and the point of zero flow for the individual pools and runs with measuring points were also surveyed to the same common datum at each reach.

Macrohabitat

At each transect, a semi-permanent boundary marker (16-penny galvanized nail) was cemented into a boulder or tacked into a tree on each stream bank. These semi-permanent markers ensured precision because they allowed the location of each transect to be determined by survey and allowed the exact locations of the transects to be reoccupied for resampling. A tagline, flagged at 1-ft intervals, was stretched from bank to bank and interval numbers increased from left to right (fig. 3). Habitat-related information including flow regime, depth, velocity, potential channel width (estimated as edge of stream bank vegetation), active channel width, riparian density (determined with a densiometer), canopy cover (determined with a clinometer), and stream bank substratum were recorded at each transect (fig. 4).

Microhabitat and Macrofauna Abundance

Information on habitat availability and utilization was recorded at each transect. Each transect was subdivided into rectangular cells 1 ft wide, as flagged on the tagline, and extending 2 ft downstream of the tagline. A minimum waiting period of 20 minutes was observed after the disturbance of the tagline being stretched across the stream to allow the animals to return to their normal behaviors. Kinzie and others (1984) noted that the native fish in Hawaiian streams returned to normal activities in less than one minute after an observer disturbance. All observations were made during daylight hours. The abundances of stream fauna (fish, shrimp, and snails) in each cell were quantified using snorkel surveys. Snorkelers entered the water downstream of the tagline and stealthily made their way upstream to the downstream end of the cell. All the macrofauna in each cell were identified to the species level. Fish that were too small to identify (less than 1 in.) were classified as fry (table 1). The total length of each native fish was visually estimated. Steel bolts of known size were used as references that were visually rechecked at the start of each survey. The maximum diameters of the hihiwai were determined using calipers after Brasher (1997a). The snails were carefully placed downstream of the observer, after their maximum diameters were determined, to prevent duplicate counting. The cell locations of individual animals were recorded, and the habitat variables (depth, velocity, and substrate) were measured at each individual cell following the completion of the fish survey. Depth was determined as the height of the water column at the center of each cell. Velocity was determined as the 0.6-depth water-column velocity at the center of each cell. Where emergent substrate was in the center of the cell, measurements were made in the remaining submerged part of the cell. Substrate was visually determined as the percent bottom cover of each substrate category (table 2) within each cell. The percent of each cell that was not completely submerged was recorded where applicable.

Figure 3. Snorkeler observing fish at a transect. Flagging tape on tagline is at 1-ft intervals.

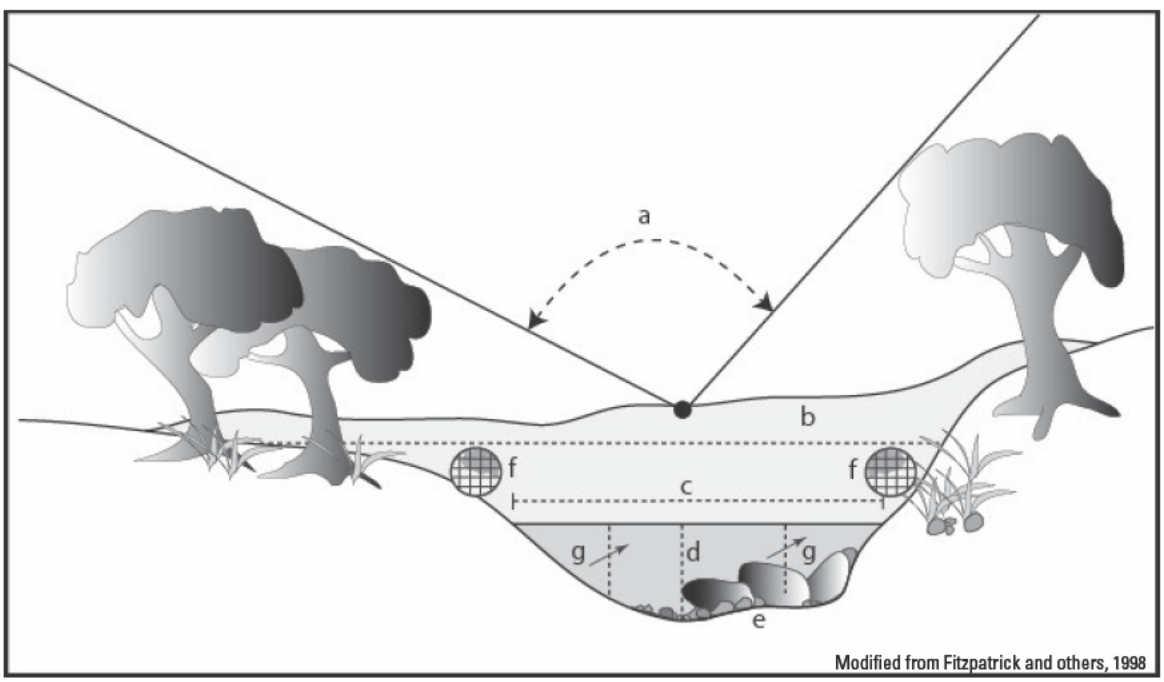


Figure 4. Habitat variables measured at each transect. (a) Open canopy angle; (b) potential channel width; (c) active channel width; (d) cell depth; (e) substrate composition; (f) riparian cover; and (g) flow.

Table 1. Size class categories for select native Hawaiian fishes (from Kinzie and others, 1984).

[Abbreviations: <, less than; >, greater than]

Species	Size class category (inches)		
	Fry	Juvenile	Adult
Lentipes concolor (alamoo)	< 1	1 – 1.75	> 1.75
Awaous guamensis (nakea)	< 1	1 – 3	> 3
Sicyopterus stimpsoni (nopili)	< 1	1 – 1.5	> 1.5

Table 2. Substrate size range categories (modified from Brasher, 1997b).

[Abbreviations: n/a, not applicable; >, greater than]

Substrate category	Size range	
	Inches	Millimeters
Organic Debris (Org)	n/a	n/a
Sand (Sd)	0.002 - 0.08	> 0.05 - 2
Gravel (Gr)	> 0.08 - 0.8	> 2 - 20
Cobble (Cb)	> 0.8 - 4	> 20 - 100
Rock (Rk)	> 4 - 12	> 100 - 300
Boulder (Bl)	> 12	> 300
Bedrock (Br)	n/a	n/a

Replicate observations were made at the Kopiliula lower site to compare the repeatability of the habitat variables measured and to provide a comparison of seasonal changes in species or habitat occurrence. Measurements were first collected on August 20–21, 2002 and then repeated on July 21–22, 2003 (table 3). Discharge was higher during the second visit, hence the observed depths, water velocities and calculated Froude numbers were slightly higher in each transect relative to the first visit. The overall distribution and abundance of species compares well between the first and second visit, with about 14 percent fewer individuals observed during the second visit relative to the first visit. Overall, the substrate classification generally agreed between the first and second visit (table 3). The overall stream morphology changed very little between the first and second survey, mainly due to the abundance of larger material in the reach and the lack of significant high streamflow to rearrange this larger material. This replicate sampling was done to show the general repeatability of measurements at an individual transect over time and was not designed to be a rigorous statistical analysis of sampling repeatability. Such an analysis was beyond the time and budget constraints of this project.

Stream Water Temperature

Stream water temperatures, which could have an effect on stream ecology and taro cultivation, were measured at 13 of the intensively studied stream reaches in 5 streams in the study area—Waikamoi, Honomanu, Wailuanui, Kopiliula, and Hanawi Streams (fig. 2). Temperature measurements were not made at the Waikamoi and Honomanu lower sites because these stream reaches were usually dry.

Field Methods

Stream temperatures were measured every 15 minutes using StowAway® Tidbit® thermistors from Onset Computer Corporation that were designed to operate in the -20°C to 50°C temperature range. Each thermistor was calibrated in the laboratory following USGS procedures (U.S. Geological Survey, 1997 to present) before installation in the field. Each thermistor was installed inside an 8-in. piece of 1.25-in. diameter galvanized steel pipe bolted into the stream channel below the lowest water level expected. Monitoring locations were in the shade, where possible, and chosen to avoid potentially stagnant or zero-flow reaches of the stream channel. Each thermistor was field checked in place using a calibrated alcohol thermometer during each site visit when data were retrieved. The 15-min temperature data collected as part of this study are obtainable in digital form by contacting the USGS Pacific Islands Water Science Center. The periods over which stream temperatures were monitored ranged from 13 to 20 months with a common monitoring period for all sites between October 10, 2002 and September 25, 2003 (table 4). Comparisons of temperature results between stream monitoring sites are referenced to this common monitoring period.

Results and Discussion of Temperature Measurements

Average stream temperatures ranged from 16.8°C to 21.6°C with the lowest temperatures measured generally at the highest altitude sites (table 4). The exception is at the Hanawi middle site, where the lowest average temperatures in the study area were measured downstream from Big Spring. The site with the highest average temperatures, Wailuanui lower, is downstream of where several taro loi (ponds) discharge water into the stream channel. Water that travels through taro loi tends to be warmer due to solar heating in the shallow, open-water bodies. Water temperatures increased in a downstream direction in Waikamoi and Wailuanui Streams, indicating only minor input of colder ground water nearer the coast. In Hanawi and Kopiliula Streams, water temperatures decreased in a downstream direction, indicating that colder ground water is discharging into these streams between monitoring sites.

Table 3. Comparison of habitat observations at the Kopiliula lower site for August 2002 and July 2003, northeast Maui, Hawaii.

[Transect Kopiliula-lower-4 was not observed during first site visit. Abbreviations: ft^3/s; cubic ft per second; ft; foot, ft/sec, foot per second]

Date of observations	Discharge (ft^3/s)	Average depth (ft)	Average velocity (ft/sec)	Average Froude number	Number of species observed					Percentage of substrate category						
					Hihiwai	Nopili	Nakea	Akupa	Aholehole	Bedrock	Boulder	Cobble	Rock	Gravel	Sand	Organic
Kopiliula-lower-1																
8/20/2002	2.4	0.34	0.38	0.12	41	12	1	0	1	0	40	15	23	3	0	19
7/21/2003	4.1	.34	.51	.20	52	8	1	0	0	0	28	21	8	9	2	33
Kopiliula-lower-2																
8/20/2002	2.4	.84	.15	.03	20	9	3	1	1	0	58	15	18	9	0	0
7/22/2003	3.0	.87	.01	.02	42	1	9	3	1	0	58	15	18	9	0	0
Kopiliula-lower-3																
8/20/2002	2.4	.73	.17	.04	56	11	18	2	6	0	68	9	13	10	0	0
7/21/2003	4.1	.87	.21	.04	41	6	12	2	3	0	60	15	18	5	0	0
Kopiliula-lower-5																
8/21/2002	2.1	.58	.14	.03	45	6	4	0	0	0	73	12	13	2	0	0
7/21/2003	4.1	.59	.16	.04	53	2	0	1	0	8	52	17	19	4	0	0
Kopiliula-lower-6																
8/21/2002	2.1	1.67	.04	.01	0	0	11	1	5	5	41	17	20	15	2	0
7/21/2003	4.1	1.68	.07	.01	1	1	5	0	5	8	50	11	18	13	1	0
Kopiliula-lower-7																
8/21/2002	2.1	.54	.12	.03	57	13	6	2	1	0	78	6	13	4	0	0
7/22/2003	3.0	.63	.21	.05	52	6	5	0	0	0	80	5	15	1	0	0
Kopiliula-lower-8																
8/21/2002	2.1	.76	.09	.02	22	5	9	1	1	0	58	12	21	10	0	0
7/22/2003	3.0	.64	.16	.04	1	8	5	0	0	0	54	21	17	8	0	0
Kopiliula-lower-9																
8/21/2002	2.1	.73	.01	.02	31	15	6	0	2	0	61	8	23	7	2	0
7/21/2003	4.1	.72	.17	.04	14	12	6	0	0	0	63	11	10	16	0	0
Kopiliula-lower-10																
8/21/2002	2.1	.73	.12	.03	2	5	5	0	0	0	52	14	17	13	4	0
7/22/2003	3.0	.51	.22	.06	1	10	5	0	0	0	47	15	13	24	1	0
Total in reach																
8-02					274	76	63	7	17							
7-03					257	54	48	6	9							

Table 4. Fifteen-minute temperature data from selected stream sites, northeast Maui, Hawaii.

[˚C, degrees Celsius]

Site	Altitude (feet)	Period of record	Temperature (˚C)			Percent of readings over 27˚C	Longest period over 27˚C (hours)	Temperature (˚C)		
			Average during common period	Range during common period	Average daily variation during common period			Average	Range	Daily variation
Hanawi										
Upper	1,318	10/9/02–11/25/03	19.2	14.3–24.9	1.1	0.00		19.3	14.3–24.9	1.1
Middle	500	10/9/02–1/16/04	16.8	15.3–21.4	0.9	.00		16.9	15.3–21.4	.9
Lower	20	10/9/02–1/15/04	18.5	15.7–21.4	1.6	.00		18.6	15.7–21.4	1.5
Kopiliula										
Upper	1,292	8/6/02–11/25/03	18.9	13.8–23.4	1.4	.00		19.2	13.8–23.4	1.4
Middle	580	8/6/02–1/16/04	21.1	15.2–28.5	3.0	.57	5	21.1	15.2–28.5	2.7
Lower	15	8/9/02–1/16/04	20.7	15.4–27.2	2.3	.02	2	20.8	15.4–27.2	2.1
Wailuanui										
Upper	1,287	8/6/02–4/15/04	19.4	14.0–25.8	2.2	.00		19.3	14.0–25.8	2.0
Middle	640	8/6/02–9/25/03	20.2	15.2–25.2	1.7	.00		20.4	15.2–25.2	1.7
Lower	20	7/30/02–11/25/03	21.6	15.8–25.1	1.7	.00		21.8	15.8–25.8	1.6
Honomanu										
Upper	1,733	8/26/02–1/14/04	18.1	13.6–23.9	1.4	.00		18.2	13.6–23.9	1.4
Waikamoi										
Upper	1,294	10/10/02–1/14/04	19.6	14.2–30.7	1.4	.05	1.5	19.5	14.2–30.7	1.3
Middle-upper	720	8/26/02–1/15/04	21.2	15.4–28.9	2.6	.44	6.5	21.2	15.4–28.9	2.4
Middle-lower	505	8/8/02–4/15/04	21.3	15.6–26.3	2.3	.00		21.1	15.6–26.3	2.1

Daily fluctuations in temperature ranged from about 0.9°–3.0°C (figs. 5-9) with the smallest daily fluctuations recorded downstream of the ground-water input from Big Spring. The lowest temperatures were measured generally between 6:00 a.m. and 7:00 a.m. and the highest temperatures were measured generally between 1:00 p.m. and 2:00 p.m. Seasonal temperature fluctuations ranged about 10° to 16°C in all sites but the Hanawi middle and lower sites, downstream from Big Spring, where the seasonal fluctuations were only about 6°C. The coldest temperatures were measured in February and the warmest in the summer months of June through August.

Water temperature is important to the aquatic biota living in the streams as well as to taro cultivation using diverted stream water. In general, the stream temperatures measured at any of the monitoring sites were not elevated enough to adversely effect native aquatic macrofauna growth or mortality or high enough to cause wetland taro to be susceptible to fungi and associated rotting diseases. Temperatures greater than 30°C have been shown to affect native species growth adversely whereas temperatures of 33° — 35°C are considered maximum temperatures for native species survival (Hathaway, 1978). Penn (1997) uses 27°C as the threshold temperature above which wetland taro are more susceptible to these diseases. The average measured stream water temperatures were well below this threshold at all monitored sites. A small percentage (less than one percent) of the 15-min measurements was above 27°C at four of the sites (Kopiliula middle and lower, and Waikamoi upper and middle-upper) during the study (table 4). The longest period when temperatures were above 27°C was 6.5 hours at the Waikamoi middle-upper site.

Hydrologic Conditions at Time of Study

Overall hydrologic conditions in the study area were drier than normal during the period when stream reaches were intensively studied (7/30/02–7/23/03). Median daily streamflow at gaging station 5180 (West Wailuaiki Stream) near the middle of the study area (pl. 1) during this period was 5.6 ft^3/s whereas long-term median daily streamflow (1914–2001) was 10 ft^3/s (Gingerich, 2005). In general, streamflow has to be 20–30 ft^3/s at the 1,700–1,400 ft diversion before water will overtop the diversion dams and flow downstream to the lower reaches. Most of the habitat and streamflow measurements were made during base-flow conditions when all flow was diverted at the 1,700-1,400 ft diversion and only flow gained downstream of the diversion was measured at the middle and lower sites (fig. 10). The exception was at the Honomanu lower site, where the diverted stream is dry; therefore, habitat and streamflow measurements were made at a higher flow condition such that flows overtopped the diversion dam, allowing water to flow to the lower site.

Streamflow, measured at the time that habitat measurements were made, was below the estimated median total flow at diverted conditions for each respective stream reach at 9 of the 15 sites and below the estimated median base flow at diverted conditions at 6 of the 15 sites (table 5). In general, the persistent low streamflow conditions during the study meant that aquatic habitat measurements were made during the driest conditions.

Stream Reconnaissance Surveys on Other Streams in Study Area

Intensive study and subsequent habitat modeling was limited to five reference streams in the study area. The effects of streamflow on habitat in other streams therefore was estimated on the basis of information gathered using a variety of techniques including field reconnaissance, aerial digital photography of the streams, and GIS analysis of stream and stream-basin characteristics. Stream reconnaissance surveys were conducted in as many streams as could be reached by hiking, to identify significant gaining or losing reaches, and to provide information on additional factors, other than flow, that may control the occurrence of native species. For example, natural factors that might limit upstream migration of native species include waterfalls and landslides. Human-related factors include introduced alien aquatic species, diversion structures, waste discharges, and stream-channel modifications.

Where accessible by hiking, lower, middle, and upper reaches of each reconnaissance-level stream were visited to observe stream and habitat conditions at sites comparable to the lower, middle, and upper intensively studied sites. A brief snorkel survey was made at each site along a 100-ft reach and native and introduced species and individuals were counted (appendix A). Visual classification of the reach type (riffles, runs, pools) and substrate percentages were made and stream temperature was measured. In addition, any significant waterfalls, springs, dry reaches, and stream diversions were noted and, if possible, GPS coordinates were obtained for these features.

A series of high-resolution digital photographs was obtained with a helicopter-mounted camera along each stream in the study area from the coast to about 1,700 ft altitude. Although heavy vegetative cover and a lack of georeferencing for these images limits their use for digital analysis, the images were useful for determining the locations of significant features along each stream, including large waterfalls and pools (pl. 1).

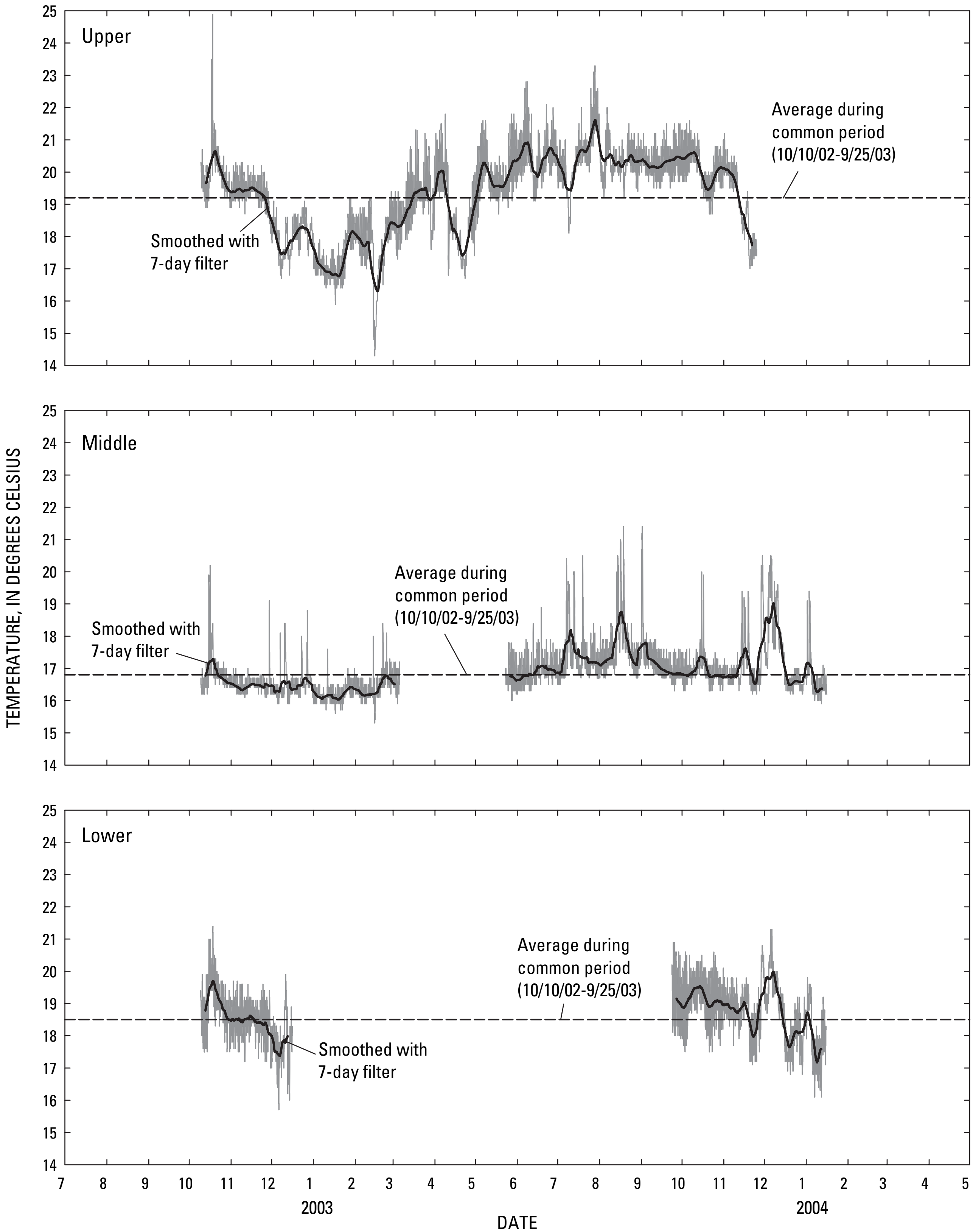


Figure 5. Temperature measurements in Hanawi Stream, northeast Maui, Hawaii.

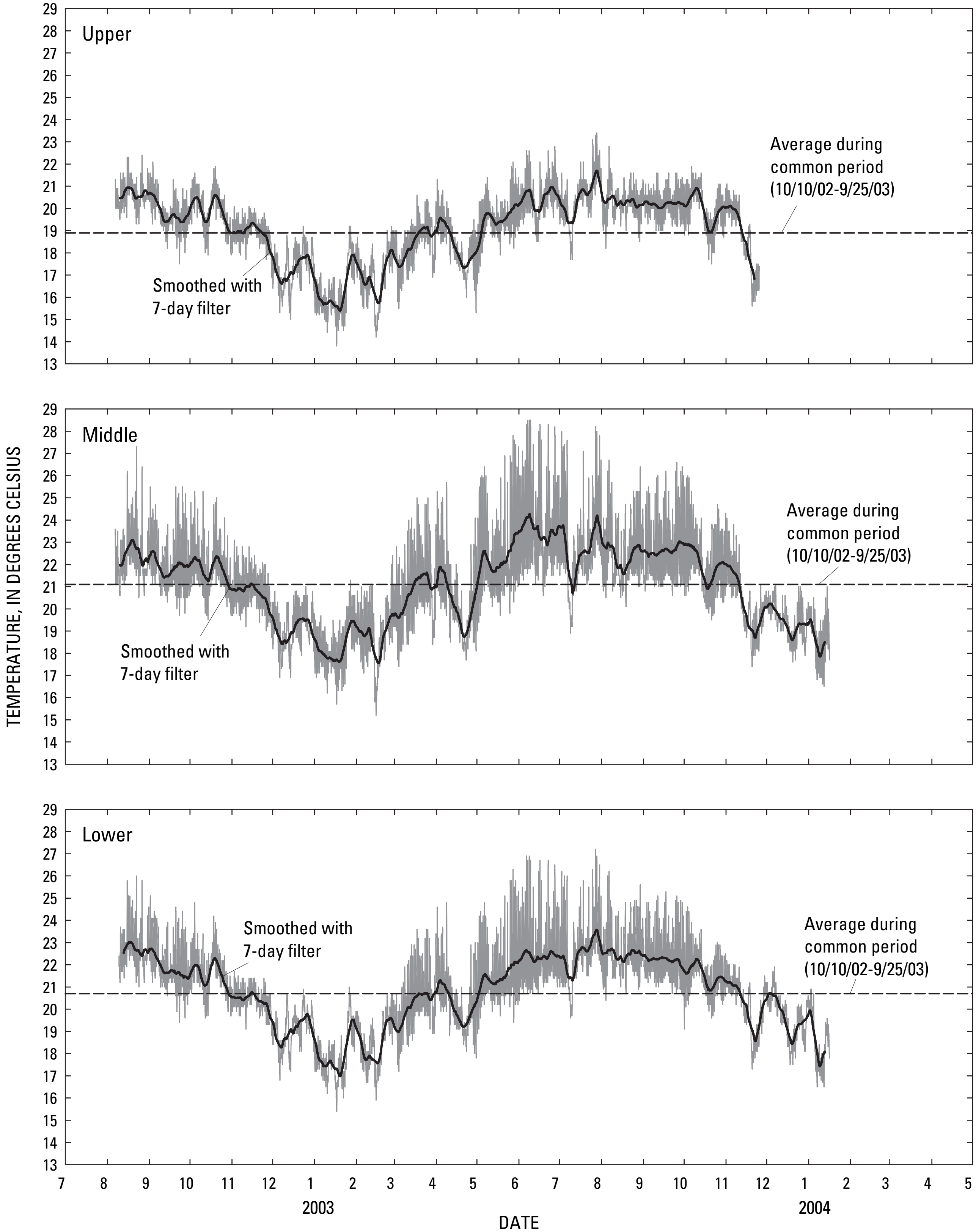


Figure 6. Temperature measurements in Kopiliula Stream, northeast Maui, Hawaii.

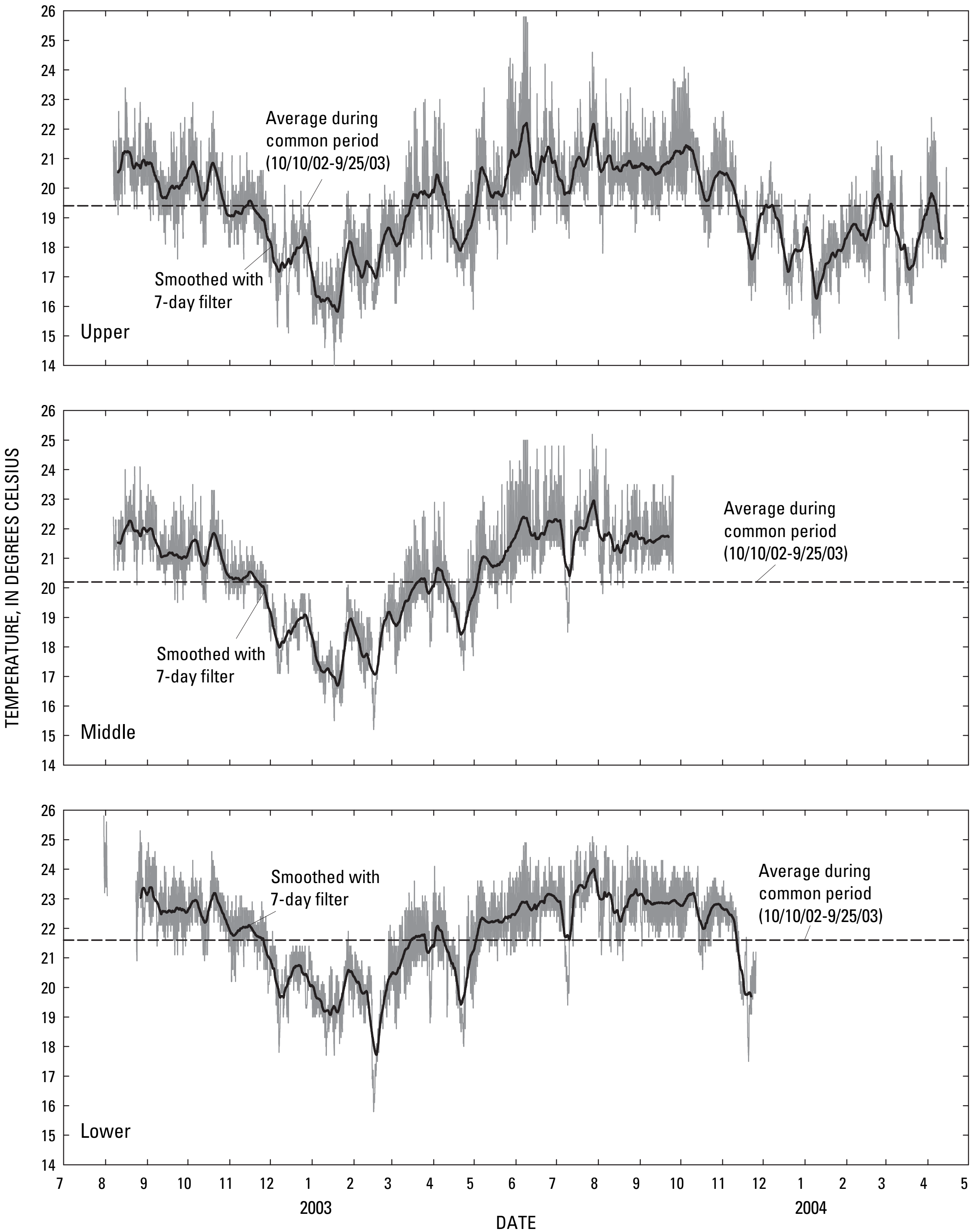


Figure 7. Temperature measurements in Wailuanui Stream, northeast Maui, Hawaii.

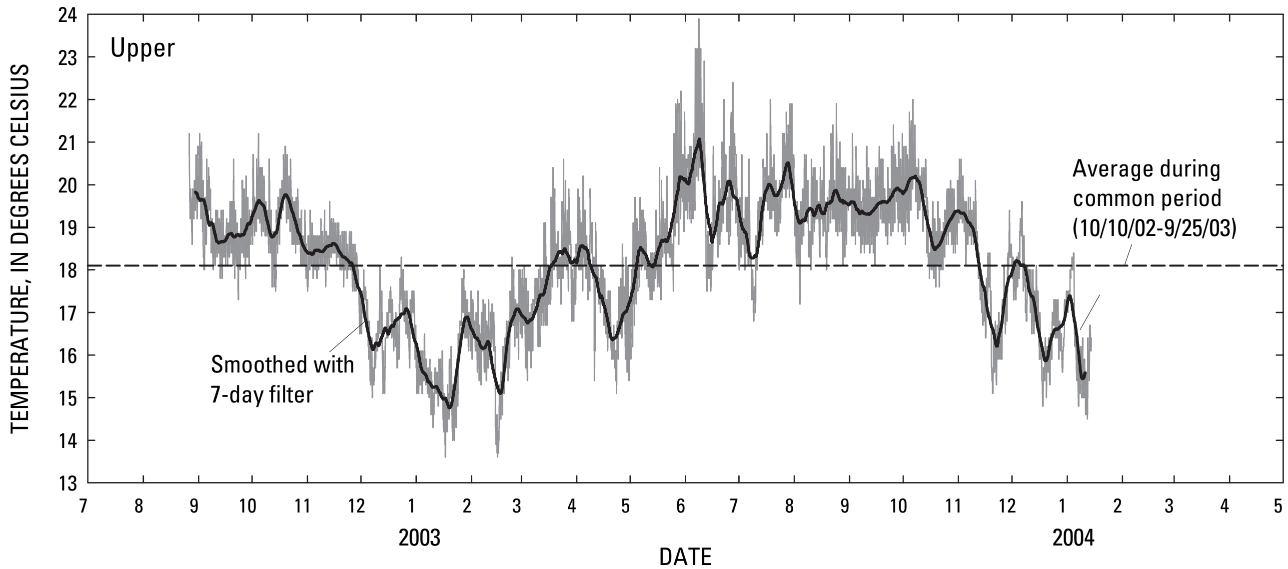


Figure 8. Temperature measurements in Honomanu Stream, northeast Maui, Hawaii.

Numerical Habitat Modeling of Intensively Studied Streams

The availability of aquatic habitat was estimated for diverted and undiverted conditions at the intensively studied stream sites using PHABSIM, an approach that combines one-dimensional hydraulic modeling of water depth and velocity with data indicating aquatic species preferences (Waddle, 2001). Hydrologic data, collected over a range of low-flow discharges, were used to calibrate hydraulic models of selected transects across the streams. The models were then used to predict water depth and velocity (expressed as a Froude number, a combination of depth and velocity) over a discharge range up to estimates of natural median streamflow determined during this study (Gingerich, 2005). The biological importance of the stream hydraulic attributes was then assessed with the suitability criteria for each native species and life stage (where available) to produce a relation between discharge and habitat availability. The final output was expressed as a weighted habitat area of streambed (synonymous with weighted usable bed area in Waddle, 2001) for a representative stream reach. Selected information needed to set up the PHABSIM models is listed in table 6.

Water Depth and Stage-Discharge Relations

PHABSIM calculates water-surface elevations using one or any combination of (1) stage-discharge or rating curves, (2) Manning's equation, or (3) step-back-water water-surface profiles (Waddle, 2001). For this study, estimated water-surface elevations were determined using stage-discharge relations developed for individual pools or runs containing biology transects in each intensively studied stream reach. The stage-discharge relations were developed from sets of stream-discharge and water-surface elevation measurements collected at each stream reach during various low-flow and median-flow conditions. Water-surface elevations were measured relative to a set of semi-permanent measuring points drilled into bedrock or large boulders along the selected stream reach as near as possible to the locations of biology transects. In each reach, the altitude of each of the measuring points, each 1-ft segment of the cross-channel biology transects, and the thalweg of the stream reach were determined to a common datum using turning-point leveling surveys. A description of the method used to estimate the stage-discharge relations from field data and plots of all stage-discharge relations used in the PHABSIM models are included in appendix B. In the stage-discharge application of PHABSIM, each individual transect is considered independently and is not hydraulically connected to the other transects in the stream reach. However, water-surface elevations for individual transects along a stream reach were compared to ensure that they "made sense" hydraulically, i.e. that water would not flow uphill from transect to transect.

It was not possible to develop measurement-based stage-discharge relations for the biology transects in some of the riffles because riffle sections commonly have highly variable water-surface elevations along the transect and over time. Therefore, stage-discharge relations for the riffles were estimated in two ways to cover the range of possible water-surface elevations that could be expected in a riffle by assuming (1) no water-surface elevation rise with increased

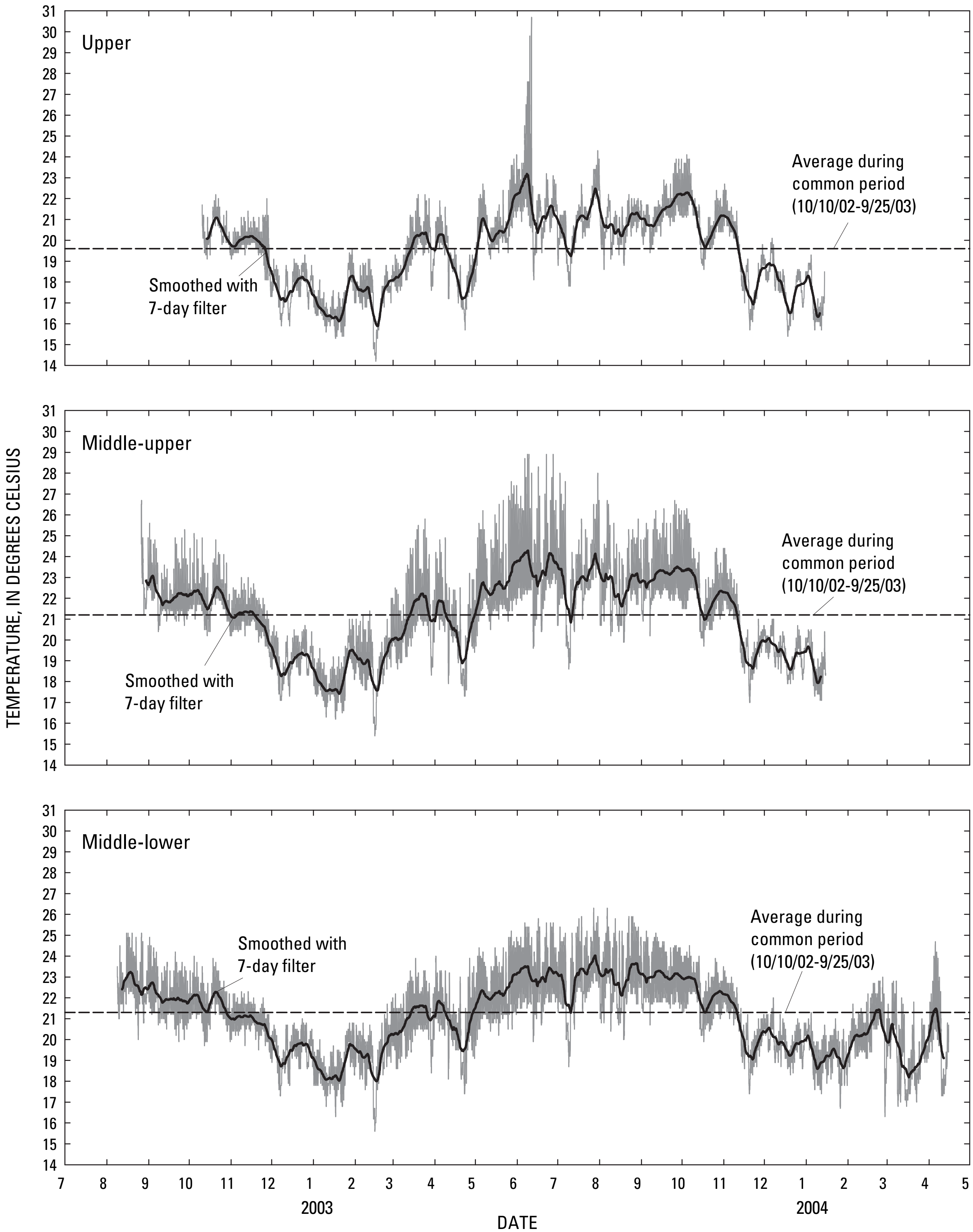


Figure 9. Temperature measurements in Waikamoi Stream, northeast Maui, Hawaii.

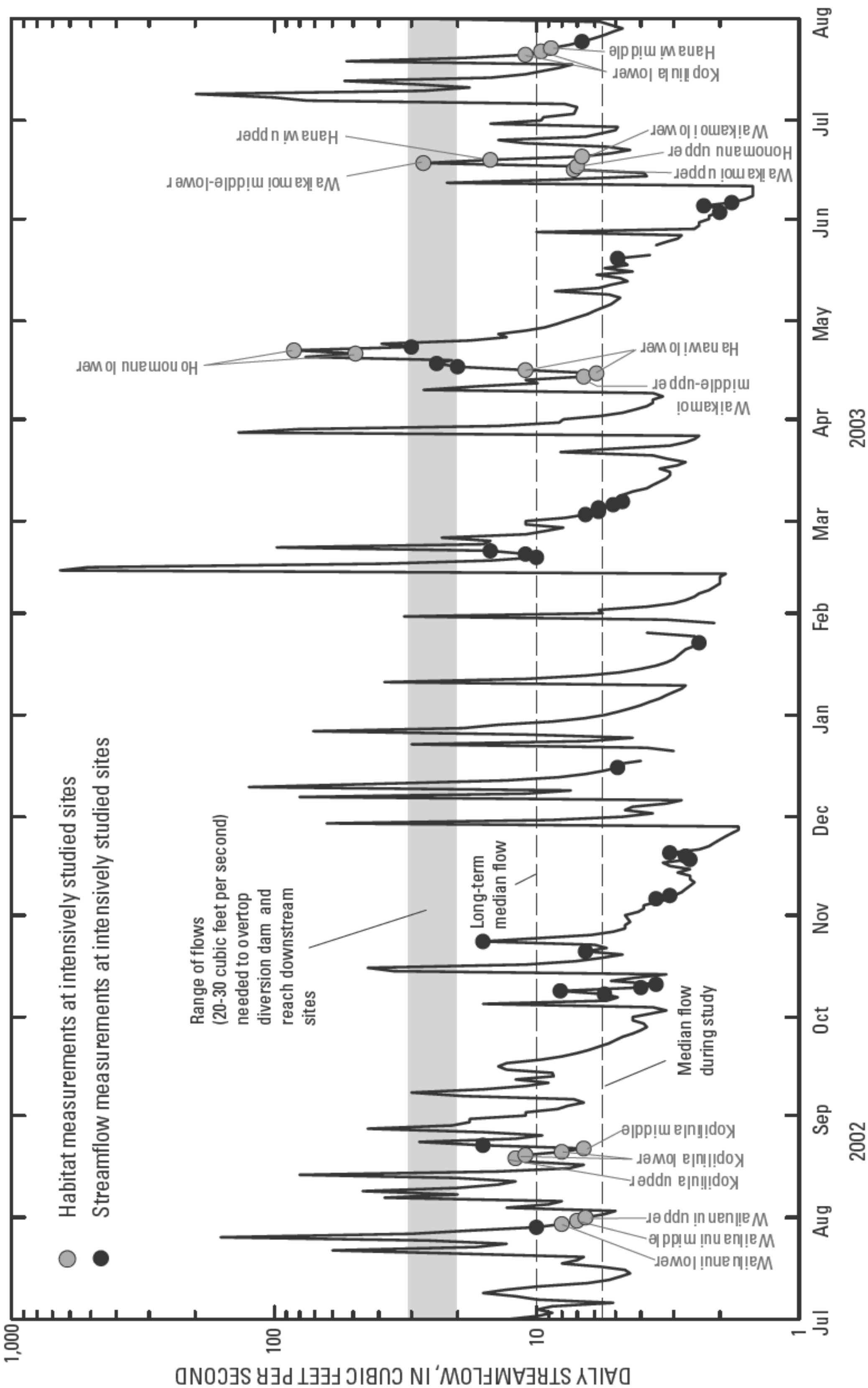


Figure 10. Timing of habitat and low-flow measurements compared to streamflow at gaging station 5180 (West Wailuaiki), northeast Maui, Hawaii.

Table 5. Comparison of median base flow under diverted conditions to flow conditions when stream habitat measurements were made, northeast Maui, Hawaii.

[Values of median base flow from Gingerich (2005). Number in ***bold italic*** is considered maximum at site downstream of unquantified but known losing reach, ft^3/s, cubic foot per second]

Stream site	Estimated median total flow under diverted conditions (ft^3/s)	Estimated median base flow under diverted conditions (ft^3/s)	Streamflow during habitat measurements (ft^3/s)
Hanawi lower	25	21	20
Hanawi middle	12	11	5.7
Hanawi upper	7.1	4.6	11–12
Kopiliula lower	4.7	2.8	2.1, 4.1
Kopiliula middle	2.0	1.2	0.71
Kopiliula upper	8.0	5.0	10
Wailanui lower	1.7	1.1	2.7
Wailuanui middle	1.6	1.0	1.4
Wailuanui upper	3.2	2.0	2.6
Honomanu lower	***8.7***	.0	1.9–12
Honomanu upper	5.7	2.8	8.2
Waikamoi lower	.80	.50	.020
Waikamoi middle lower	.40	.20	.10
Waikamoi middle upper	2.3	1.6	.84
Waikamoi upper	7.0	3.5	7.2

discharge, or (2) the same stage-discharge relation as the nearest run. The first method (model A) would be most appropriate for a steep riffle where increased discharge would result in faster water velocity but little or no rise in water level, whereas the second method (model B) would be appropriate for a flatter riffle that responded to increased discharge similarly to a run. PHABSIM simulations were developed for both models to determine a likely habitat range that would be available with increased discharge.

The stage-discharge relations, which were developed independently of PHABSIM, were manually inserted into the simulations to force PHABSIM results to produce the desired water-surface elevations. Discharge increases averaged about 6 ft^3/s from diverted to natural median base flows in the diverted reaches that were simulated in this study. For this average increased discharge, water-surface elevation increases for all transects (riffles and runs) in the diverted reaches averaged about 0.29 ft when using reach model A and about 0.39 ft when using reach model B. The reach having the highest average rise in water level was at the Waikamoi middle-lower site, where water-level rises in all of the modeled transects averaged about 0.5 ft and 0.8 ft when using models A and B, respectively. In general, the middle reaches of the modeled streams had the greatest rises in water levels, primarily because these reaches currently have the lowest flows due to diversions and lack of significant ground-water input. The reach having the lowest average rise in water level was at the Hanawi Lower site, where water-level rises in all of the transects averaged about 0.02 ft and 0.03 ft when using riffle models A and B, respectively. Because the median base flow in this reach is relatively high (about 21 ft^3/s) compared to the amount diverted upstream (about 4 ft^3/s), the water-level rise from diverted to undiverted conditions is relatively small.

Velocity Estimation

Water velocities in the stream transects are estimated using PHABSIM after water levels are estimated. Velocities are modeled for each transect independently using an empirical approach. Typically, velocities are estimated at the center of each 1-ft wide cell in the transect and compared to velocities that were measured at the corresponding location in the stream. Ideally, velocity measurements collected at several different discharges could be used as calibration targets for the model. The calibration is achieved by adjusting local values of Manning's number (n), a measure of streambed roughness, until modeled velocities closely match measured values (Waddle, 2001). For this study, this approach was not feasible due to several factors, including the lack of opportunity to collect velocity measurements at higher discharges and the complexity of water flow in the streambed at the low-flow conditions available during the study. Instead, to generalize

Table 6. Selected information needed for PHABSIM models from intensively studied stream sites, northeast Maui, Hawaii.

[Measuring points shown in italics were used to estimate water-surface elevations for simulations at sites where stage-discharge relations were not developed. Estimated, stage-discharge relation developed to allow a 1 foot rise in water level at upper range of desired discharge. Abbreviations: PHABSIM, Physical Habitat Simulation System Model; Wi, Waikamoi; Hn, Honomanu; W, Wailuanui; Kp, Kopiliula; Hw, Hanawi; U, upper; M, middle; L, lower; MP, measuring point; c, cascade; 5080, USGS gaging station 16650800]

Stream	Site	Distance from downstream end of reach (feet)			Transect no.	Source of stage-discharge relation used in model	Representative reach length used in PHABSIM model (feet)
		Riffle	Run	Pool			
Waikamoi	Upper			0-29	1	WiU-MP1	17
		29-45					
			45-60		2	WiU-MP2	12.5
		60-77			3	WiU-MP3	12.5
			77-99				
		99-111			4	*WiU-MP4*	12.5
			111-124				
		124-138					
			138-147		5	WiU-MP4	12.5
				147-240	6, 7	WiU-MP4	17, 17
Total length		59	59	122			100
Percentage of reach		25	25	51			100
Waikamoi	Middle-upper			0-35	1	WiMU-MP1	11.5
			35-50		2	WiMU-MP1	10
		50-55					
			55-72				
		72-83					
			83-96		3	WiMU-MP2	10
		96-107					
				107-143	4	WiMU-MP2	11.5
		143-152					
			152-171				
		171-177					
				177-193	5	*WiMU-MP2*	11.5
		193-200					
				200-258	6	*WiMU-MP2*	11.5
		258-271					
			271-300		7	*WiMU-MP2*	10
		300-312			8	*WiMU-MP2*	24
Total length		74	93	145			100
Percentage of reach		24	30	46			100

Table 6. Selected information needed for PHABSIM models from intensively studied stream sites, northeast Maui, Hawaii.—Continued

[Measuring points shown in italics were used to estimate water-surface elevations for simulations at sites where stage-discharge relations were not developed. Estimated, stage-discharge relation developed to allow a 1 foot rise in water level at upper range of desired discharge. Abbreviations: PHABSIM, Physical Habitat Simulation System Model; Wi, Waikamoi; Hn, Honomanu; W, Wailuanui; Kp, Kopiliula; Hw, Hanawi; U, upper; M, middle; L, lower; MP, measuring point; c, cascade; 5080, USGS gaging station 16650800]

Stream	Site	Distance from downstream end of reach (feet)			Transect no.	Source of stage-discharge relation used in model	Representative reach length used in PHABSIM model (feet)
		Riffle	Run	Pool			
Waikamoi	Middle-lower			0-48			
			48-56		B1, B2	WiML-MPC	10, 10
		56-63					
				63-85			
			85-93				
		93-100					
			100-119				
				119-144	B3, B4	WiML-MP1	12, 12
			144-149				
		149-152					
			152-163				
		163-193			B5	*WiML-MP1*	11
			193-211		B6	*WiML-MP1*	10
		211-214					
			214-226				
				226-254	B7, B8	WiML-MP2	12
		254-267					
			267-277				
		277-281			B9	*WiML-MP2*	11
				281-305			
Total length		67	91	147			100
Percentage of reach		22	30	48			100
Honomanu	Upper	0-13			B1	*HnU-MP2*	13.7
			13-35		B2	HnU-MP2	11.7
				35-78	B3	HnU-MP2	12
		78-98			B4	*HnU-MP3*	13.7
			98-121		B5	HnU-MP3	11.7
				121-130	B6	HnU-MP3	12
			130-145				
				145-166			
		166-196			B7	HnU-MP4	13.7
			196-220				
		220-267					
			267-288		B8	HnU-MP6	11.7
		288-300					
Total length		122	105	73			100
Percentage of reach		41	35	24			100

Table 6. Selected information needed for PHABSIM models from intensively studied stream sites, northeast Maui, Hawaii.—Continued

[Measuring points shown in italics were used to estimate water-surface elevations for simulations at sites where stage-discharge relations were not developed. Estimated, stage-discharge relation developed to allow a 1 foot rise in water level at upper range of desired discharge. Abbreviations: PHABSIM, Physical Habitat Simulation System Model; Wi, Waikamoi; Hn, Honomanu; W, Wailuanui; Kp, Kopiliula; Hw, Hanawi; U, upper; M, middle; L, lower; MP, measuring point; c, cascade; 5080, USGS gaging station 16650800]

Stream	Site	Distance from downstream end of reach (feet)			Transect no.	Source of stage-discharge relation used in model	Representative reach length used in PHABSIM model (feet)
		Riffle	Run	Pool			
Honomanu	Lower		0-100		B1, B2, B3, B4	HnL-MP1, HnL-MP2, HnL-MP3, HnL-MP3	25, 25, 25, 25
Total length		0	100	0			100
Percentage of reach		0	100	0			100
Wailuanui	Upper		0-15		B1, B2	WU-MPC	10.3, 10.3
		15-43					
				43-57			
		57-58c					
			58-67		B3	WU-MP1	10.3
		67-86			B4	WU-MP2	21
			86-102				
		102-127			B5	*WU-MP2*	21
				127-148	B6	WU-MP3	13.5
		148-159c					
			159-181				
				181-201	B7	WU-MP4	13.5
Total length		84	62	55			100
Percentage of reach		42	31	27			100
Wailuanui	Middle	0-12c					
			12-33				
				33-50			
		50-66c			B1	*WM-MP1*	17
		66-106					
		106-118c					
		118-129c			B2	*WM-MP1*	17
		129-145					
				145-167			
		167-176			B3	*WM-MP1*	15
				176-206	B4	*WM-MP1*	11.5
				206-239	B5	*WM-MP1*	11.5
		239-268			B6	WM-MP1	15
		268-278c					
		278-292c					
			292-309		B7	*WM-MP1*	12
Total length		199	38	72			100
Percentage of reach		64	12	23			100

Table 6. Selected information needed for PHABSIM models from intensively studied stream sites, northeast Maui, Hawaii.—Continued

[Measuring points shown in italics were used to estimate water-surface elevations for simulations at sites where stage-discharge relations were not developed. Estimated, stage-discharge relation developed to allow a 1 foot rise in water level at upper range of desired discharge. Abbreviations: PHABSIM, Physical Habitat Simulation System Model; Wi, Waikamoi; Hn, Honomanu; W, Wailuanui; Kp, Kopiliula; Hw, Hanawi; U, upper; M, middle; L, lower; MP, measuring point; c, cascade; 5080, USGS gaging station 16650800]

Stream	Site	Distance from downstream end of reach (feet)			Transect no.	Source of stage-discharge relation used in model	Representative reach length used in PHABSIM model (feet)
		Riffle	Run	Pool			
Wailuanui	Lower	0-26			B1	WL-MPC	15
			26-55				
		55-70					
			70-154		B2, B3	WL-MP2	11, 11
		154-216					
			216-234		B4	WL-MP2	11
		234-247			B5	WL-MP2	15
			247-270		B6	WL-MP3	11
		270-294			B7	WL-MP4	15
			294-314		B8	WL-MP4	11
Total length		140	174	0			100
Percentage of reach		45	55	0			100
Kopiliula	Upper		0-32				
		32-51			B1	KpU-MP1	13.5
			51-59				
		59-94			B2	*KpU-MP1*	13.5
			94-105		B3	KpU-MP2	13.3
		105-144			B4	*KpU-MP2*	13.5
			144-160		B5	KpU-MP3	13.3
		160-184					
			184-198		B6	*KpU-MP3*	13.3
		198-257			B7	*KpU-MP3*	13.5
			257-302				
				302-326	B8	KpU-MP4	7
Total length		176	127	24			100
Percentage of reach		54	39	7			100

Table 6. Selected information needed for PHABSIM models from intensively studied stream sites, northeast Maui, Hawaii.—Continued

[Measuring points shown in italics were used to estimate water-surface elevations for simulations at sites where stage-discharge relations were not developed. Estimated, stage-discharge relation developed to allow a 1 foot rise in water level at upper range of desired discharge. Abbreviations: PHABSIM, Physical Habitat Simulation System Model; Wi, Waikamoi; Hn, Honomanu; W, Wailuanui; Kp, Kopiliula; Hw, Hanawi; U, upper; M, middle; L, lower; MP, measuring point; c, cascade; 5080, USGS gaging station 16650800]

Stream	Site	Distance from downstream end of reach (feet)			Transect no.	Source of stage-discharge relation used in model	Representative reach length used in PHABSIM model (feet)
		Riffle	Run	Pool			
Kopiliula	Middle			0-113	B1	KpM-MPC	18
		113-163			B2	*KpM-MP1*	14
		163-179					
			179-261		B3	KpM-MP1	9
		261-291					
			291-339		B4	KpM-MP2	9
		339-392					
			392-434		B5	KpM-MP3	9
				434-457			
			457-523		B6	KpM-MP4	9
		523-562			B7	KpM-MP5	14
				562-617	B8	KpM-MP6	18
				617-663			
Total length		188	238	237			100
Percentage of reach		28	36	36			100
Kopiliula	Lower		0-21				
		21-54			B1	KpL-MP1	24
			54-99		B2	KpL-MP2	8
				99-128	B3	KpL-MP2	9
			128-152				
				152-192	B4	*KpL-MP2*	9
			192-217		B5	*KpL-MP2*	8
		217-227c					
				227-293	B6	KpL-MP3	9
		293-336					
			336-382		B7	*KpL-MP4*	8
		382-388c					
			388-409		B8	KpL-MP4	8
				409-435			
			435-457		B9	KpL-MP5	8
				457-510	B10	KpL-MP5	9
Total length		122	203	175			100
Percentage of reach		24	41	35			100

Table 6. Selected information needed for PHABSIM models from intensively studied stream sites, northeast Maui, Hawaii.—Continued

[Measuring points shown in italics were used to estimate water-surface elevations for simulations at sites where stage-discharge relations were not developed. Estimated, stage-discharge relation developed to allow a 1 foot rise in water level at upper range of desired discharge. Abbreviations: PHABSIM, Physical Habitat Simulation System Model; Wi, Waikamoi; Hn, Honomanu; W, Wailuanui; Kp, Kopiliula; Hw, Hanawi; U, upper; M, middle; L, lower; MP, measuring point; c, cascade; 5080, USGS gaging station 16650800]

Stream	Site	Distance from downstream end of reach (feet)			Transect no.	Source of stage-discharge relation used in model	Representative reach length used in PHABSIM model (feet)
		Riffle	Run	Pool			
Hanawi	Upper	0-40			B1	HwU-MP1	14
			40-66		B2, B3	HwU-MP1	11, 11
		66-73c					
			73-93		B4	5080 staff plate	11
				93-129	B5	5080 staff plate	12
			129-152				
		152-180			B6	*5080 staff plate*	14
			180-191				
		191-215			B7	*5080 staff plate*	14
				215-235	B8	HwU-MP2	12
Total length		99	80	56			100
Percentage of reach		42	33	24			100
Hanawi	Middle	0-30			B1, B2	*HwM-MP7*	15.3, 15.3
				30-50	B3, B4	HwM-MP6	7.5, 7.5
		50-98					
			98-144		B5,B6	HwM-MP7	8, 8
		144-172			B7	HwM-MP8	15.3
			172-187		B8	HwM-MP8	8
		187-218c					
			218-232				
				232-300	B9, B10	HwM-MP9	7.5, 7.5
Total length		137	75	88			100
Percentage of reach		46	24	30			100
Hanawi	Lower	0-60			B1	*HwL-MP3*	10
			60-88				
		88-159			B2	*HwL-MP3*	10
			159-182		B3	HwL-MP3	10
		182-194			B4, B5	HwL-MP4	10, 10
			194-325		B6, B7	HwL-MP4	10, 10
		325-485			B8, B9	HwL-MP6	10, 10
			485-500		B10	HwL-MP7	10
Total length		303	197	0			100
Percentage of reach		61	39	0			100

the model for representative conditions, the velocity estimates at any vertical in the transect were directly related to the flow depth by first distributing the velocities across the transect using the equation

$$v_i = [1.486 S_e^{1/2} d_i^{2/3}] / q_i \ , \qquad (1)$$

where:

v_i is mean column velocity for an individual cell, *i*, in the transect, in feet per second,

S_e is energy slope for the transect,

d_i is individual cell depth, in feet, and

q_i is discharge through an individual cell, in cubic feet per second.

The distributed velocities were then scaled using a velocity adjustment factor to maintain mass balance between the measured discharge in the transect and the sum of the modeled discharges (modeled velocity multiplied by cell area) for each individual cell in the transect. Manning's *n* was set at a value of 0.06 for all cells in all transects and held constant throughout the range of streamflow simulated. The modeled results were compared to measured velocities in the riffle, run, and pool transects to determine that the modeled velocities reasonably matched typical field conditions.

The magnitude and range of velocities simulated by the PHABSIM transect models compare favorably with the velocity measurements made in the streams (figs. 11-13). These plots show the distribution of velocity measurements made in the run, pool, and riffle transects. The median velocity and the range of velocities that includes 90 percent of the measurements are also indicated. The plots also show the range and median velocities estimated from the PHABSIM models for the natural and diverted conditions. The plot showing the riffle transects includes velocity information for riffle models A and B.

The median measured water velocity for diverted conditions (sites downstream of major diversions) in cells (*n*=945) in run habitat was 0.14 ft/s and the median modeled water velocity in 527 cells representing run habitat for diverted conditions was 0.12 ft/s (table 7). The median measured water velocity for natural conditions (sites upstream of major diversions) in run habitat was 0.25 ft/s (*n*=374) and the median modeled water velocity in cells representing run habitat for estimated natural conditions (sites upstream and downstream of major diversions) was 0.30 ft/s (*n*=972). Higher water velocities are expected under natural conditions because greater streamflow generally results in deeper and faster water movement. Median measured and simulated water velocities for cells in pool and riffle habitat compare similarly (table 7), and both habitat types have higher velocities under natural conditions. For natural-condition riffle habitats, modeled velocities are highest for model A, when the riffles are constrained to have no water-level rise with increased streamflow as more water is forced through the same stream transect. However, modeled velocities are closest to measured velocities for model B, in which the water-level rises are based on stage-discharge relations from nearby runs.

The PHABSIM documentation recommends that the approach used for estimating water velocity in this study be used only where field conditions prevent the collection of reliable velocity measurements at several discharges (Waddle, 2001). For this study, velocity measurements were collected in each cell during the biological surveys but were not used directly to calibrate the velocity model because of two factors: (1) the lack of velocity measurements for higher streamflow under natural conditions and (2) the variable flow patterns caused by the rough stream bed and complex channel geometry at low flow in the stream reaches. Because the diversion systems collect all low streamflow up to 80 percent of the time (Gingerich, 2005), the only time during the study when the stream downstream of the major diversions was flowing at a desired higher discharge was immediately before or after a high streamflow event. During these times, it was not practicable or safe to measure velocity at the study reaches because of rapidly changing streamflow and water levels in the streams. Therefore, little opportunity was available to confirm estimated conditions at higher flows with measured values from the streams. Efforts to get controlled water releases past the diversions so velocity measurements could be made safely and reliably were unsuccessful. Although velocity measurements were available for lower, diverted streamflow conditions, the modeled velocity values were not directly calibrated to these measurements. The velocities resulting from the simplistic one-dimensional cross-sectional models cannot be expected to reproduce the velocities measured in the highly complex three-dimensional flow domain of the stream channel. However, the velocity distributions simulated by the PHABSIM models are reasonable representations of generalized conditions in the stream and are considered adequate for estimating usable habitat area based on these flow conditions.

Estimation of Usable Habitat Area

The habitat program HABTAE within PHABSIM was used to estimate habitat area for the simulated streamflow of interest. HABTAE uses the depth and velocity estimates from the earlier modeling stages and suitability criteria for each species and life stage to predict the streambed area represented by an individual transect that will have habitat suitable for each species and life stage of interest. The suitability criteria developed in this study relate the depth and water velocity, expressed as the Froude number, and the substrate to suitable habitat for adult and juvenile alamoo, hihiwai, adult and juvenile nakea, adult and juvenile nopili, and opae, (appendix C). Specific settings in HABTAE were used to tailor the simulation (Waddle, 2001). A velocity replacement setting of 4 allowed the program to consider the Froude number, a combination of depth and velocity, rather than the standard approach of considering depth and velocity independently. Because the aquatic species of interest are benthic, the program option to simulate usable streambed area rather than usable water column area was selected. The standard

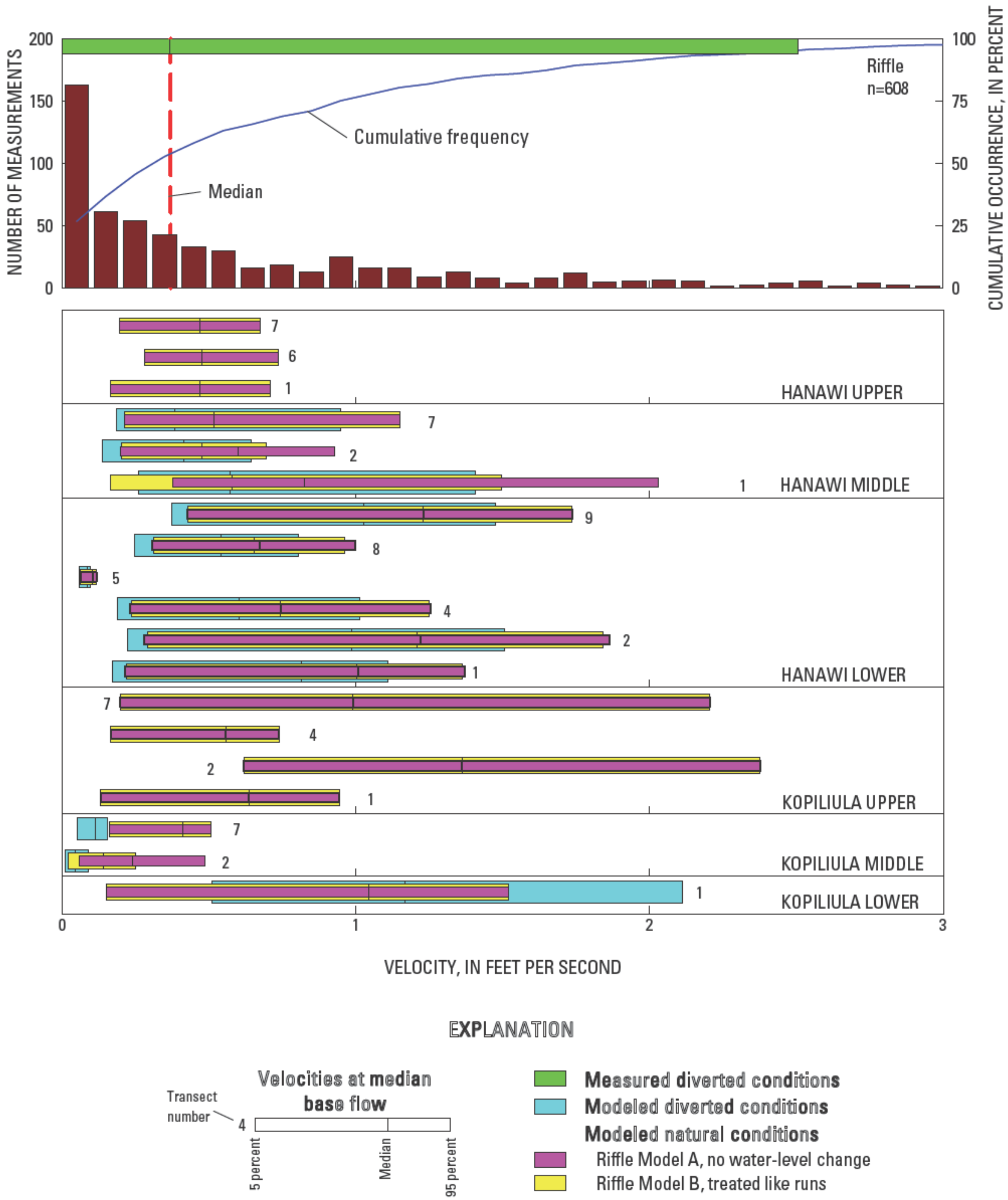


Figure 11. Comparison of PHABSIM modeled velocity values to measured velocities for all riffle transects in stream study reaches, northeast Maui, Hawaii.

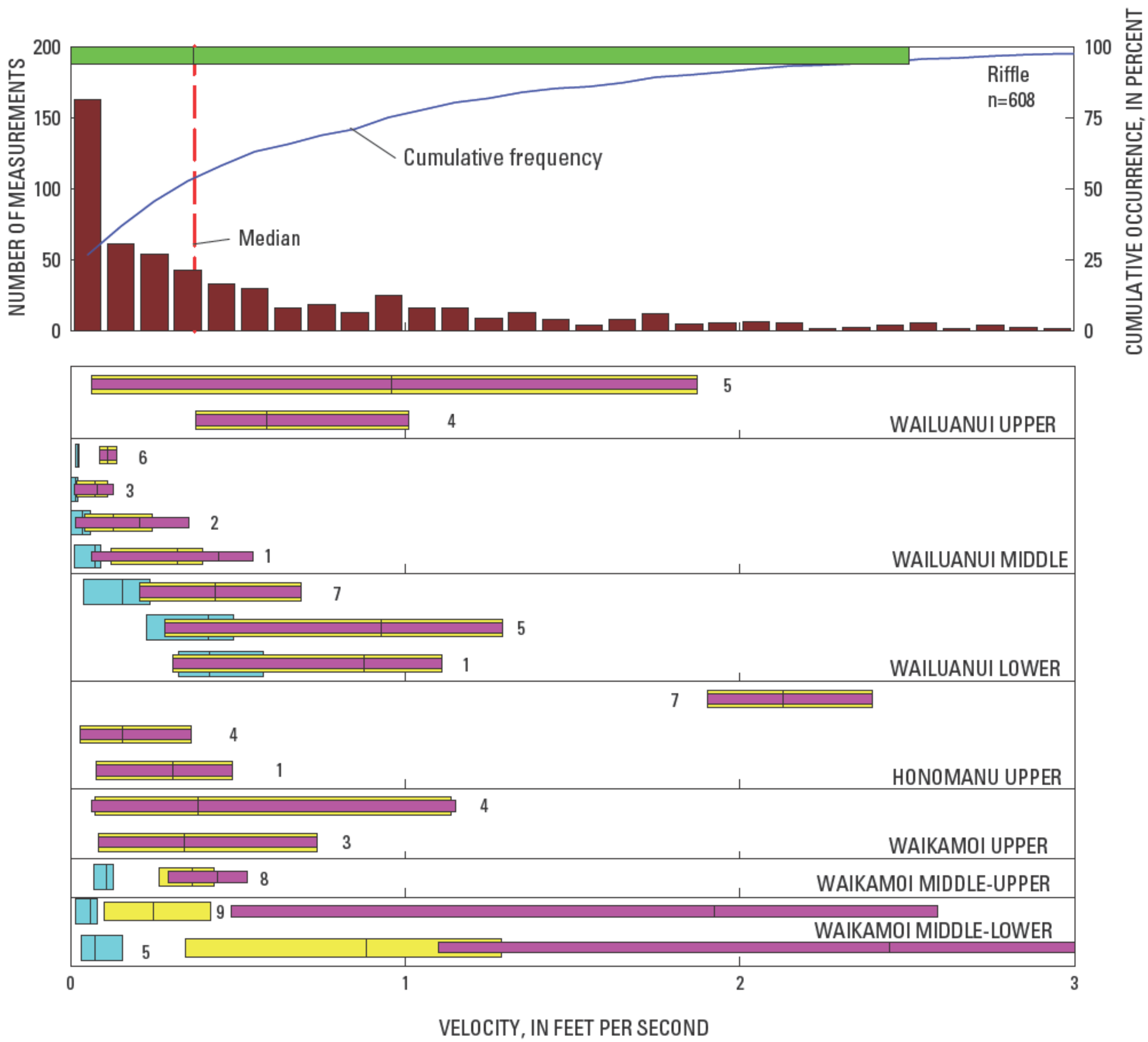


Figure 11. Comparison of PHABSIM modeled velocity values to measured velocities for all riffle transects in stream study reaches, northeast Maui, Hawaii—*Continued.*

multiplicative calculation was used to derive the composite index (*CI*) score for each cell using the equation

$$CI_i = Fr_i * S_i , \qquad (2)$$

where:

Fr_i is the Froude number suitability for cell i, ranging from 0 to 1, and

S_i is the substrate suitability for cell i, ranging from 0 to 1.

The resulting *CI* value, combined with the surface area of the streambed for various streamflow conditions, represents the weighted suitability, where a suitability of 1.0 indicates maximum habitat for the indicated species and life stage. The habitat area represents the sum of the products of the *CI* values and surface areas for all transect cells in the study reach. PHABSIM models were run using both sets of depth and velocity conditions developed for the two methods of treating riffles in the models.

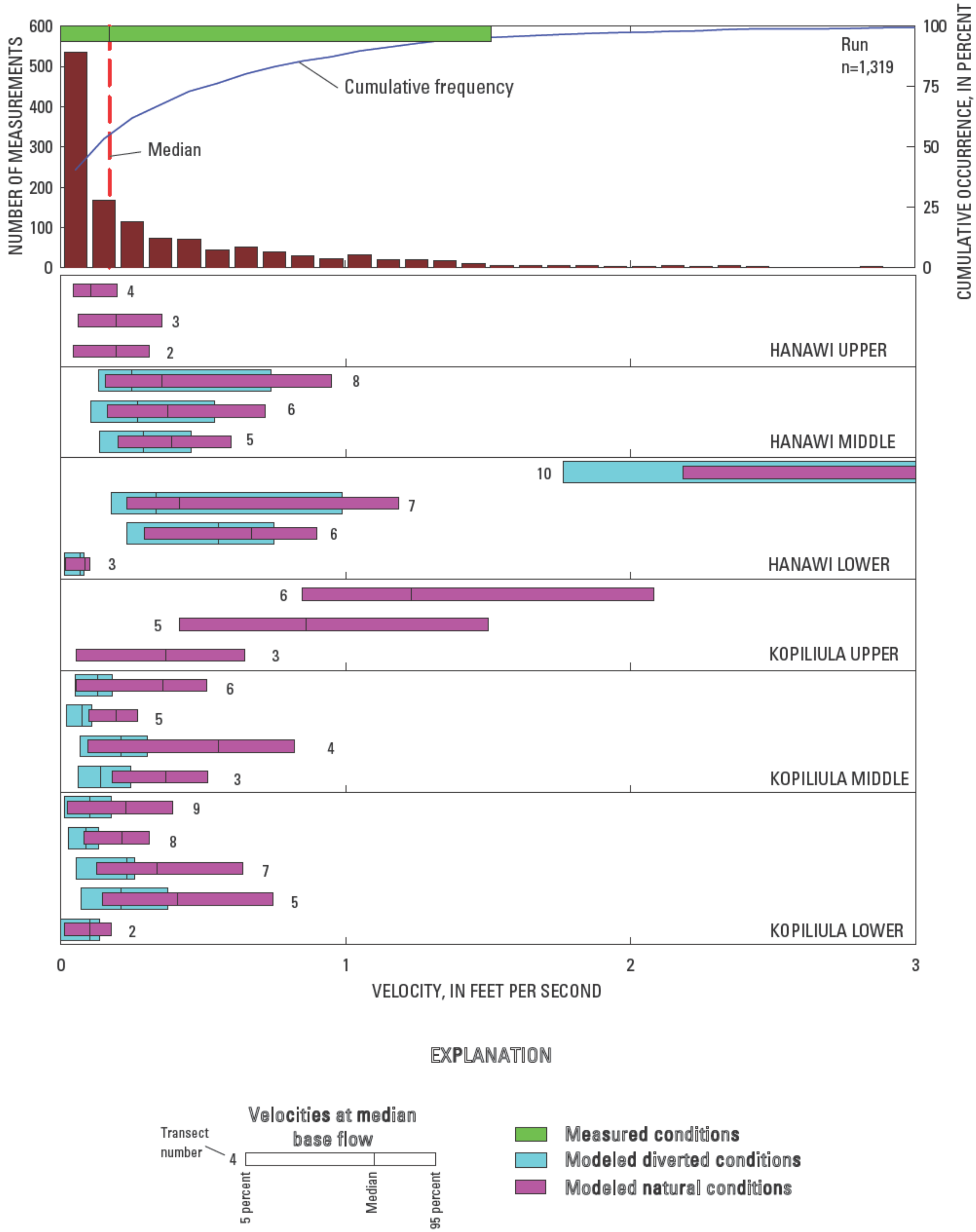


Figure 12. Comparison of PHABSIM modeled velocity values to measured velocities for all run transects in stream study reaches, northeast Maui, Hawaii.

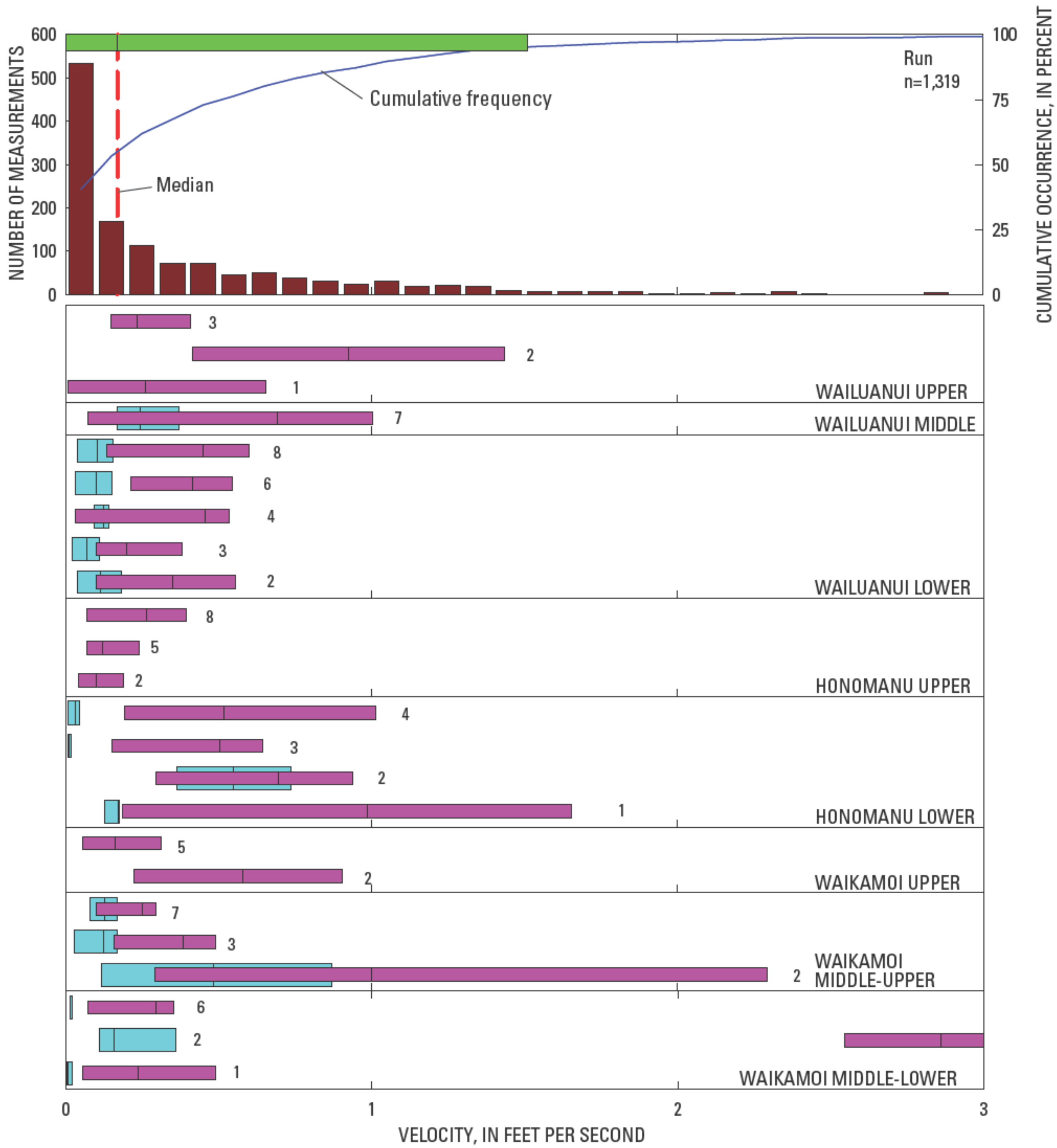


Figure 12. Comparison of PHABSIM modeled velocity values to measured velocities for all run transects in stream study reaches, northeast Maui, Hawaii—*Continued.*

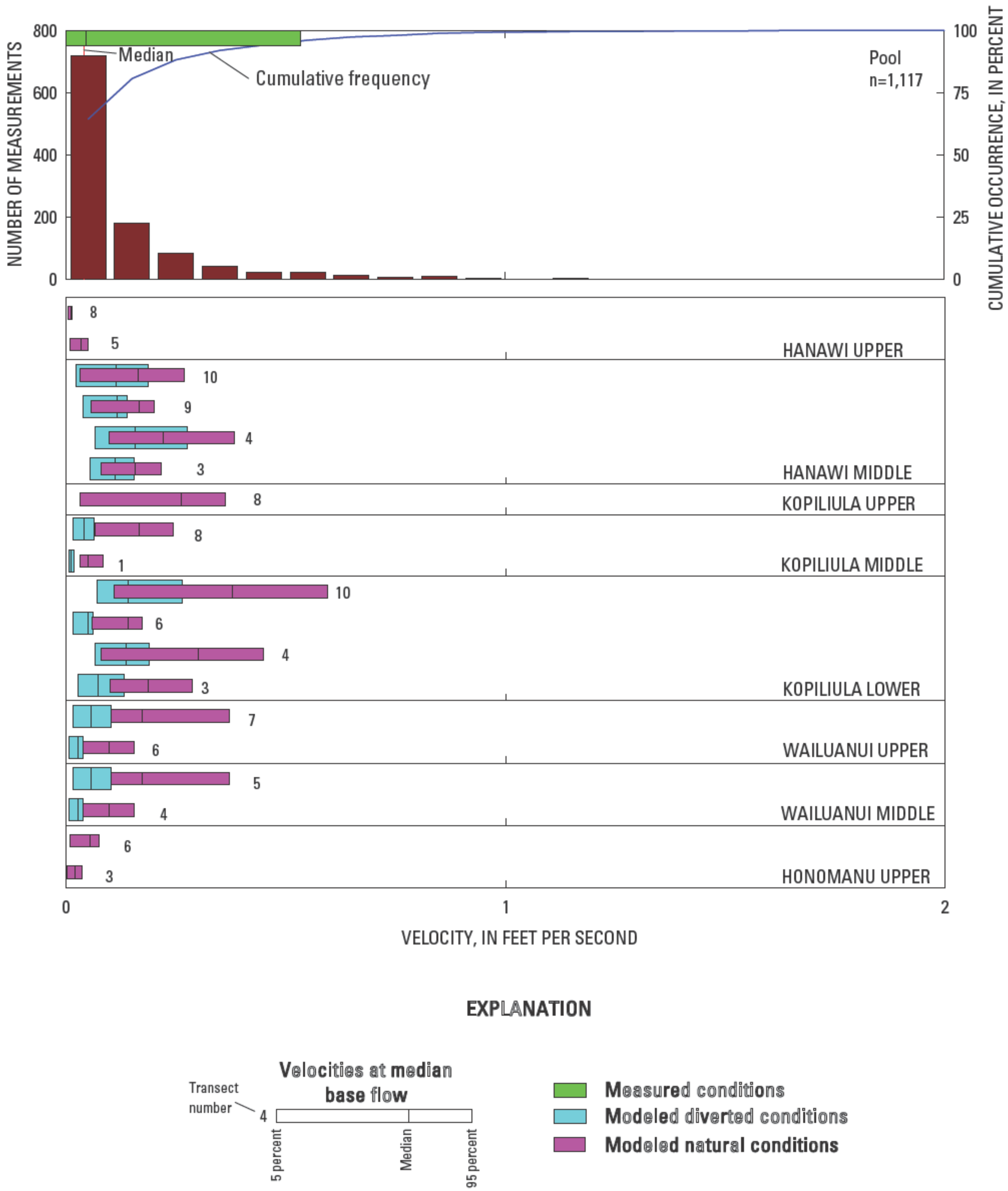


Figure 13. Comparison of PHABSIM modeled velocity values to measured velocities for all pool transects in stream study reaches, northeast Maui, Hawaii.

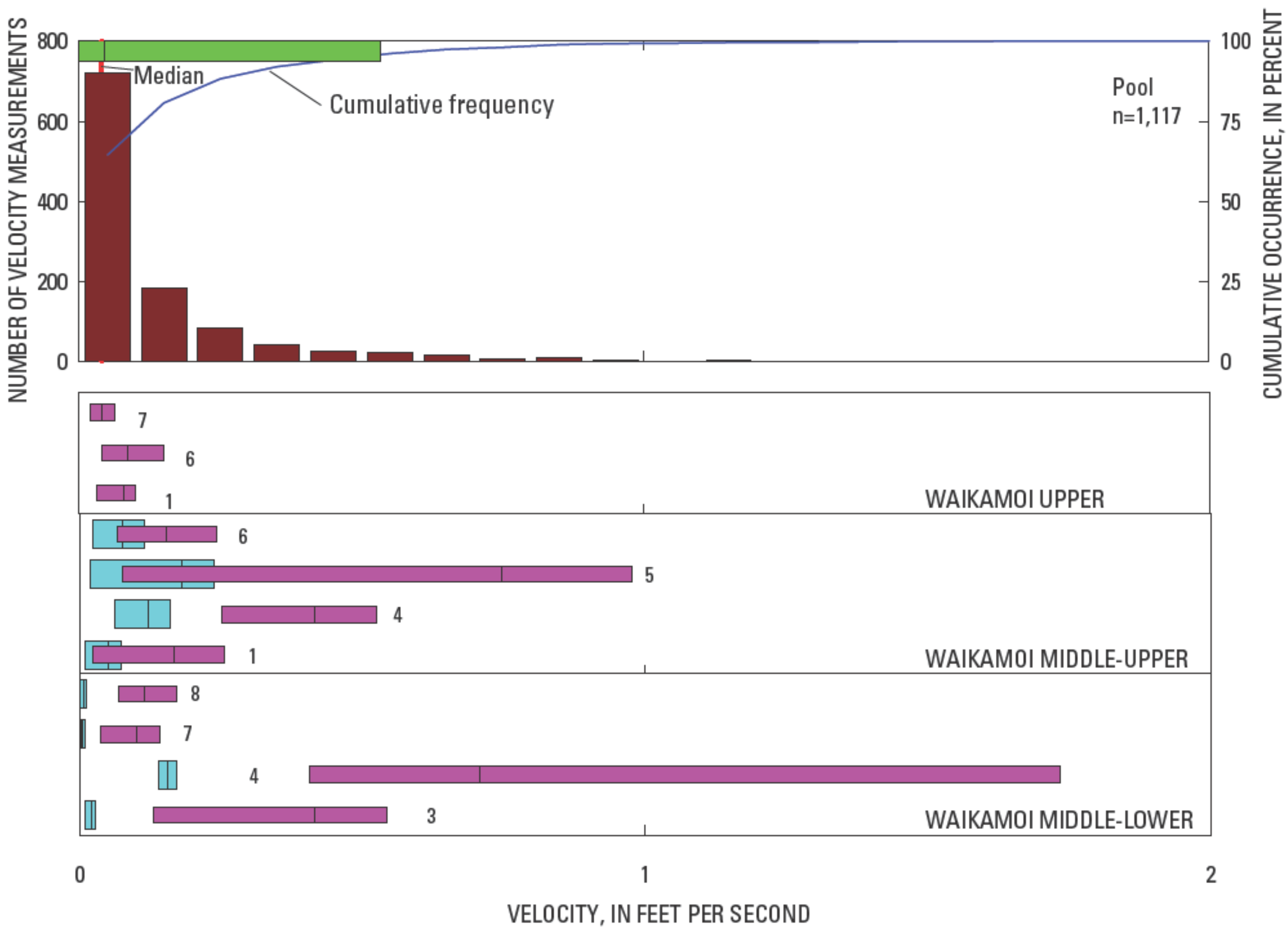


Figure 13. Comparison of PHABSIM modeled velocity values to measured velocities for all pool transects in stream study reaches, northeast Maui, Hawaii—*Continued.*

Table 7. Measured and simulated stream velocities for intensively studied stream reaches, northeast Maui, Hawaii.

[Observed velocities for natural conditions were collected at upper habitat sites upstream of major diversions. ft/s, foot per second]

Habitat type	Diverted conditions				Natural (undiverted) conditions			
	Median velocity (ft/s)		Number of measurements		Median velocity (ft/s)		Number of measurements	
	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
Run	0.14	0.12	945	527	.25	.30	374	972
Pool	.05	.06	652	489	.02	.10	465	856
Riffle	.34	.32	434	398	.39	[1].47	174	[1]678
						[2].43		[2]740

[1] Riffle model A, riffles having no water-level change.

[2] Riffle model B, riffles having water-level change like nearby run.

Estimation of Habitat in Intensively Studied Streams under Diverted and Natural Conditions

All comparisons of habitat change are presented relative to habitat conditions at natural median base flow. The estimated values of diverted and natural annual median base flow were first presented in Gingerich (2005). Habitat at the four lower stream reaches (Hanawi lower, Kopiliula lower, Wailuanui lower, and Honomanu lower) was evaluated for hihiwai, adult nakea, and adult and juvenile nopili. Habitat for opae and adult and juvenile alamoo was not evaluated at these lower sites because these species do not typically live in the lower stream reaches, although occasional sightings were noted during this study. Conversely, only opae and adult and juvenile alamoo were considered at the middle and upper stream reaches because the other species are not typically found at these altitudes.

Habitat in Individual Reaches

PHABSIM model results are presented in plots showing the area of estimated usable bed habitat over a streamflow range that includes the diverted and natural base-flow estimates (figs. 14-18). The results are also presented as habitat relative to natural conditions with 100 percent of natural habitat available at natural median base flow and 0 percent of habitat available for a dry stream. The plots present results using both riffle models to determine the range of results possible depending on the method used to estimate the effects of increased streamflow at unmeasured riffle reaches.

In general, the plots show a decrease in habitat for all modeled species as streamflow is decreased from natural conditions. The exception is at Hanawi lower and middle sites, where the amount of habitat available under diverted conditions is virtually the same as would be available under natural conditions (fig. 18). The results also indicate only minor differences in available habitat for the adult and juvenile nopili, adult nakea, and hihiwai, mainly because of the similarity in the habitat suitability criteria developed in this study for each of the species. At most of the middle sites, more habitat for opae is present than for alamoo at a given streamflow. The differences in results using riffle models A and B are also relatively minor with the exception of the Waikamoi middle-lower reach. For this reach, the difference in values of habitat area at natural median base flow determined using models B and A is about 37 percent of the habitat area determined using riffle model B. This difference is mainly because this reach has the largest difference in modeled water level rise between riffle models A and B (0.3 ft).

Several different measures are presented to show the relation between streamflow and aquatic species (fish and hihiwai) (table 8) and opae habitat (table 9) to aid in the comparison of results from each of the intensively studied streams. Median base-flow estimates for diverted and natural conditions show the relative streamflow at each site. The relative amount of habitat available under diverted conditions compared to expected natural conditions ranges from 0 percent at the Honomanu lower site, which is dry under diverted conditions, to about 100 percent at the Hanawi lower and middle sites, where the discharge from Big Spring maintains steady streamflow. The diverted sites downstream of only one diversion have about 50 to 57 percent of their expected natural habitat, and the site downstream of two major diversions (Waikamoi middle-lower) has about 27 to 46 percent of expected natural habitat (table 8). Opae habitat for diverted conditions is as low as 40 percent at the Waikamoi middle-lower site to as much as 95 percent at the Hanawi middle site (table 9). Relative habitat at each site is also compared by noting the streamflow amount needed to produce habitat of 50 and 90 percent of the expected habitat at natural conditions. These values were not determined for the Hanawi lower and middle sites because the PHABSIM model was developed only for flows ranging from diverted to natural median base flow. At these flows, the Hanawi lower and middle sites maintained higher than 90 percent of expected natural habitat.

At six of the seven remaining sites, a flow of about 1 ft^3/s will maintain 50 percent of the expected natural habitat and a flow of about 4 ft^3/s will maintain 90 percent of the expected natural habitat (table 8). At Kopiliula lower, about 2.6 ft^3/s is needed to maintain 50 percent of the expected natural habitat and about 7.6 ft^3/s is needed to maintain 90 percent of the expected natural habitat. These relations are also shown on the available habitat plots (figs. 14-18). For opae, greater than 50 percent of the expected natural habitat is already maintained at the diverted conditions with the exception of the Waikamoi middle-lower site, where as much as 0.61 ft^3/s flow is needed (table 9). Streamflow of about 2.4 to 4.4 ft^3/s will maintain 90 percent of the expected natural opae habitat. Results from stream to stream are also compared by noting the percentage of expected natural habitat available when base flow is at 50 and 90 percent of the natural median base flow. The relative amount of expected habitat available at 50 percent of natural median base flow ranges from 70 to 92 percent, with the lowest relative amount available at the Kopiliula lower site (table 8). The highest values are at the Honomanu lower site, where 50 percent of the natural median base flow would produce about 90 percent of the expected natural habitat. As expected, the impact of maintaining 50 percent of natural streamflow is greatest in a stream that is dry under diverted conditions. Maintaining 90 percent of base flow results in 94 to 101 percent of expected natural habitat in the stream reaches. For opae, maintaining 50 percent of natural median base flow results in 82 to 92 percent of expected natural opae habitat and flows at 90 percent of natural median base flow result in relative habitat of 97 to 99 percent of expected natural opae habitat (table 9).

Quantifying the range of estimated errors in the simulation results of habitat models is difficult. One source of error that was analyzed was the possible range of stage-

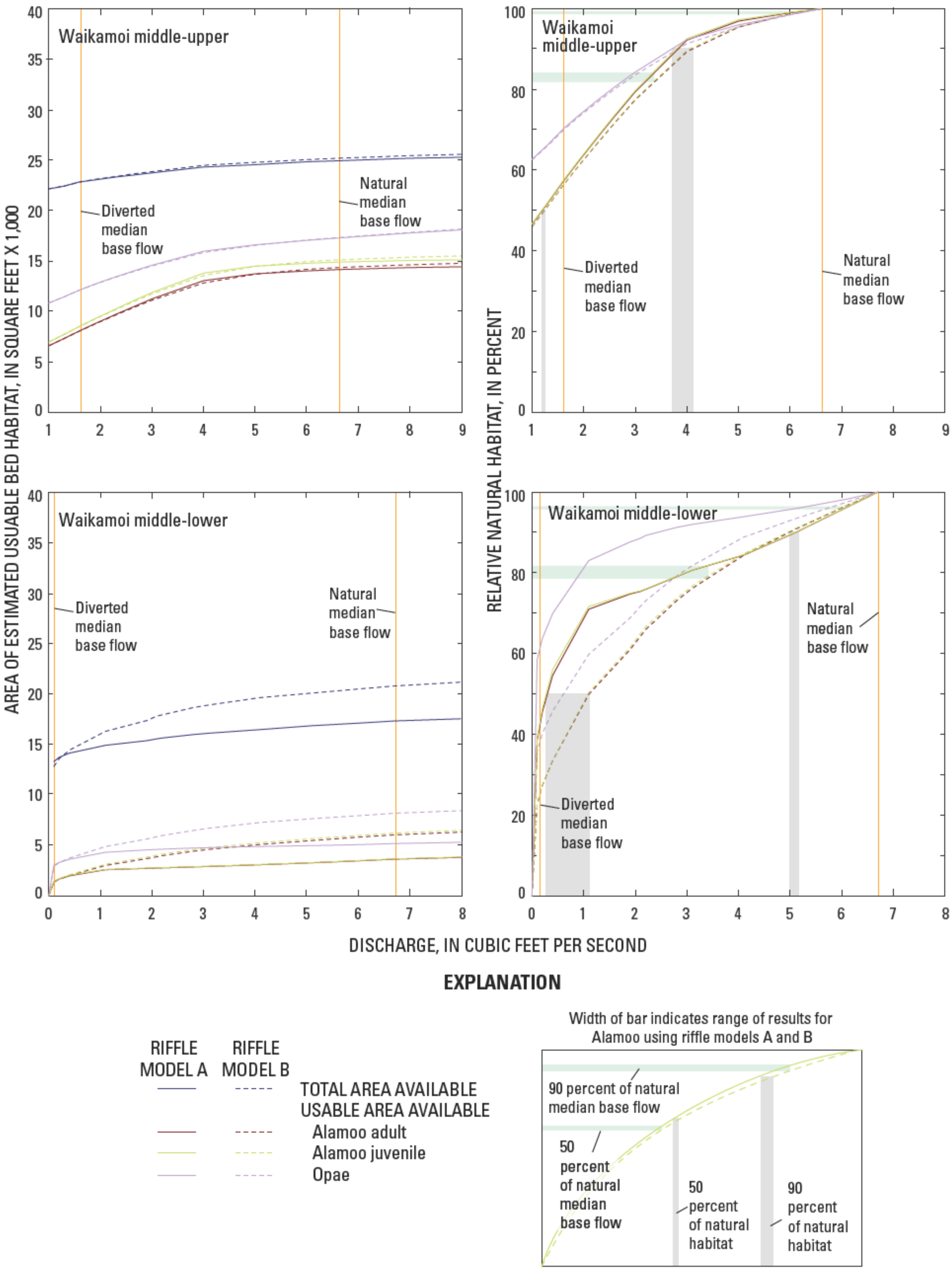


Figure 14. Total estimated habitat and percent of estimated habitat relative to natural habitat at selected discharges in Waikamoi Stream, northeast Maui, Hawaii.

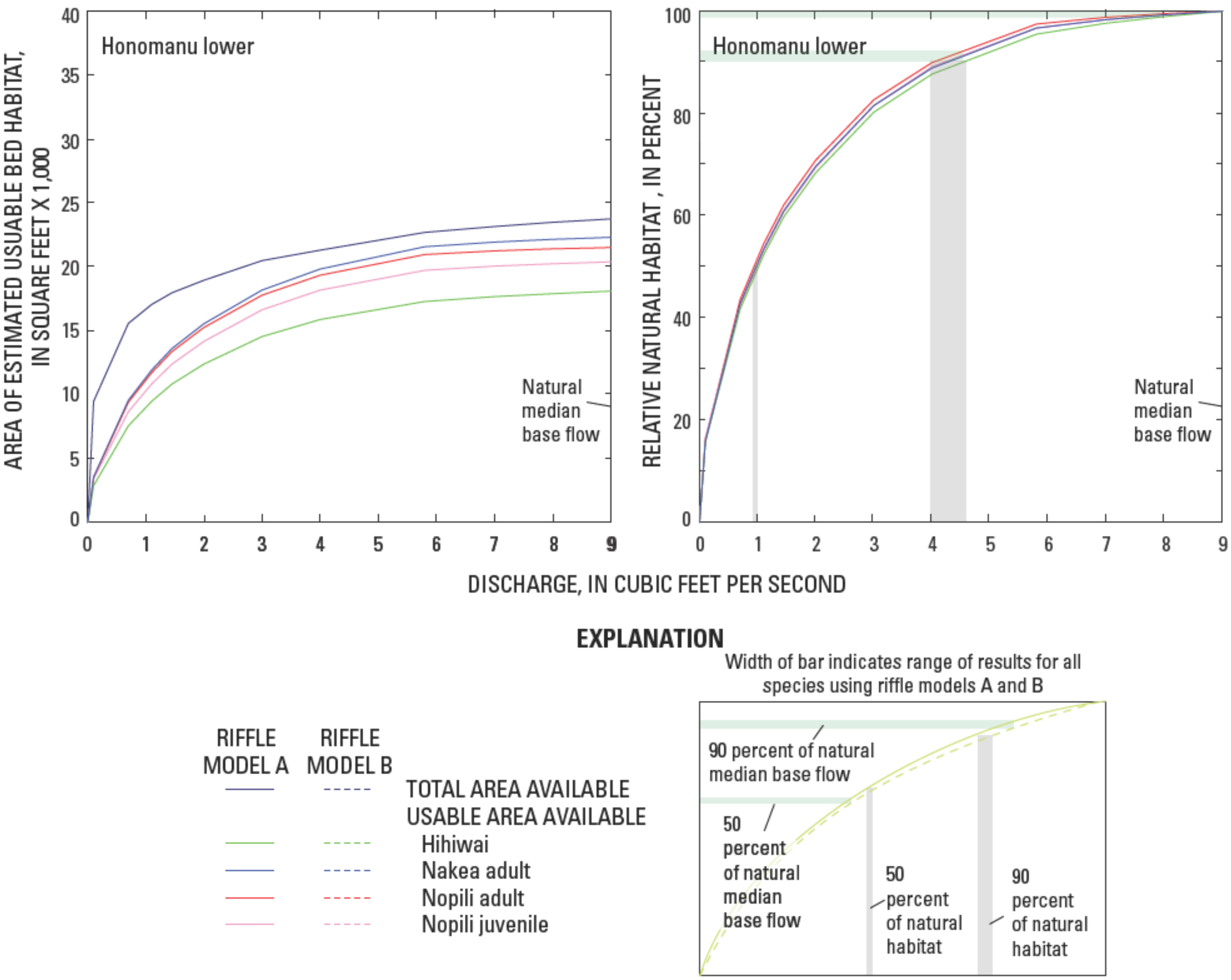


Figure 15. Total estimated habitat and percent of estimated habitat relative to natural habitat at selected discharges in Honomanu Stream, northeast Maui, Hawaii.

discharge relations used to estimate the water-surface elevations in each model. The standard error was calculated for each stage-discharge equation best fit to the measured data used in the Waikamoi middle-lower model. Minimum and maximum best-fitting equations were generated using plus and minus one standard error, and PHABSIM models were tested using both extremes. The Waikamoi middle-lower model was chosen because it has the largest range in estimated results between riffle models A and B and would therefore have the largest range of possible error. The range of results incorporating the potential errors in the stage-discharge relations was not significantly larger than the range determined using the results from adult and juvenile alamoo for both riffle models. Therefore, the ranges presented in tables 8 and 9 are considered wide enough to include the potential errors in the stage-discharge relations.

Another way of presenting the PHABSIM model results is in the form of habitat-duration curves that show the percentage of time an indicated habitat condition would be equaled or exceeded (fig. 19). These plots include the results for natural and diverted conditions for all species modeled using the average from riffle models A and B. These curves are based on the available estimates of flow duration at each stream reach developed earlier in the study for total flow and base flow (Gingerich, 2005). The habitat-duration curves for the upper sites include only natural conditions because the sites are upstream of the major diversions so diverted conditions are not present at these sites. Because only median or lower flows were modeled, the curves do no show habitat availability at higher flows.

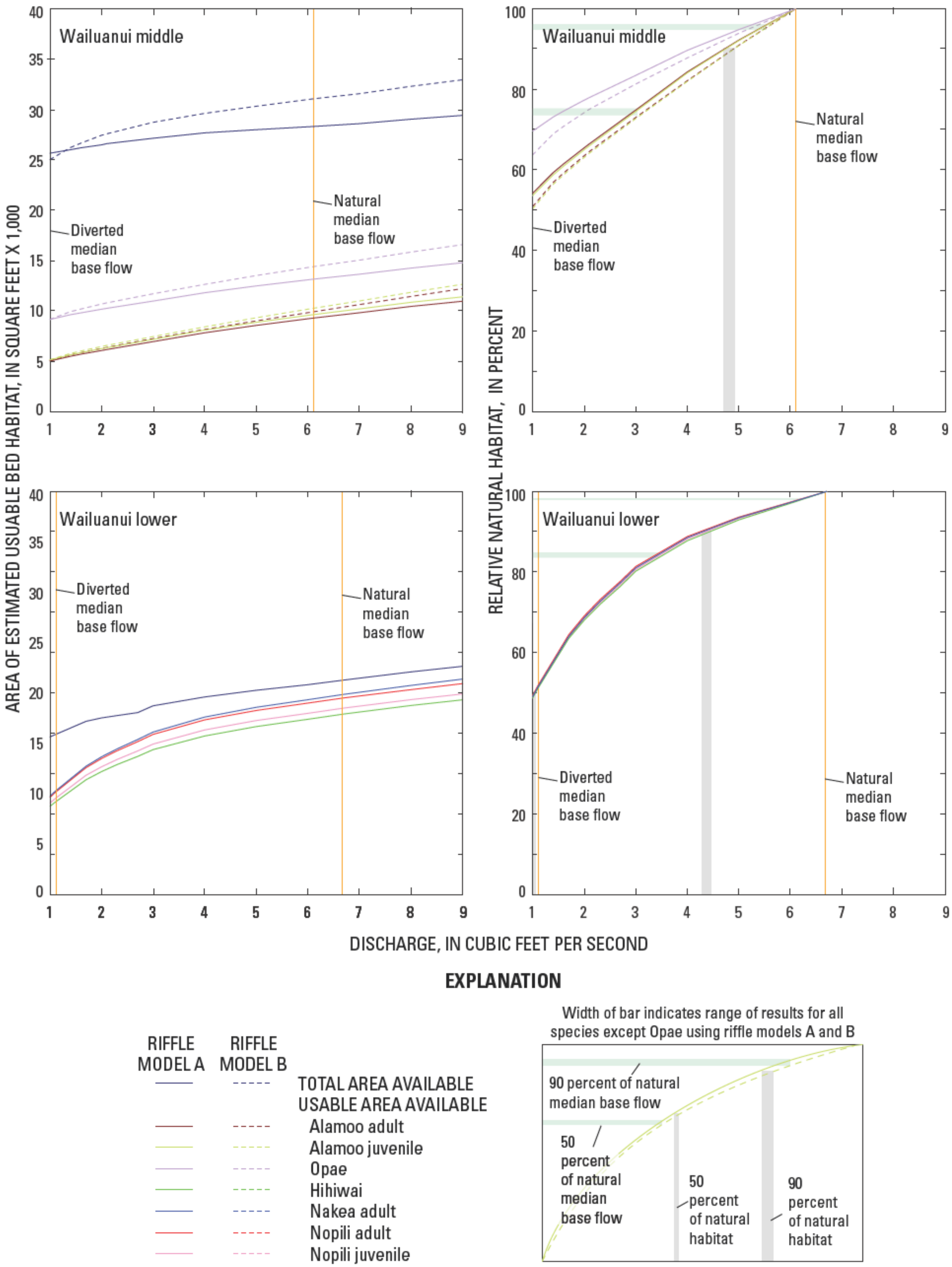


Figure 16. Total estimated habitat and percent of estimated habitat relative to natural habitat at selected discharges in Wailuanui Stream, northeast Maui, Hawaii.

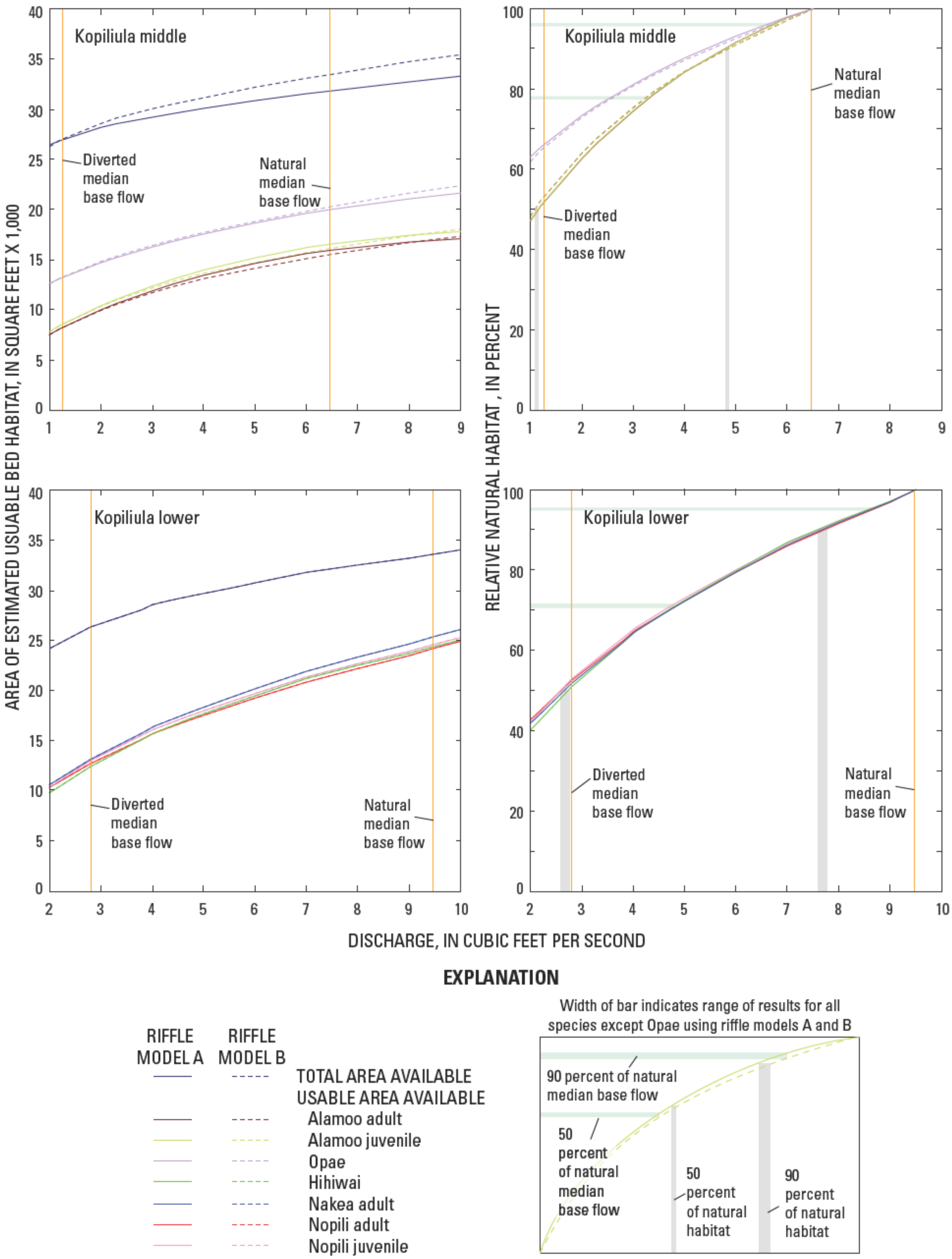


Figure 17. Total estimated habitat and percent of estimated habitat relative to natural habitat at selected discharges in Kopiliula Stream, northeast Maui, Hawaii.

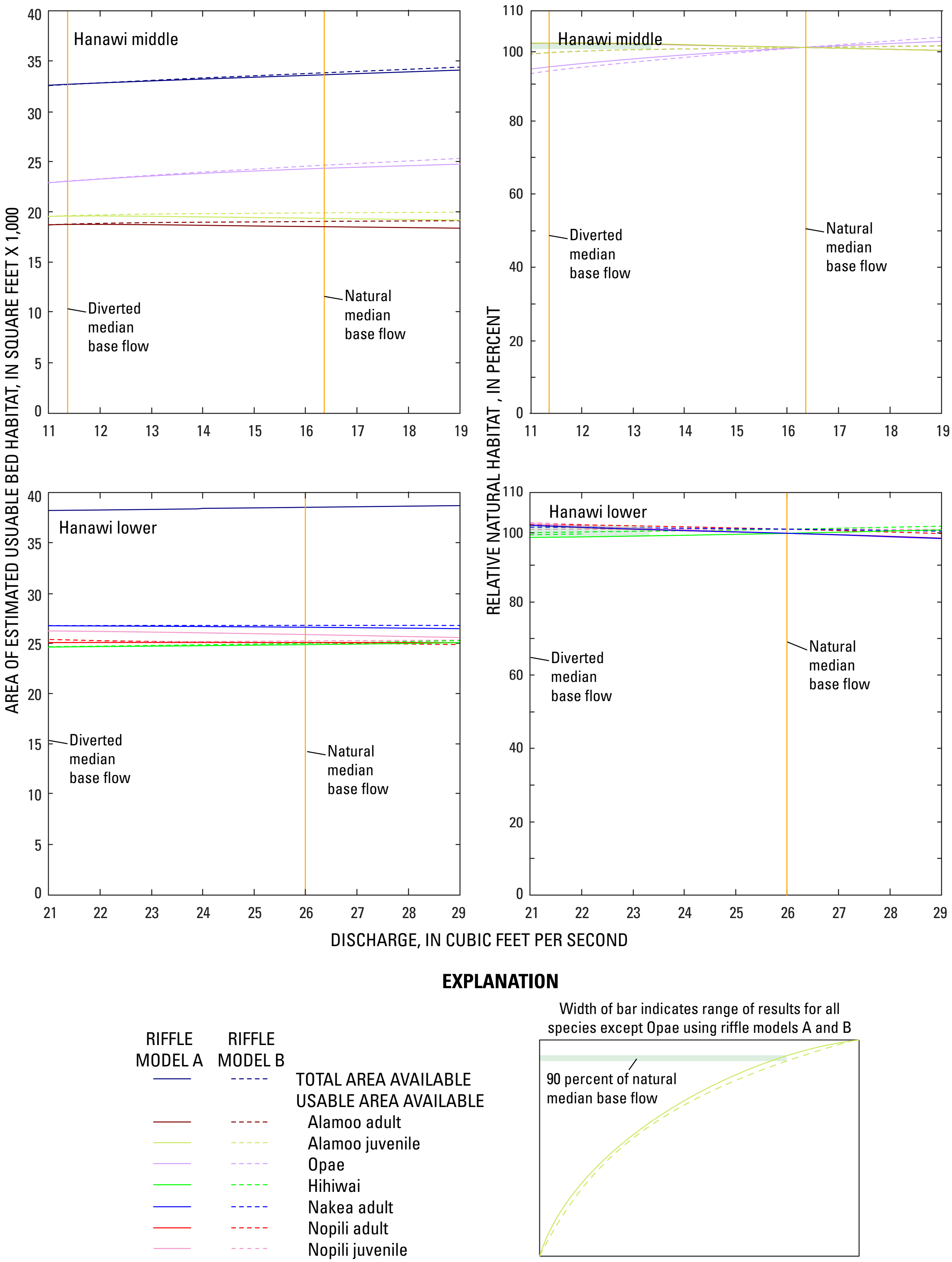


Figure 18. Total estimated habitat and percent of estimated habitat relative to natural habitat at selected discharges in Hanawi Stream, northeast Maui, Hawaii.

Table 8. Summary of PHABSIM modeled habitat for intensively studied diverted stream sites, northeast Maui, Hawaii.

[ft^3/s, cubic foot per second; ft^2, square feet; values shown represent a range of results for all aquatic species except opae using riffle models A and B; NA, not applicable]

Stream site	Median base flow remaining in stream (ft^3/s)		Habitat available at diverted median base-flow conditions relative to habitat available at natural median base-flow condition (percent of natural habitat)	Flow needed to produce habitat relative to habitat available at natural median base-flow conditions (ft^3/s)		Amount of habitat relative to habitat available at natural median base-flow conditions with flow at percentage of natural base flow	
	Diverted conditions	Natural (undiverted) conditions		50 percent of natural habitat	90 percent of natural habitat	50 percent of natural base flow	90 percent of natural base flow
Hanawi lower	21	26	99 – 101	NA	NA	NA	99 – 101
Hanawi middle	11	16	99 – 101	NA	NA	NA	100 – 101
Kopiliula lower	2.8	9.5	51 – 53	2.6 – 2.7	7.6 – 7.7	70 – 71	94 – 95
Kopiliula middle	1.2	6.5	51 – 52	1.1 – 1.2	4.8	77 – 78	96 – 97
Wailanui lower	1.1	6.7	51 – 52	1 – 1.1	4.2 – 4.4	83 – 84	97
Wailuanui middle	1.0	6.1	50 – 54	.66 – 1	4.7 – 4.9	73 – 75	95 – 96
Honomanu lower	0	9.0	0	.94 – 1	4 – 4.5	90 – 92	99 – 100
Waikamoi middle-lower	.20	6.7	27 – 46	.13 – 1.1	4.9 – 5.1	78 – 82	96
Waikamoi middle-upper	1.6	6.6	56 – 57	1.2	3.8 – 4.1	81 – 84	99

Table 9. Summary of PHABSIM modeled opae habitat for intensively studied diverted middle stream sites, northeast Maui, Hawaii.

[ft^3/s, cubic foot per second; ft^2, square feet; values shown represent a range of results using riffle models A and B; NA, not applicable]

Stream site	Median base flow remaining in stream (ft^3/s)		Habitat available at diverted median base-flow conditions relative to habitat available at natural median base-flow condition (percent of natural habitat)	Flow needed to produce habitat relative to habitat available at natural median base-flow conditions (ft^3/s)		Amount of habitat relative to habitat available at natural median base-flow conditions with flow at percentage of natural base flow	
	Diverted conditions	Natural (undiverted) conditions		50 percent of natural habitat	90 percent of natural habitat	50 percent of natural base flow	90 percent of natural base flow
Hanawi middle	11	16	94 – 95	NA	NA	NA	98 – 99
Kopiliula middle	1.2	6.5	65 – 66	NA	4.4 – 4.5	82 – 83	97
Wailuanui middle	1.0	6.1	64 – 70	NA	4.1 – 4.4	82 – 84	97
Waikamoi middle-lower	.20	6.7	40 – 64	.61	2.4 – 4.4	84 – 92	97 – 98
Waikamoi middle-upper	1.6	6.6	70	NA	3.7 – 3.8	86 – 87	98

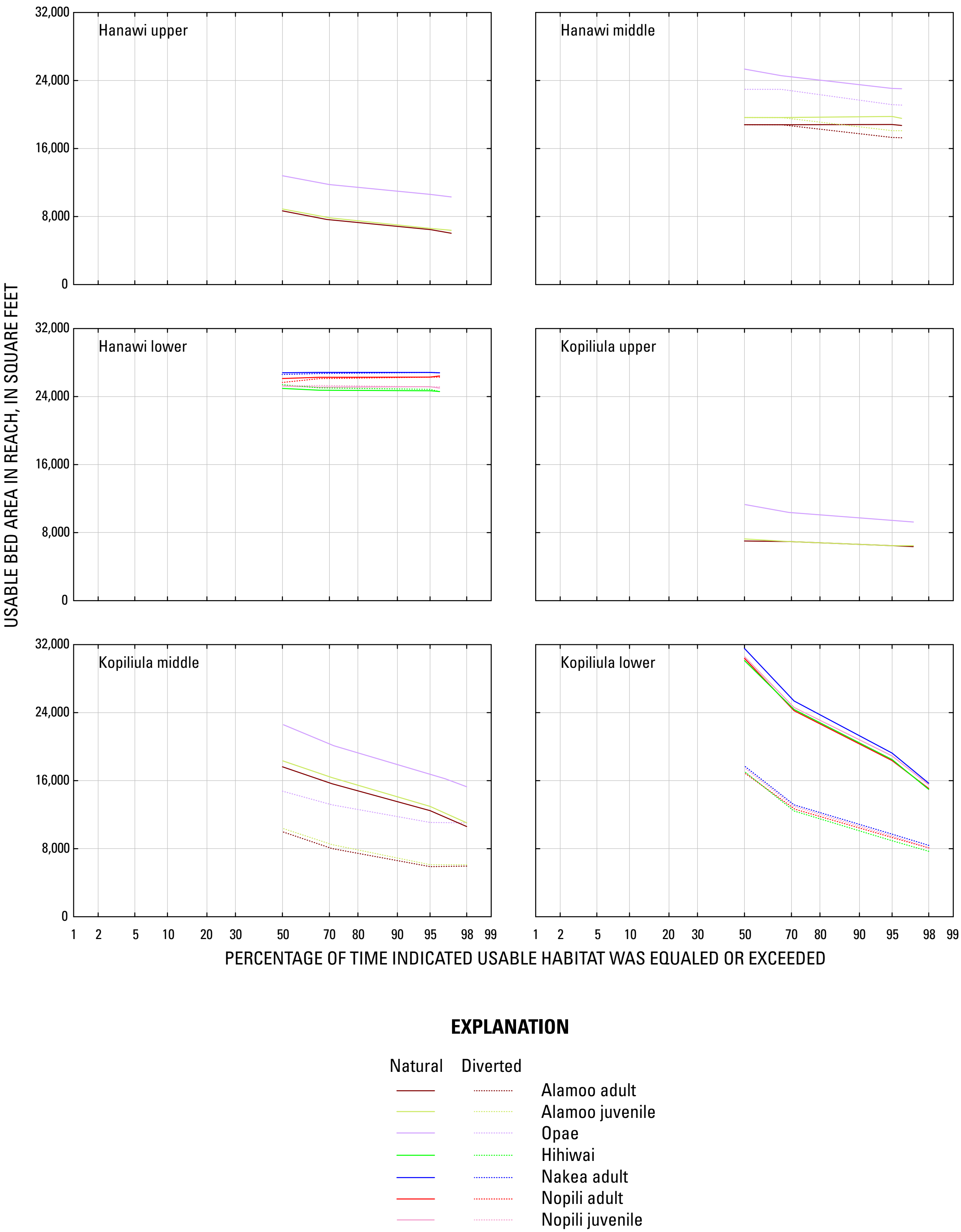


Figure 19. Habitat-duration curves for selected stream reaches in study area, northeast Maui, Hawaii.

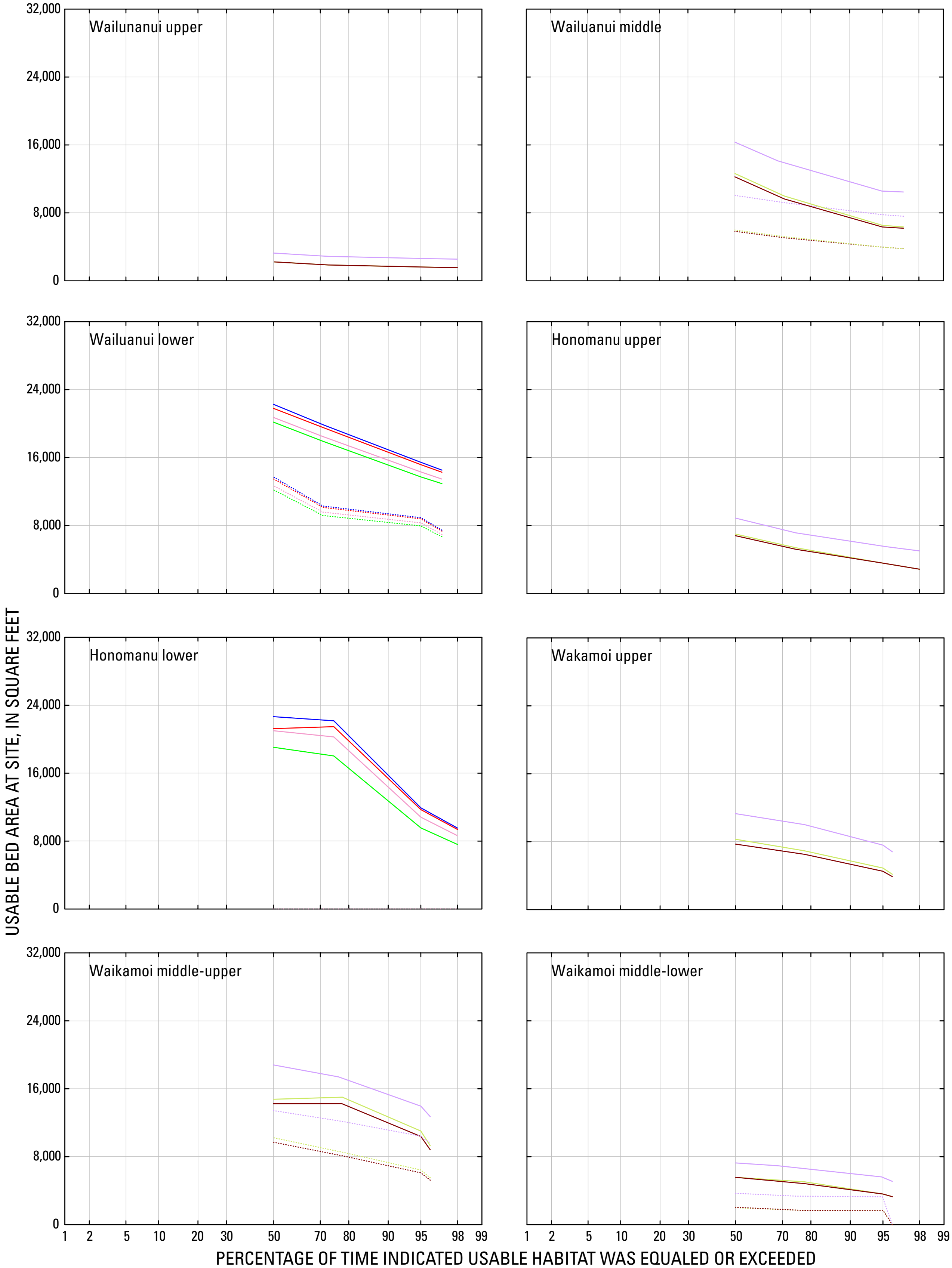


Figure 19. Habitat-duration curves for selected stream reaches in study area, northeast Maui, Hawaii—*Continued.*

Generalized Relation Between Habitat Availability and Streamflow

A relation between the flow in a stream and the resulting amount of available habitat created in the stream could be used to estimate relative habitat for diverted streams in the study area that were not intensively studied. In order to develop this relation, the PHABSIM modeling results for the intensively studied streams have been normalized to indicate the amount of habitat at diverted conditions relative to natural conditions (dividing estimated habitat at diverted median base flow by estimated habitat at natural median base flow) compared to the amount of base flow at diverted conditions relative to natural conditions (dividing diverted median base flow by natural median base flow) for alamoo, nakea, nopili, and hihiwai (fig. 20) and for opae (fig. 21). Sites that are dry (Honomanu lower or Waikamoi lower) or nearly dry (Waikamoi middle-lower) have the lowest relative amount of estimated habitat and plot toward the upper right of the graph, and sites where the habitat reduction due to diversions is small (Hanawi lower and middle) plot toward the lower left of the graph. The height of each bar represents the range of results for an individual stream reach for all species (alamoo, nakea, nopili, and hihiwai on fig. 20 and for opae on fig. 21) using riffle models A and B. A best-fitting line ($r^2 = 0.958$) through the median of each of the modeled results for alamoo, nakea, nopili, and hihiwai is described by the equation

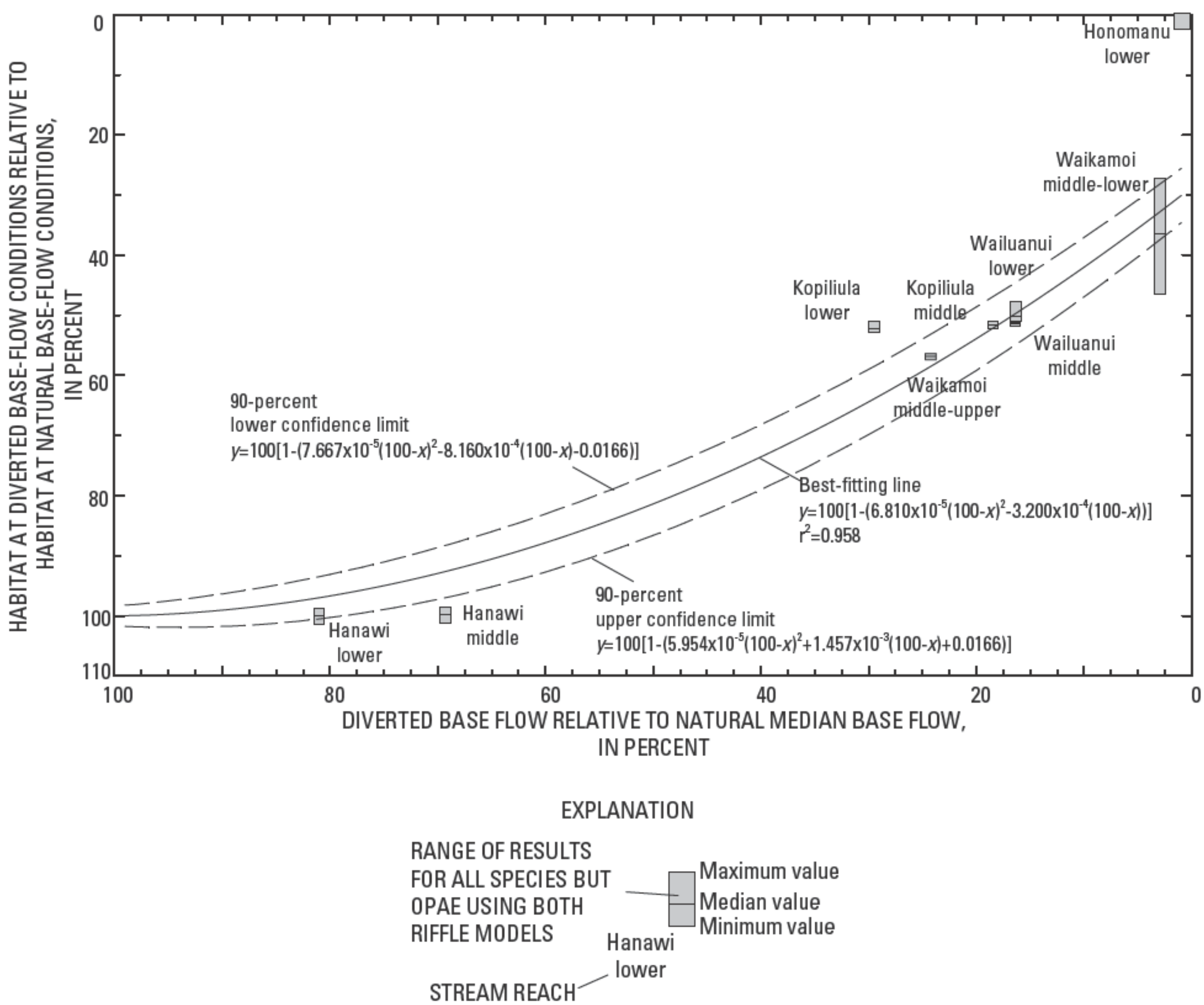


Figure 20. Results of PHABSIM models (for alamoo, nakea, nopili, and hihiwai) normalized to show relative habitat for given relative base flow at intensively studied diverted stream reaches, northeast Maui, Hawaii. Relative values represent the diverted base flow or habitat divided by natural base flow or habitat.

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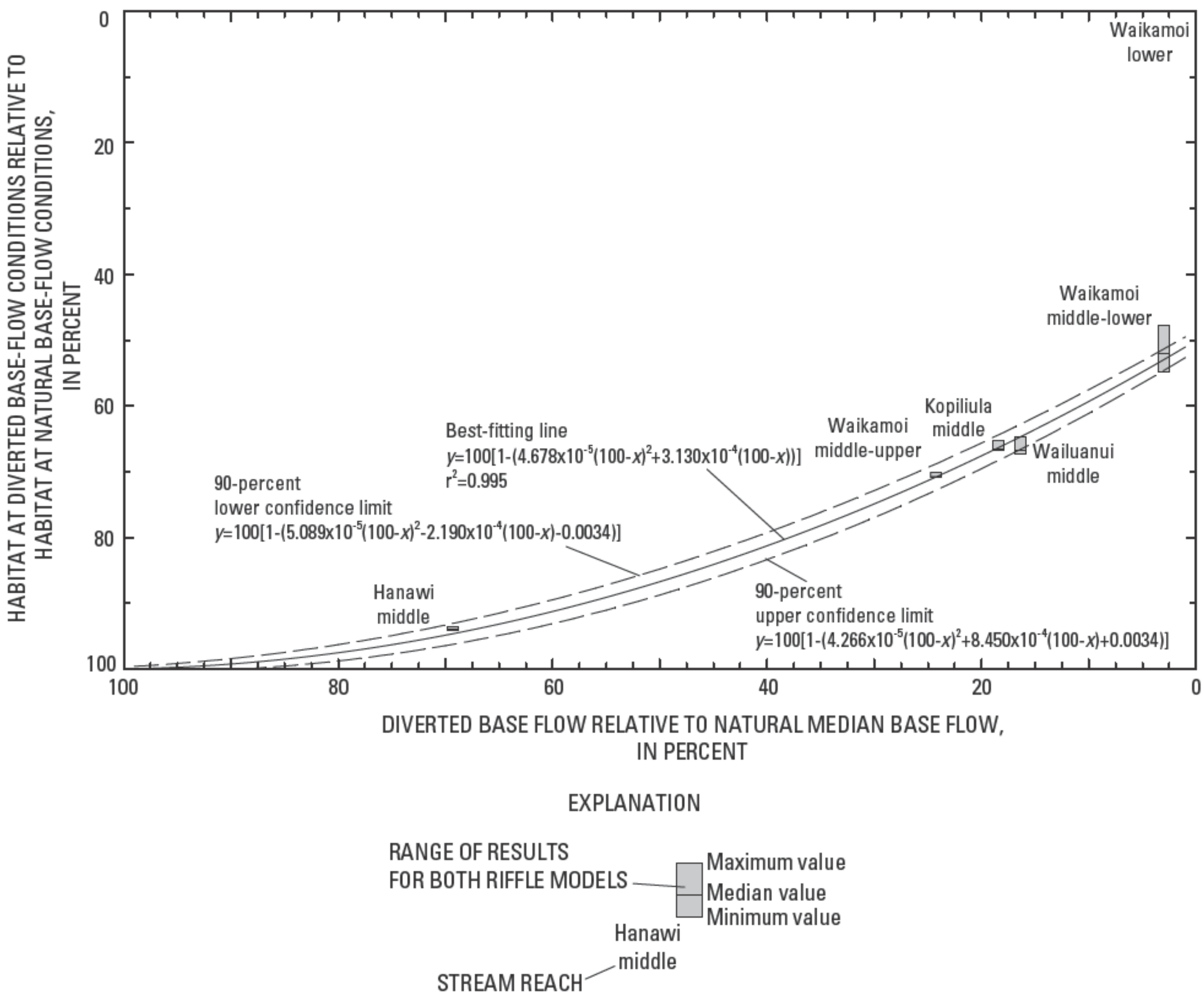

Figure 21. Results of PHABSIM models for opae normalized to show relative habitat for given relative base flow at intensively studied diverted stream reaches, northeast Maui, Hawaii. Relative values represent the diverted base flow or habitat divided by natural base flow or habitat.

$$y = 100[1 - (6.810\text{x}10^{-5}(100 - x)^2 - 3.200\text{x}10^{-4}(100 - x))], \qquad (3)$$

where:

y is the habitat at diverted base-flow conditions relative to expected habitat at natural median base-flow conditions, in percent, and

x is the median diverted base flow relative to natural median base flow, in percent.

Equations describing the upper and lower 90-percent confidence limits were also developed:

$$y = 100[1 - (5.954\text{x}10^{-5}(100 - x)^2 + 1.457\text{x}10^{-3}(100 - x) + 0.0166)] \qquad (4)$$

upper confidence limit

$$y = 100[1 - (7.667x10^{-5}(100 - x)^2 - 8.160x10^{-4}(100 - x) - 0.0166)] \qquad (5)$$

lower confidence limit

A best-fitting line ($r^2 = 0.995$) through the median of each of the modeled results for opae is described by the equation

$$y = 100[1 - (4.678\text{x}10^{-5}(100 - x)^2 + 3.130\text{x}10^{-4}(100 - x))] \qquad (6)$$

Equations describing the upper and lower 90-percent confidence limits were also developed

$$y = 100[1 - (4.266\text{x}10^{-5}(100 - x)^2 + 8.450\text{x}10^{-4}(100 - x) + 0.0034)] \quad (7)$$
upper confidence limit

$$y = 100[1 - (5.089\text{x}10^{-5}(100 - x)^2 - 2.190\text{x}10^{-4}(100 - x) - 0.0034)] \quad (8)$$
lower confidence limit

For both relations, the equations are valid for relative base flow that is greater than 0 percent of natural median base flow. When the base flow is reduced to 0 percent (stream is dry), obviously, the available habitat amount is also reduced to 0 percent. The model results indicate that the addition of even a small amount of water to a dry stream has a significant effect on the amount of habitat available.

These equations relating base flow to habitat can be used to provide an estimate of the relative habitat available compared to natural conditions in the study area streams for which estimates of diverted and natural median base flow have been determined but for which detailed habitat models were not developed. These equations should be considered applicable only for the study area and further study would be needed before applying these relations to diverted streams outside the study area.

Estimation of Habitat in Other Streams under Diverted and Natural Conditions

Intensive study and subsequent habitat modeling was limited to 5 reference streams of the 21 streams flowing to the ocean in the study area. In the remaining streams, estimates of the relative amount of habitat at median diverted base flow were made at selected sites using the relations determined from the results of the PHABSIM modeling of the intensively studied stream reaches. The stream sites listed in table 10 are those for which estimates of diverted and natural median base flow were made in this study (Gingerich, 2005). These sites include middle and lower altitude sites on each of the streams in the study area.

Values of base flow in the stream at diverted conditions relative to natural conditions were calculated by dividing the value of diverted median base flow by natural median base flow. The relative amount of expected habitat at diverted median base-flow conditions is expressed as a range of values between the upper and lower 90-percent confidence limits defined by equations 4 and 5 for the combined results for alamoo, nopili, nakea, and hihiwai, and by equations 7 and 8 for opae (table 10). Where available, the State of Hawaii Division of Land and Natural Resources Division of Aquatic Resources stream codes are also included for the sites listed in table 10.

The values of relative base flow range from 0 percent (stream dry at selected reach) to 100 percent (no significant diversion) of median base flow at natural conditions. Reaches having no significant diversion (Waiaaka lower and middle, Nuaailua lower, Wahinepee lower and middle, and Kolea lower) are in streams in which the major diversions are in the upper reaches of the stream. Therefore, only a small water volume is diverted from the stream relative to the amount gained from ground water downstream of the diversion. Values of relative base flow at diverted conditions between 0 and 60 percent are in stream reaches in which a significant part of the total streamflow is gained from ground-water inflow downstream of the major diversions. In these reaches, the diversion has a relatively smaller effect on streamflow. Most of these streams are in the eastern part of the study area, where many springs have been mapped and ground-water discharge to streams is expected to be significant (Gingerich, 1999). The median base-flow estimates for diverted and natural conditions at four of the stream reaches (Waiokomilo middle, Ohia lower, Palauhulu middle, and Honomanu middle) are considered maximums because these sites are downstream of unquantified but known losing stream reaches. Therefore, the estimates of relative base flow are considered minimums for these sites.

Estimates of relative habitat at diverted conditions range from 100 percent for stream sites with relatively small or no diversion to 0 percent for stream sites that are dry due to diversion. The maximum relative habitat at a stream site that is not dry is about 37 percent of expected natural habitat for alamoo, nopili, nakea, and hihiwai, and 58 percent of expected natural habitat for opae at the Haipuaena middle-lower site, where the base flow at diverted conditions is about 10 percent of natural conditions. The estimates of relative habitat at diverted conditions for the four stream reaches in which the relative base-flow estimates are identified to be minimums should be considered as minimums but the data are insufficient to further refine these estimates.

Streams (below 2,000 ft altitude) are classified into reaches having the same relative amount of habitat at diverted conditions relative to natural conditions by extrapolating the estimates from the selected sites in tables 8 and 10 using the knowledge gained from field reconnaissance, aerial digital photography of the streams, and GIS analysis of stream and stream-basin characteristics (pl. 1). All stream segments upstream of the 1,400-1,700 ft altitude diversion are considered to have no reduction in base flow. Dry stream segments extend immediately downstream of the major diversions on each stream. The downstream extent of the dry segments depends on the location of springs or gaining sections of each stream. The amount of input from a spring or gaining section determines into which category the next downstream segment is classified. Significant waterfalls (greater than about 10 ft high) and pools are also represented on plate 1. These features were not included in the representative reaches and not specifically modeled using PHABSIM so the results from the habitat models are not specifically applicable to these features. However,

Table 10. Summary of relative base flow and available habitat in diverted stream reaches, northeast Maui, Hawaii.

[ft^3/s, cubic foot per second; values of diverted and natural median base flow from Gingerich [2005]; base flow estimates in ***bold italic*** are considered maximums at sites downstream of unquantified but known losing reaches, therefore corresponding relative changes in base flow and habitat are considered minimums; lower and upper limit of change in habitat range [excluding opae] determined from equations 4 and 5; lower and upper limit of change in opae habitat range determined from equations 7 and 8; NA, not available; DAR, State of Hawaii Department of Land and Natural Resources Division of Aquatic Resources]

Stream reach	Median base flow remaining in stream (ft^3/s)		Median base flow at diverted conditions relative to median base-flow at natural conditions (percent of natural conditions)	Habitat available at diverted conditions (excluding opae) relative to habitat available at natural conditions (percent of natural conditions)	Habitat available for opae at diverted conditions relative to habitat available at natural conditions (percent of natural conditions)	DAR stream code
	Diverted conditions	Natural (undiverted) conditions				
Kapaula lower (KL)	2.6	5.7	46	83 – 73	86 – 82	64021001
Kapaula middle (KM)	2.1	5.1	41	80 – 69	84 – 80	64021001
Waiaaka lower (WaL)	1.1	1.1	100	100	100	not assigned
Waiaaka middle (WaM)	.77	.77	100	100	100	not assigned
Paakea lower (PaL)	4.6	5.5	84	101 – 94	99 – 97	64019001
Paakea middle (PaM)	3.8	4.7	81	100 – 93	99 – 96	64019003
Waiohue lower (WeL)	2.1	7.5	28	68 – 57	76 – 71	64018001
Waiohue middle (WeM)	1.0	6.0	17	55 – 45	67 – 63	64018001
Puakaa middle (PuM)	1.1	2.2	50	87 – 76	89 – 85	64017002
East Wailuaiki lower (EWL)	1.5	7.2	21	60 – 49	70 – 66	64016001
East Wailuaiki middle (EWM)	1.0	6.8	15	53 – 43	65 – 61	64016001
West Wailuaiki lower (WWL)	1.2	7.2	17	55 – 45	67 – 63	64015001
West Wailuaiki middle (WWM)	.80	6.8	12	49 – 39	63 – 59	64015001
Waiokomilo lower (WoL)	2.6	8.7	30	70 – 59	77 – 73	64013001
Waiokomilo middle (WoM)	***3.7***	6.1	61	93 – 83	93 – 90	64013001
Ohia lower (OL)	***4.7***	NA	NA	NA	NA	64012001
Palauhulu lower (PhL)	4.8	***11***	44	***82 – 71***	85 – 81	64011002
Palauhulu middle (PhM)	5.9	9.3	63	***94 – 85***	94 – 91	64011004
Nuaailua lower (NL)	7.1	7.4	96	102 – 98	100 – 99	64010001
Nuaailua middle (NM)	2.2	2.5	88	102 – 96	100 – 98	64010001
Honomanu middle (HnM)	3.8	6.7	57	***91 – 81***	92 – 88	64009003
Punalau lower (PlL)	.60	4.5	13	51 – 41	64 – 60	64008001
Punalau middle (PlM)	3.9	3.9	100	100	100	64008001
Haipuaena lower (HaL)	1.1	5.5	20	59 – 49	70 – 66	64007001
Haipuaena middle-lower (HaML)	.50	4.9	10	47 – 37	61 – 58	64007001
Haipuaena middle-upper (HaMU)	.80	4.3	19	58 – 47	68 – 65	64007001
Puohokamoa lower (PL)	2.1	11	19	58 – 48	69 – 65	64006001
Puohokamoa middle-lower (PML)	1.1	10	11	48 – 38	62 – 58	64006001
Puohokamoa middle-upper (PMU)	2.0	8.4	24	63 – 53	72 – 68	64006001
Wahinepee lower (WpL)	.90	1.8	50	87 – 76	89 – 85	64036001
Wahinepee middle (WpM)	.90	.90	100	100	100	64036001
Waikamoi lower (WiL)	.0	7.0	0	0	0	64004001
Kolea lower (KaL)	.90	3.4	27	66 – 55	74 – 70	64003001
Kolea middle (KaM)	3	3	100	100	100	64003001

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the large pools represented on plate 1 are not expected to change significantly in depth or velocity over the range of streamflows (median base flow from diverted to natural conditions) considered in this analysis. Therefore, the large pools, which are the last features to dry up at the lowest flow conditions, would provide about the same amount of habitat under most flow conditions. Although large waterfalls are a major controlling factor in the distribution and migration of the different species along the stream, they provide habitat mainly for migration. This type of habitat is not considered in the PHABSIM model used for this study.

For an example of how the streams are classified, Waikamoi Stream has a segment with no reduction in flow above the Koolau Ditch diversion (diversions at higher altitudes are considered minor) and a short segment of dry stream immediately downstream of the diversion. Between the Koolau and Manuel Luis Ditches, gains of ground water in Waikamoi and Alo (tributary) Streams maintain base flow enough so that more than 50 percent of the natural habitat is available. Downstream of the Manuel Luis diversion, the stream is dry until more base flow is gained to provide about 25 to 50 percent of natural habitat. Closer to the coast, Waikamoi Stream has some losing reaches and the stream goes dry, thus providing no habitat. The large terminal waterfall at the mouth of Waikamoi Stream excludes all species but opae and alamoo from migrating upstream. Therefore, the other species do not need to be considered when addressing the amount of habitat in this stream.

At the other end of the study area, Hanawi Stream has a segment with no reduction in flow above the Koolau Ditch diversion and a short segment of dry stream immediately downstream of the diversion. Farther downstream, gains in the stream increase flow such that the base flow maintains about 50 to 75 percent of habitat relative to natural conditions. Downstream of Big Spring and several other springs, flow increases enough so that the habitat is nearly 100 percent of natural all the way to the coast.

To compare how the non-intensively studied stream reaches compare to the intensively studied stream reaches the results from table 10 are placed in the same format as fig. 20 (fig. 22). In fig. 22, the green band represents the 90-percent confidence boundary for the best-fitting line through the PHABSIM model results at the intensively studied stream reaches for alamoo, nopili, nakea, and hihiwai. This plot is useful to depict the distribution of the streams sites affected by diversion. Those sites, generally in the eastern part of the study area, having the most relative habitat because of significant ground-water input to the stream downstream of the diversion, plot toward the lower left of the graph, near the results for the Hanawi lower and middle reaches. Those reaches in streams with the lowest relative habitat are generally downstream of multiple diversions in the western part of the study area, similar to Waikamoi middle-lower and middle-upper reaches. Although not shown, a similar plot for the opae results would show a similar relationship.

Guidelines for Using Study Results

The results presented in Gingerich (2005) and this report summarize the hydrology and habitat characteristics of the streams in the study area. The estimates of natural and diverted streamflow characteristics in Gingerich (2005) provide the hydrologic basis for the habitat modeling presented in this report. The primary habitat analysis tool PHABSIM was used to provide output of estimated usable bed area in relation to stream discharge for individual species and life stages. The usable bed area is thought to be proportional to habitat availability (Bovee and others, 1998). This output is illustrated by curves (figs. 14-18) that show the relative change in estimated usable bed area for individual species at the intensively studied stream reaches as streamflow is reduced from estimated natural base-flow conditions to diverted base-flow conditions. The maximum, percentiles, or inflections could be chosen from these curves at the level of habitat or flow desired or at points above which greater flow amounts provide only minimal gains in habitat. For the streams in the study area, the curves are practically the same for each of the native species of interest; therefore, flows that are considered beneficial to one species will benefit the other species to about the same extent. These curves can be applied to stream reaches where intensive studies were not undertaken by using the relation between relative base-flow and relative habitat to estimate habitat for stream reaches where the estimated base-flow is known. Stream reaches with similar amounts of relative base flow are assumed to have similar amounts of relative available habitat (pl. 1).

Some hypothetical example applications of the curves are provided to explain further their utility. One example would be to determine the amount of streamflow needed to maintain 50 percent of natural habitat in a stream reach. For the Wailuanui lower site, table 8 and figure 16 show that about 1–1.1 ft^3/s of flow is needed to provide the desired amount of habitat. If the desired habitat was 75 percent of natural habitat, figure 16 shows that 2.6–2.7 ft^3/s of flow is needed to provide the desired habitat. If a target is to maintain 50 percent of median base flow in the same stream reach, table 8 and figure 16 show that 83–84 percent of the natural habitat would be available at this flow. Figure 16 shows that 75 percent of natural base flow (5.0 ft^3/s) would maintain about 92 percent of natural habitat. If the same questions were asked for the lower reaches of West or East Wailuaiki Stream, the same relations would be the most appropriate to apply because these streams are adjacent to Wailuanui Stream and the amount of natural base flow estimated for the lower reach of all three streams is similar. Another application is to use the curves to determine where a given amount of water returned to a diverted stream would provide the most gain in habitat. For example, if 3 ft^3/s were available to return to a stream, inspection of the curves on figures 14-18 indicates that the most value in terms of habitat gain would be at the Honomanu lower site, where the amount of habitat would increase from 0 percent to about 80 percent

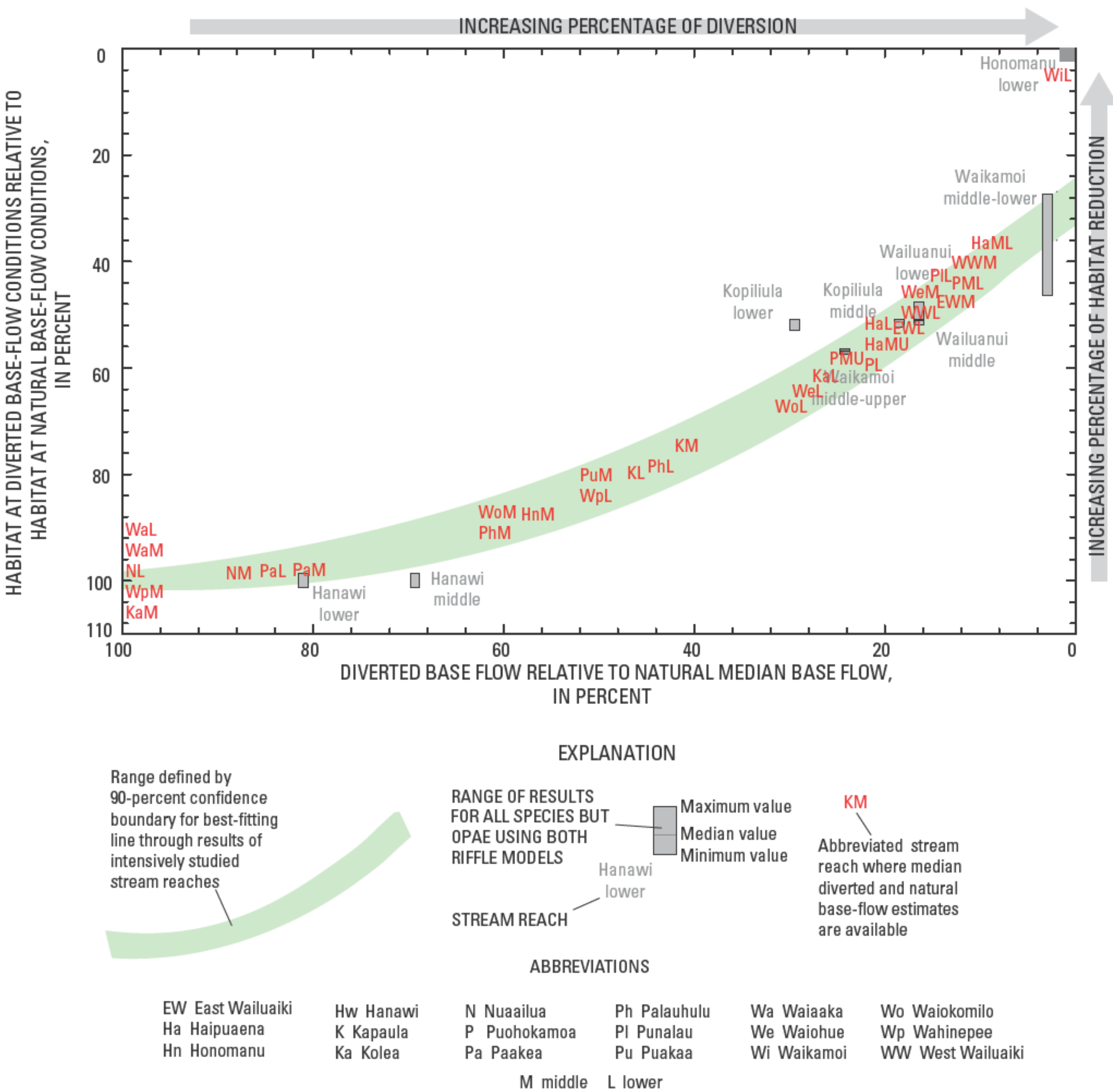

Figure 22. Comparison of stream reaches to intensively studied diverted stream reaches, northeast Maui, Hawaii. Relative change is the difference between natural and diverted conditions divided by natural conditions.

of natural conditions with the addition of 3 ft^3/s of flow. Other streams reaches that are dry under diverted conditions would show similar changes as the Honomanu lower site.

Where “bottlenecks” prevent the upstream migration of species, care must be taken to consider if a particular species would be expected to inhabit a stream reach. The large waterfalls on many streams in the study area generally prevent the upstream migration of all but opae and alamoo. Therefore, it is not appropriate to estimate habitat changes for the other species upstream of large waterfalls and usually not appropriate to estimate opae and alamoo habitat downstream of the same large waterfalls. Dry stream reaches are “bottlenecks” to any species migration, and changes in habitat in upstream reaches are not relevant if the species cannot migrate upstream to inhabit these reaches.

This information is intended to provide relative estimates of the change in aquatic habitat due to surface-water diversions. Other factors of importance in determining whether a particular species will inhabit a stream reach include the available recruitment pool, food source, the presence of predatory alien species, and high flow events in the streams. This study was not designed to address these issues nor the other considerations for instream flow standards such as offstream uses, taro cultivation, or aesthetics. The mechanisms by which the various components of instream flow requirements are integrated and the relative importance they are assigned within the water-management decision process is beyond the scope of this study.

The results from PHABSIM provide a science-based linkage between biology and stream hydrology; however, no single answer results from this approach. The results are meant to show relative changes in habitat with changes in base flow. These results are intended to be used along with other biological and hydrological information in development, negotiations, or mediated settlements for instream flow requirements.

Needs for Additional Data

Additional data are needed to improve and confirm the estimates of habitat conditions at undiverted conditions. Velocity measurements in transects at natural conditions downstream of surface-water diversions would allow comparison with the modeled velocities at natural conditions. These measurements would require a return of water to the streams equal to natural base flow for a period sufficient to make measurements at a steady discharge throughout the reach of interest. Reliable estimates of streamflow statistics in dry or losing streams [as listed in the Needs for Additional Data section of Gingerich (2005)] are needed to improve estimates of habitat and habitat changes with base-flow changes in those streams.

Beyond the scope of this study, many factors that affect the presence of native aquatic species in northeast Maui streams need further investigation. Examples include, but are not limited to:

1. What is the affect of alien species on the migration and living conditions of the native species?
2. What is the fate of animals upon reaching a dry stream reach during upstream migration?
3. At what rate and at what locations will native species population return to natural levels if diversions were removed?
4. Why were opae seen in abundance above the major diversions but alamoo were not observed at all?
5. To what extent do native and alien species use the diversion ditches and tunnels for migration between streams?
6. What is the affect of taro loi on the migration and life cycle of native species?
7. What are the effects of stream diversions on native aquatic insect species?

Summary and Conclusions

For more than a century, surface-water diversion systems have been used to transport water from the wet, northeastern part of Maui, Hawaii, to the drier, central part of the island, mainly for large-scale sugarcane cultivation. With few exceptions, the diversions capture all of the base flow and an unknown percentage of total streamflow at each stream crossing, causing the streams to go dry or be diminished in flow downstream of the diversions. The Hawaii State Water Code mandates that the Commission on Water Resource Management establish a statewide instream-use protection program to protect beneficial instream uses including but not limited to maintenance of fish and wildlife habitat. The scientific information generated by this study will allow the Commission to further its work on documenting water rights and uses associated with northeast Maui streams and analyzing the economic effects of curtailing existing uses on the streams, and to then establish technically defensible instream flow standards for those streams.

Of the 22 named streams that reach the coast in the study area, five (Waikamoi, Honomanu, Wailuanui, Kopiliula, and Hanawi Streams) were chosen as representative streams for intensive study on the basis of several factors, including the amount of flow downstream of major surface-water diversions, stream terminus, impacts from human activities, existing hydrologic and biologic data, geographic location, and access. These five streams represent most of the range of hydrologic conditions encountered in the study area. On each of the five selected streams, representative reaches were selected immediately upstream of major diversions, midway to the coast, and near the coast.

This study focused on some of the native fish, snails, and shrimp species found in Hawaiian streams. Three of the five native fish species were observed in sufficient abundance for consideration in the study. The three fish species considered were the endemic gobies alamoo and nopili, and the indigenous goby nakea. The akupa was not observed in abundances large enough to consider and the teardrop goby naniha was not observed during this study. The hihiwai and opae abundances were also sufficient for consideration in the study.

Habitat selection models are widely used to evaluate habitat quality and predict effects of habitat alteration on animal populations. One habitat selection model for fish, the Physical Habitat Simulation System (PHABSIM) has been a basis for management decisions at hundreds of water projects in many countries, and similar approaches are widely used for managing terrestrial wildlife habitat. This model incorporates hydrology, stream morphology and microhabitat preferences to create relations between streamflow and habitat availability. PHABSIM simulates habitat/discharge relations for various species and life stages and allows quantitative habitat comparisons at different streamflows of interest.

A 300- to 500-ft length of channel was investigated at each of the intensively studied reaches on the five intensively studied streams to collect data that could be used for habitat modeling of the reaches. Each study reach was stratified at the level of three habitat types: riffle, run, and pool. The individual reach lengths were summed by habitat type and the proportion of each habitat type within the reach was calculated. Seven to ten transects were located randomly within each reach, with the number of transects per habitat type based on the proportion of the habitat type within the reach. Hydrological data were collected at 1-ft intervals along each transect to characterize hydraulic and geomorphologic conditions. At each interval, depth and velocity were measured and a substrate type was determined and the number and size of each species in a 1-ft by 2-ft area was noted. Additional habitat-related information including flow regime, potential channel width, active channel width, riparian density, canopy cover, and stream-bank substratum were recorded at each transect.

Stream water temperatures, which could have an effect on stream ecology and taro cultivation, were measured at 13 of the intensively studied stream reaches. Average stream temperatures ranged from 16.8° to 21.6°C, with the lowest temperatures measured generally at the highest altitude sites. Water temperatures increased in a downstream direction in Waikamoi and Wailuanui Streams, indicating only minor input of colder ground water nearer the coast. In Hanawi and Kopiliula Streams, water temperatures generally decreased in a downstream direction, indicating that colder ground water is discharging into these streams between monitoring sites. Daily fluctuations in temperature ranged about 0.9° to 3.0°C with the smallest daily fluctuations recorded downstream of the ground-water input from Big Spring. Seasonal temperature fluctuations ranged about 10° to 16°C in all sites but the Hanawi middle and lower sites, downstream from Big Spring, where the seasonal fluctuations were only about 6°C. The coldest temperatures were measured in February and the warmest in the summer months of June through August. In general, the stream temperatures measured at any of the monitoring sites were not elevated enough to adversely effect the growth or mortality of native aquatic macrofauna or cause wetland taro to be susceptible to fungi and associated rotting diseases.

Overall hydrologic conditions in the study area were drier than normal during the period when stream reaches were intensively studied (7/30/02–7/23/03). Median daily streamflow at the U.S. Geological Survey gaging station on West Wailuaiki Stream during this period was 5.6 ft^3/s, whereas long-term median daily streamflow (1914–2001) was 10 ft^3/s. Most of the habitat and streamflow measurements were made during base-flow conditions, when all flow was diverted and only the flow gained downstream of the diversion was measured. Streamflow, measured at the time that habitat measurements were made, was below the estimated median total flow for each respective stream reach at nine of the 15 sites and below the estimated median base flow at six of the 15 sites.

Intensive study and subsequent habitat modeling was limited to five reference streams of the 22 named streams flowing to the ocean in the study area. The effects of streamflow on habitat in the other streams were therefore estimated using information gathered using a variety of techniques including field reconnaissance, aerial digital photography of the streams, and geographic information system (GIS) analysis of stream and stream-basin characteristics.

The availability of aquatic habitat was estimated for diverted and undiverted conditions at the intensively studied stream sites using PHABSIM. Hydrologic data, collected over a range of low-flow discharges, were used to calibrate hydraulic models of selected transects across the streams. The models were then used to predict water depth and velocity (expressed as a Froude number, a combination of depth and velocity) over a range of discharges up to estimates of natural median streamflow. The biological importance of the stream hydraulic attributes was then assessed with the suitability criteria for each native species and life stage (adult and juvenile alamoo, adult and juvenile nopili, adult nakea, hihiwai, and opae) developed as part of this study to produce a relation between discharge and habitat availability. The final output was expressed as a weighted habitat area of streambed for a representative stream reach.

PHABSIM model results are presented in plots showing the area of estimated usable bed habitat over a range of streamflow that includes the diverted and natural base-flow estimates. The results are also presented as habitat relative to natural conditions with 100 percent of natural habitat at natural median base flow and 0 percent of habitat at 0 streamflow. In general, the plots show a decrease in habitat for all species as streamflow is decreased from natural conditions. The exception is at Hanawi lower and middle sites, where the habitat amount available under diverted conditions is virtually the same as would be available under natural conditions. The results also indicate that only minor differences in habitat exist for the adult and juvenile nopili, adult nakea, and hihiwai. At most of the middle sites, more habitat is available for opae than for alamoo at a given streamflow.

Several different measures are presented to show the relation between streamflow and habitat. The relative amount of habitat available at diverted conditions compared to expected natural conditions ranges from 0 percent at the Honomanu lower site, which is dry at diverted conditions, to about 100 percent at the Hanawi lower and middle sites, where Big Spring maintains steady streamflow. The diverted sites downstream of only one diversion have about 50 to 57 percent of their expected natural habitat, and the site downstream of two major diversions (Waikamoi middle-lower) has about 27 to 46 percent of expected natural habitat. Opae habitat for diverted conditions is as low as 40 percent at the Waikamoi middle-lower site to as much as 95 percent at the Hanawi middle site.

At six sites, a streamflow of about 1 ft^3/s will maintain 50 percent of the expected natural habitat and a streamflow of about 4 ft^3/s will maintain 90 percent of the expected natural habitat. At Kopiliula lower, about 2.6 ft^3/s is needed to maintain 50 percent of the expected natural habitat and about 7.6 ft^3/s is needed to maintain 90 percent of the expected natural habitat. For opae, greater than 50 percent of the expected natural habitat is already maintained at the diverted conditions. Streamflow of about 4 ft^3/s will maintain 90 percent of the expected natural opae habitat.

The relative amount of expected habitat available at 50 percent of natural median base flow ranges from 70 to 92 percent, and maintaining 90 percent of base flow results in 94 to 101 percent of expected natural habitat in the stream reaches. For opae, maintaining 50 percent of natural median base flow results in 82 to 92 percent of expected natural opae habitat, and flows at 90 percent of natural median base flow result in relative habitat of 97 to 99 percent of expected natural opae habitat.

Habitat-duration curves show the percentage of time that indicated habitat conditions would be equaled or exceeded and are based on the available estimates of flow duration at each stream reach developed earlier in the study for Q_{50} and Q_{95} of total flow and base flow.

The PHABSIM modeling results from the intensively studied streams were normalized to develop relations between the relative base flow in a stream at diverted conditions and the resulting amount of habitat available in the stream. The relations can be used to estimate relative habitat for diverted streams in the study area that were not intensively studied. The relations are valid for streams that are not dry. The model results indicate that the addition of even a small amount of water to a dry stream has a significant effect on the amount of habitat available.

The effects of streamflow on habitat in non-intensively studied streams was estimated using information gathered using a variety of techniques, including the use of the relation between streamflow diversion and habitat change and the field reconnaissance, aerial digital photography of the streams, and GIS analysis of stream and stream-basin characteristics. Estimates of the relative habitat range from 100 percent for stream sites with relatively small or no diversion to 0 percent for stream sites that are dry due to diversion. The maximum relative habitat at a stream site that is not dry is about 37 percent of expected natural habitat for alamoo, nopili, nakea, and hihiwai and 58 percent of expected natural habitat for opae at the Haipuaena middle-lower site, where the base flow is about 10 percent of natural conditions.

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Appendix A: Data from Study Area Stream Reconnaissance

Table A1. Summary of aquatic species observed during reconnaissance of selected stream reaches, northeast Maui, Hawaii.

[Abbreviations: ˚C, degrees Celsius; *M. lar*, *Macrobrachium lar*; –, species not observed; √, species observed but not counted]

Stream reach	Date	Altitude (feet)	Stream temperature (˚C)	Native species								Introduced species	
				Aholehole	Akupa	Alamoo	Hihiwai	Hinana	Nakea	Nopili	Opae	*M. lar*	Other
Kapaula upper (KU)	3/5/2003	1,370	19.5	–	–	–	–	–	–	–	√	–	–
Paakea lower (PaL)	3/6/2003	125	19.0	–	–	11	235	–	1	–	√	12	–
Paakea middle (PaM)	3/6/2003	565	18.0	–	–	9	–	–	–	–	250	–	–
Paakea upper (PaU)	3/4/2003	1,400	–	–	–	–	–	–	–	–	√	–	–
Waiohue lower (WeL)	3/6/2003	120	19.0	12	7	–	154	6	19	22	–	35	–
Waiohue upper (WeU)	3/4/2003	1,430	18.0	–	–	–	–	–	–	–	√	–	–
Puakaa upper (PuU)	3/4/2003	1,340	17.5	–	–	–	–	–	–	–	√	–	–
East Wailuaiki lower (EWL)	3/3/2003	35	–	–	9	–	2	–	5	–	–	4	–
East Wailuaiki middle (EWM)	3/10/2003	720	22.0	–	–	–	–	–	–	–	√	√	–
East Wailuaiki upper (EWU)	3/5/2003	1,270	17.0	–	–	–	–	–	–	–	√	–	–
West Wailuaiki lower (WWL)	3/3/2003	30	–	4	–	1	21	–	19	–	–	11	–
West Wailuaiki middle (WWM)	3/4/2003	410	19.5	–	–	1	4	–	–	–	–	16	–
West Wailuaiki upper (WWU)	3/5/2005	1,270	18.0	–	–	–	–	–	–	–	100	–	–
West Wailuanui upper (WWnU)	3/5/2003	1,200	17.5	–	–	–	–	–	–	–	14	–	–
Waiokomilo lower (WoL)	3/11/2003	95	24.5	–	–	–	–	–	–	–	–	–	Poeciliid, Koi, Dojo
Waiokomilo middle (WoM)	3/11/2003	560	21.0	–	–	–	–	–	–	–	–	–	–
Waiokomilo (Banana Spring)	3/13/2003	680	–	–	–	–	–	–	–	–	√	–	–
Waiokomilo upper (WoU)	3/5/2003	1,400	–	–	–	–	–	–	–	–	50	–	–
Ohia lower (OL)	3/12/2003	10	–	–	–	–	√	–	–	–	–	–	–
Palauhulu lower (PhL)	3/12/2003	20	19.5	–	–	3	5	5	18	30	–	30	–
Palauhulu (Store Spring)	3/12/2003	200	–	–	–	√	√	–	√	√	–	√	–
Palauhulu middle (PhM)	3/13/2003	700	–	–	–	–	–	–	–	–	10	–	–
Palauhulu (at bridge)	3/13/2003	880	–	–	–	√	–	–	–	–	√	–	–
Palauhulu (at diversion intake)	3/13/2003	1,400	–	–	–	√	–	–	–	–	√	–	–
Piinaau lower (PiL)	3/12/2003	20	21.5	–	–	–	–	–	2	–	–	5	–
Piinaau middle (PiM)	3/14/2003	800	dry	–	–	–	–	–	–	–	–	–	–
Piinaau upper (PiU)	3/13/2003	1,400	25.0	–	–	–	–	–	–	–	40	–	–
Nuaailua lower (NL)	5/5/2004	5	–	–	–	–	–	√	–	–	–	√	–
Punalau lower (PlL)	5/5/2004	5	–	–	–	–	–	√	√	–	–	√	–
Haipuaena lower (HaL)	3/7/2003	210	19.5	–	–	8	–	–	–	–	23	2	Poeciliid
Haipuaena middle-lower (HaML)	3/7/2003	400	–	–	–	1	–	–	–	–	√	√	Poeciliid
Puohokamoa lower (PL)	3/13/2003	30	20.0	–	–	21	–	–	2	–	51	15	–
Puohokamoa middle-lower (PML)	4/21/2003	600	–	–	–	–	–	–	–	–	1	25	–

Appendix B: Determination of Stage-Discharge Relations for Individual Stream Pools and Runs

Stage-discharge relations for individual stream pools and runs were estimated using straight-line rating curves (Kennedy, 1984). Using this method, measurements of gage height (water-surface altitude) are scaled by subtracting the stage of zero flow of the relevant pool or run to determine a water height above the effective stage of zero flow. These scaled heights are plotted against concurrent discharge measurements on a logarithmic scale and the data is fit with a straight line of the form

$$h = PQ^{b}$$

$$h = G - e$$

where:

- h is the water height above the stage of zero flow, in feet
- G is the gage height, in feet,
- e is the stage of zero flow, in feet,
- P is the intercept equal to Q when (G-e) is equal to 1.0,
- Q is the discharge, in cubic feet per second, and
- b is the slope of the straight line.

Tables B1 to B5 and figures B1 to B14 are data and plots of stage-discharge relations for all of the measuring points used in the PHABSIM simulations developed for this study. Each plot shows the scaled water heights and discharge data sets and the best-fitting straight-line equation for that data set. Estimates of natural (undiverted) flow at 50- (median) and 95-percentiles are shown to evaluate the applicability of using the stage discharge relation to estimate water-surface altitudes at these discharges.

Reference Cited

Kennedy, E.J., 1984, Discharge ratings at gaging stations: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 3, Chapter A10, 59 p.

Table B1. Discharge measurements, water-surface elevations, and points of zero flow for selected measuring points on Hanawi Stream, northeast Maui, Hawaii.

[All elevations are referenced to a local datum for each stream reach. Abbreviations: HwU, Hanawi upper; Hwm, Hanawai middle; Hwl, Hanawi lower; MP, measuring point; 5080, raging station 16508000; ft, foot; ft^3/s, cubic foot per second]

Date of measurement	Water surface elevation (ft)				Discharge (ft^3/s)
Hanawi upper habitat site					
	HwU-MP1	**5080 staff plate**	**HwU-MP2**		
6/19/2003	18.45	0.84	22.98		13
6/19/2003	18.41	0.84	22.93		12
7/3/2003	17.91	0.33	22.67		3.7
8/20/2003		0.99	23.04		16
6/19/2003	18.60	1.01			17
9/24/2003	17.94	0.34	22.68		3.8
5/7/2004	18.71	1.15	23.12		22
Elevation (ft)	19.73	NA	23.81		
Elevation of point of zero flow (ft)	17.07	20.23	21.96		
Hanawi middle habitat site measuring points					
	HwM-MP6	**HwM-MP7**	**HwM-MP8**	**HwM-MP9**	
10/8/2002	36.27	40.61	42.13		10
11/7/2002	36.21	40.58	42.08		9.9
12/16/2002	36.20	40.58	42.07		9.6
3/5/2003	36.16	40.52	42.01		7.5
7/23/2003	36.16	40.49	41.89	49.30	5.7
8/5/2003	36.17	40.49	41.88	49.29	8.0
9/24/2003	36.16	40.48	41.89	49.29	7.2
5/7/2004	36.16	40.81	42.50	49.42	11
Elevation (ft)	36.79	40.98	42.66	50.00	
Elevation of point of zero flow (ft)	35.06	38.95	40.16	48.43	
Hanawi lower habitat site measuring points					
	HwL-MP3	**HwL-MP4**	**HwL-MP6**	**HwL-MP7**	
10/9/2002	36.34	38.45	45.64	49.23	22
11/7/2002	36.35	38.45	45.64	49.21	21
12/16/2002	36.37	38.47	45.65	49.26	24
3/5/2003	36.24	38.34	45.67	49.09	21
4/15/2003	36.28	38.35	45.67	49.10	20
4/22/2003	36.33	38.46	45.84	49.20	39
6/3/2003	36.24	38.28	45.60	49.04	18
8/5/2003	36.29	38.34	45.66	49.07	20
9/23/2003	36.28	38.34	45.66	49.03	19
1/15/2004	36.21	38.37	45.65		21
Elevation (ft)	36.82	38.94	46.24	50.00	
Elevation of point of zero flow (ft)	35.27	37.01	44.37	47.91	

Table B2. Discharge measurements, water-surface elevations, and points of zero flow for selected measuring points on Kopiliula Stream, northeast Maui, Hawaii.

[All elevations are referenced to a local datum for each stream reach. Abbreviations: KpU, Kopiliula upper; KpM, Kopiliula middle; KpL, Kopiliula lower; MP, measuring point; c, control; ft, foot; ft^3/s, cubic foot per second]

Kopiliula upper habitat site measuring points

Date of measurement	Water surface elevation (ft) KpU-MP1	KpU-MP2	KpU-MP3	KpU-MP4	Discharge (ft^3/s)
11/18/2002				54.41	2.4
8/19/2002	46.98	48.20	49.79	54.86	10
2/20/2003	47.09	48.48		54.93	10
4/17/2003	47.73	48.77	50.55	55.78	38
8/4/2003	47.19	48.35	49.97		11
Elevation (ft)	47.78	49.05	50.00	55.36	
Elevation of point of zero flow (ft)	46.05	47.80	49.25	53.93	

Kopiliula middle habitat site measuring points

Date of measurement	KpM-MPC	KpM-MP1	KpM-MP2	KpM-MP3	KpM-MP4	KpM-MP5	KpM-MP6	Discharge (ft^3/s)
8/22/2002	19.36	27.58	28.79	31.35	31.76	32.31	32.75	.71
10/24/2002	19.38	27.56	28.80	31.34	31.74	32.29	32.75	.91
2/18/2003	19.54	27.82	28.93	31.53	31.93	32.35	32.89	2.0
2/20/2003	20.00	28.36	29.38	31.98	32.37	32.80	33.36	8.8
3/6/2003	19.36	27.67	28.80	31.36	31.81	32.27	32.74	.96
8/7/2003	19.23	27.57	28.79	31.31	31.75	32.29	32.72	1.4
9/11/2003	19.34	27.65	28.84	31.39	31.81	32.31	32.77	.97
Elevation (ft)	20.00	28.53	29.21	31.89	32.60	32.84	33.23	
Elevation of point of zero flow (ft)	18.51	26.67	28.22	30.61	30.47	31.76	31.53	

Kopiliula lower habitat site measuring points

Date of measurement	KpL-MP1	KpL-MP2	KpL-MP3	KpL-MP4	KpL-MP5	Discharge (ft^3/s)
8/20/2002	21.23	21.60	25.62	29.75	31.16	2.4
8/21/2002	21.21	21.59	25.60	29.75	31.15	2.1
10/21/2002	21.20	21.59	25.58	29.73	31.14	2.2
2/18/2003	21.44	21.86	25.85	29.93	31.30	5.5
2/20/2003	21.58	22.03	26.03	30.09	31.49	11
3/6/2003	21.23	21.60	25.65	29.71	31.01	2.3
6/5/2003	21.15	21.51	25.53	29.59	30.97	1.9
7/21/2003	21.33	21.74	25.75	29.84	31.20	4.1
7/22/2003	21.29	21.68	25.70	29.79	31.13	3.0
9/11/2003	21.16	21.62	25.65	29.73	31.07	3.7
Elevation (ft)	21.66	22.14	26.50	30.70	31.50	
Elevation of point of zero flow (ft)	20.30	20.99	25.22	29.37	30.14	

Table B3. Discharge measurements, water-surface elevations, and points of zero flow for selected measuring points on Wailuanui Stream, northeast Maui, Hawaii.

[All elevations are referenced to a local datum for each stream reach. Abbreviations: WU, Wailuanui upper; WM, Wailuanui middle; WL, Wailuanui lower; MP, measuring point; ft, foot; ft^3/s, cubic foot per second]

Date of measurement	Water-surface elevation (ft)					Discharge (ft^3/s)
Wailuanui upper habitat site measuring points						
	WU-MPC	WU-MP1	WU-MP2	WU-MP3	WU-MP4	
7/31/2002	16.23	19.59	20.45	22.85	25.07	2.6
11/6/2002	16.02	19.39	20.21	22.68	24.95	1.2
1/23/2003		19.32	20.08	22.64	24.87	0.66
3/3/2003	16.27	19.49	20.20	22.80	24.61	1.8
Elevation (ft)	16.62	20.00	20.73	23.23	25.574	
Elevation of point of zero flow (ft)	15.29	18.97	19.96	22.23	24.25	
Wailuanui middle habitat site measuring points						
	WM-MP1					
8/1/2002	25.20					1.4
10/9/2002	25.10					.51
11/19/2002	25.03					.25
3/6/2003	25.20					.76
Elevation (ft)	26.13					
Elevation of point of zero flow (ft)	24.94					
Wailuanui lower habitat site measuring points						
	WL-MPC	WL-MP2	WL-MP3	WL-MP4		
7/30/2002	15.90	18.57	19.74	20.33		2.7
8/23/2002	15.79	18.46	19.63	20.28		1.6
10/11/2002	15.67	18.40	19.58	20.35		1.1
11/5/2002	15.49	18.31	19.50	20.22		.56
3/6/2003	15.72	18.39	19.61	20.13		1.1
4/18/2003	15.98	18.61	19.75	20.45		2.6
4/23/2003	16.61	19.16	20.17	20.86		18
6/6/2003	15.38	18.16	19.42	20.11		.20
8/6/2003	15.82	18.46	19.64	20.35		1.7
9/10/2003	15.89	18.55	19.69	20.40		2.3
11/25/2003	15.83	18.49	19.64	20.36		1.6
Elevation (ft)	15.55	18.91	20.00	20.87		
Elevation of point of zero flow (ft)	14.99	17.81	18.96	19.77		

Table B4. Discharge measurements, water-surface elevations, and points of zero flow for selected measuring points on Honomanu Stream, northeast Maui, Hawaii.

[All elevations are referenced to a local datum for each stream reach. Abbreviations: HnU, Honomanu upper; HnL, Honomanu lower; MP, measuring point; ft, foot; ft^3/s, cubic foot per second]

Date of measurement	Water-surface elevation (ft)				Discharge (ft^3/s)
Honomanu upper habitat site measuring points					
	HnU-MP2	**HnU-MP3**	**HnU-MP4**	**HnU-MP6**	
11/8/2002	19.59	24.21	33.14	35.71	1.1
10/10/2002	19.68	24.32	33.22	35.91	1.8
2/19/2003	19.78	24.47	33.36	36.05	3.4
3/4/2003	19.70	24.36	33.28	35.98	2.2
6/17/2003	20.10	24.87	33.76	36.46	8.2
6/17/2003	19.96	24.68	33.59	36.30	6.8
Elevation (ft)	20.00	24.62	33.56	36.27	
Elevation of point of zero flow (ft)	19.26	23.89	32.23	35.37	
Honomanu lower habitat site measuring points					
	HnL-MP1	**HnL-MP2**	**HnL-MP3**		
4/21/2003	17.00	18.24	19.49		12
4/22/2003	16.52	17.73	19.19		1.5
Elevation (ft)	16.53	18.34	19.39		
Elevation of point of zero flow (ft)	15.83	17.05	18.12		

Table B5. Discharge measurements, water-surface elevations, and points of zero flow for selected measuring points on Waikamoi Stream, northeast Maui, Hawaii.

[All elevations are referenced to a local datum for each stream reach. Abbreviations: WiU, Waikamoi upper; WiMU, Waikamoi middle-upper; WiML, Waikamoi middle-lower; MP, measuring point; ft, foot; ft^3/s, cubic foot per second]

Date of measurement	Water-surface elevation (ft)				Discharge (ft^3/s)
Waikamoi upper habitat site measuring points					
	WiU-MP1	WiU-MP2	WiU-MP3	WiU-MP4	
10/10/2002	19.63	23.87	26.00	28.95	1.4
11/8/2002	19.54	23.74	25.81	28.81	.71
2/19/2003	19.81	24.03	26.32	29.39	3.8
3/4/2003	19.66	23.86	26.06	29.04	1.4
4/17/2003	20.05	24.28	26.65	29.90	7.3
6/16/2003	20.00	24.22	26.57	29.77	7.2
9/9/2003	19.93	24.13	26.47	29.79	5.4
Elevation (ft)	20.00	24.01	26.27	29.28	
Elevation of point of zero flow (ft)	19.17	23.36	25.07	28.59	
Waikamoi middle-upper habitat site measuring points					
	WiMU-MP1	WiMU-MP2			
10/10/2002	19.52	21.73			.51
11/20/2002	19.49	21.72			.46
2/19/2003	19.58	21.85			1.2
3/4/2003	19.55	21.77			.50
4/14/2003	19.50	21.66			.84
5/20/2003	19.44	21.59			.52
5/22/2003	19.64	21.84			1.3
7/25/2003	19.54	21.75			1.1
8/6/2003	19.52	21.69			1.0
9/12/2003	19.59	21.75			.76
Elevation (ft)	20.00	22.17			
Elevation of point of zero flow (ft)	19.16	20.96			
Waikamoi middle-lower habitat site measuring points					
	WiML-MPC	WiML-MP1	WiML-MP2		
10/11/2002	16.95	22.43	30.30		.18
11/20/2002	16.92	22.43	30.61		.24
3/7/2003	16.89	22.39	30.33		.14
4/17/2003	17.01	22.51	30.99		.43
6/6/2003	16.96	22.44	30.34		.12
6/18/2003	16.89	22.38	30.39		.16
7/25/2003	16.88	22.38	30.41		.17
8/6/2003	16.87	22.38	30.47		.14
9/8/2003	16.89	22.40	30.72		.25
4/15/2004		22.83	30.99		2.2
Elevation (ft)	16.71	23.59	31.19		
Elevation of point of zero flow (ft)	16.50	22.12	30.21		

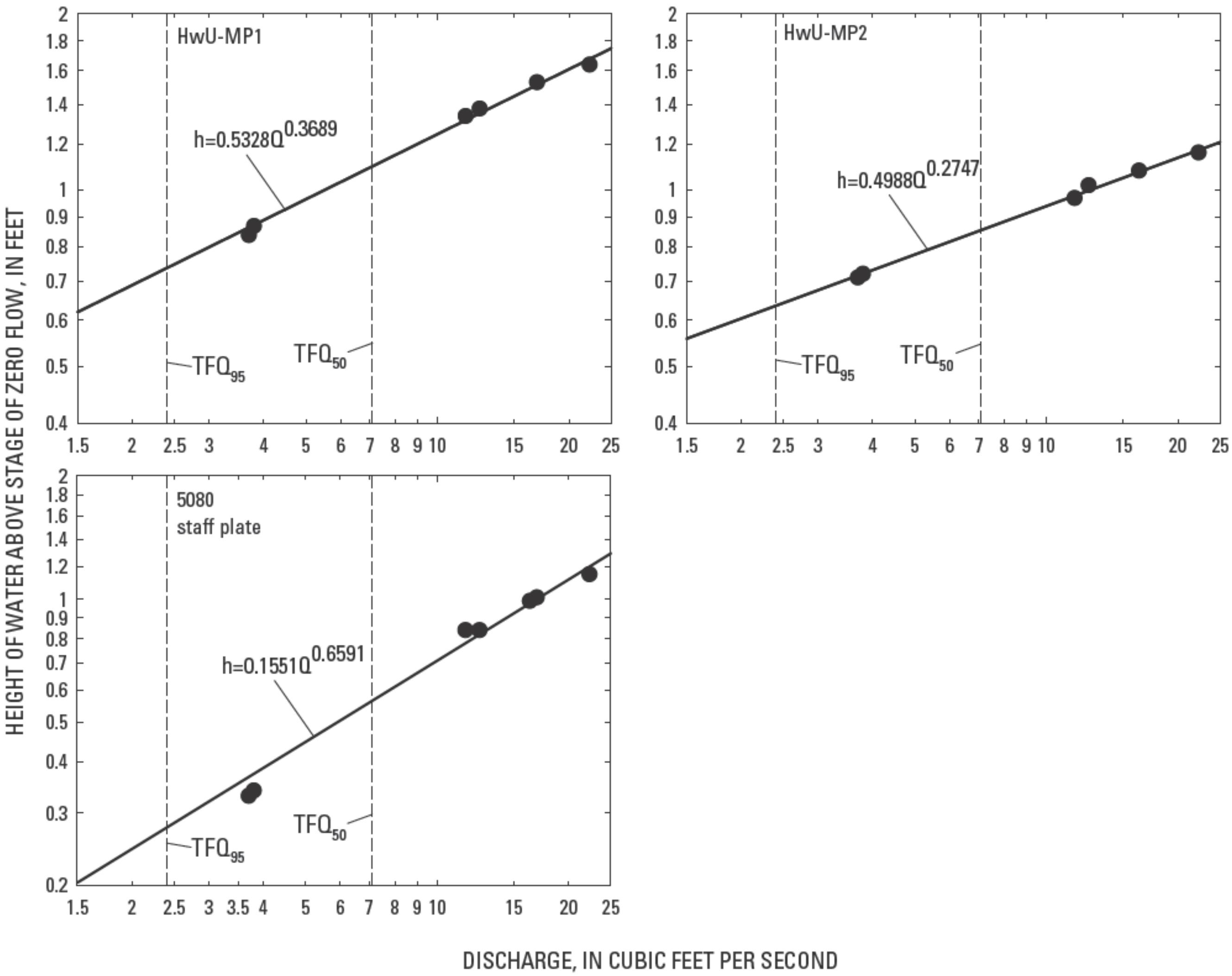

Figure B1. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Hanawi upper habitat site, northeast Maui, Hawaii.

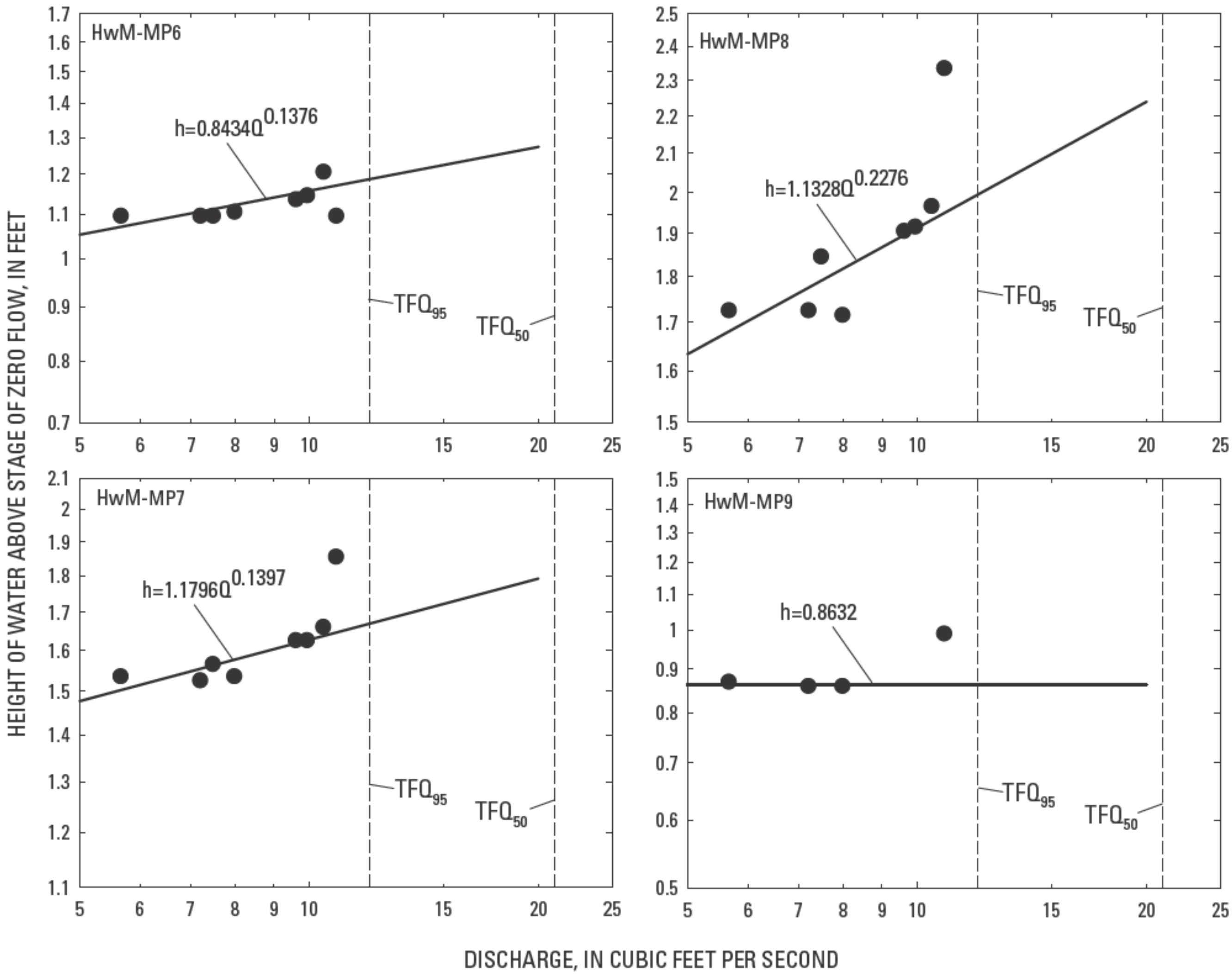

Figure B2. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Hanawi middle habitat site, northeast Maui, Hawaii.

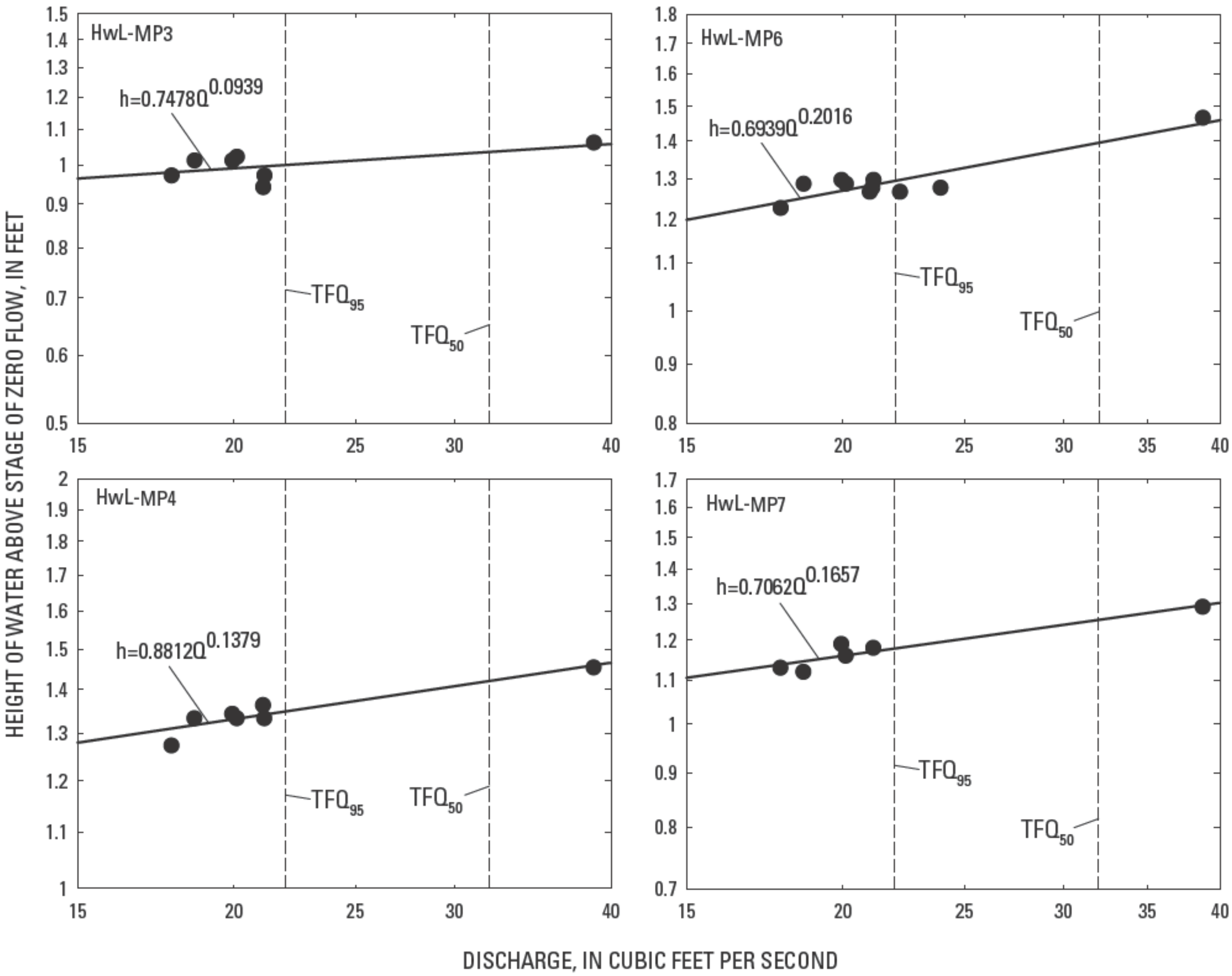

Figure B3. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Hanawi lower habitat site, northeast Maui, Hawaii.

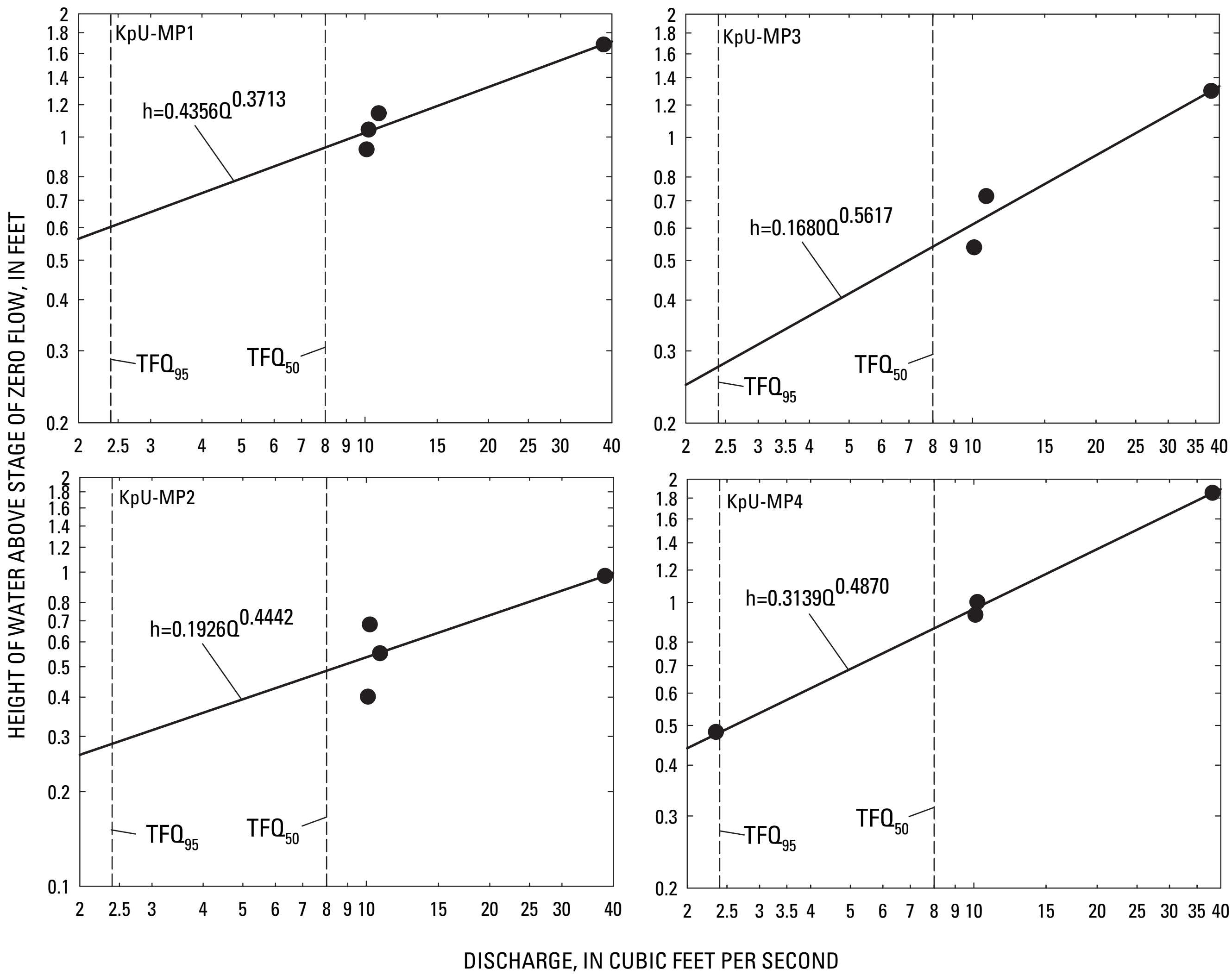

Figure B4. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Kopiliula upper habitat site, northeast Maui, Hawaii.

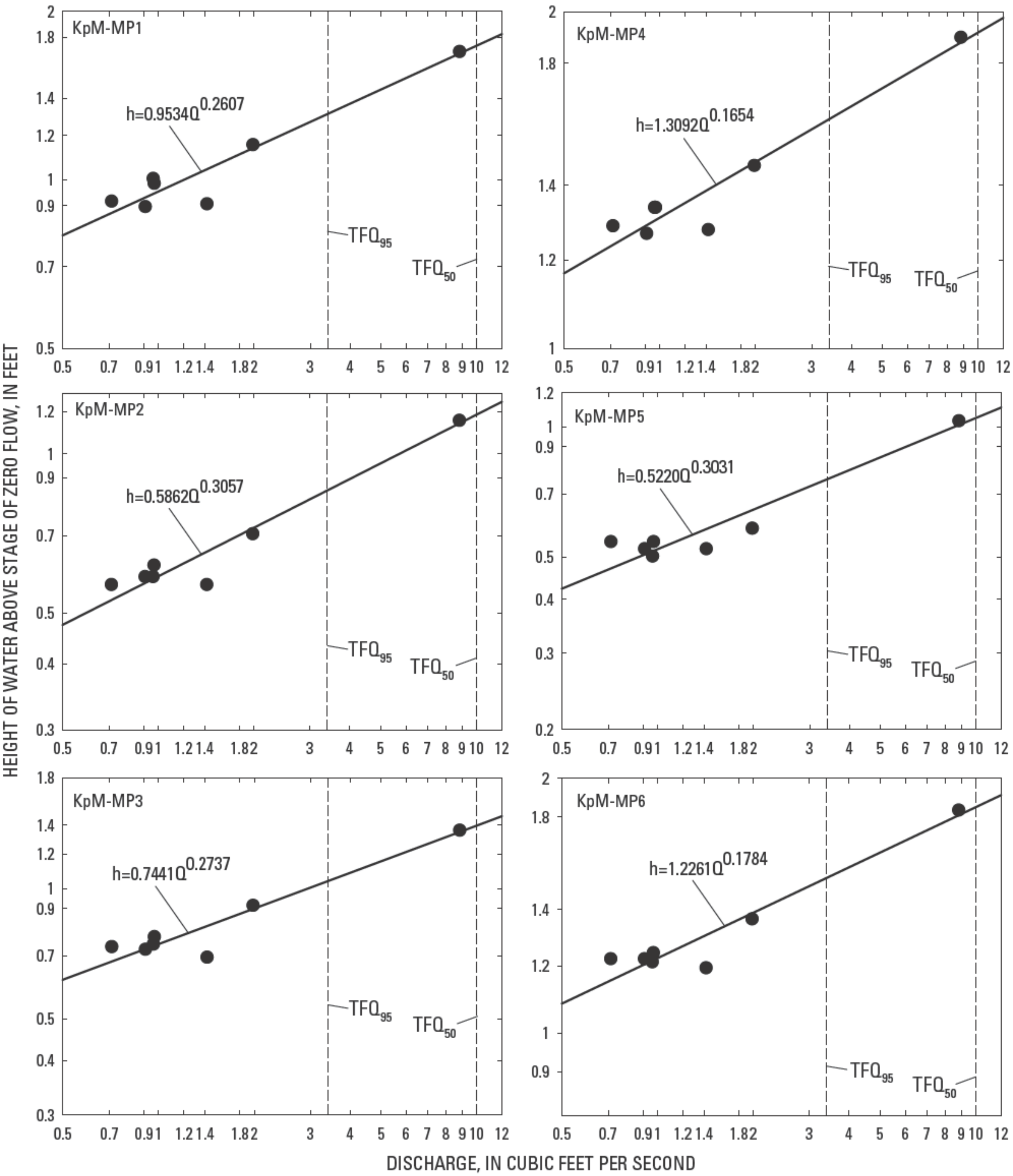

Figure B5. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Kopiliula middle habitat site, northeast Maui, Hawaii.

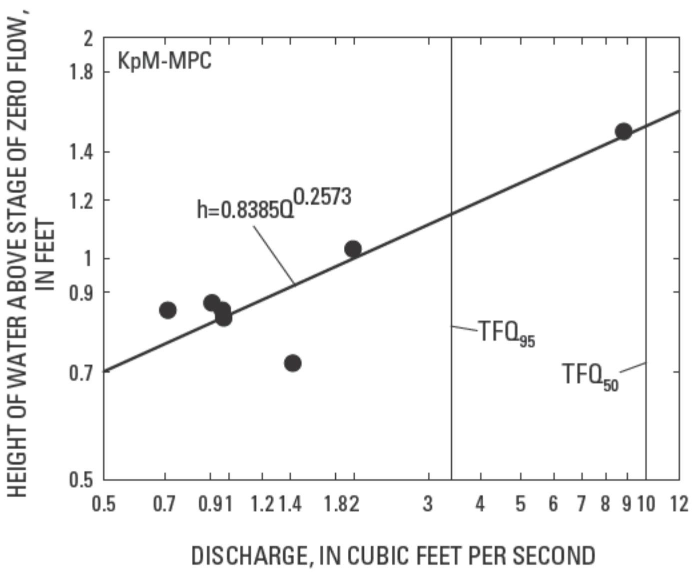

Figure B5. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Kopiliula middle habitat site, northeast Maui, Hawaii—*Continued.*

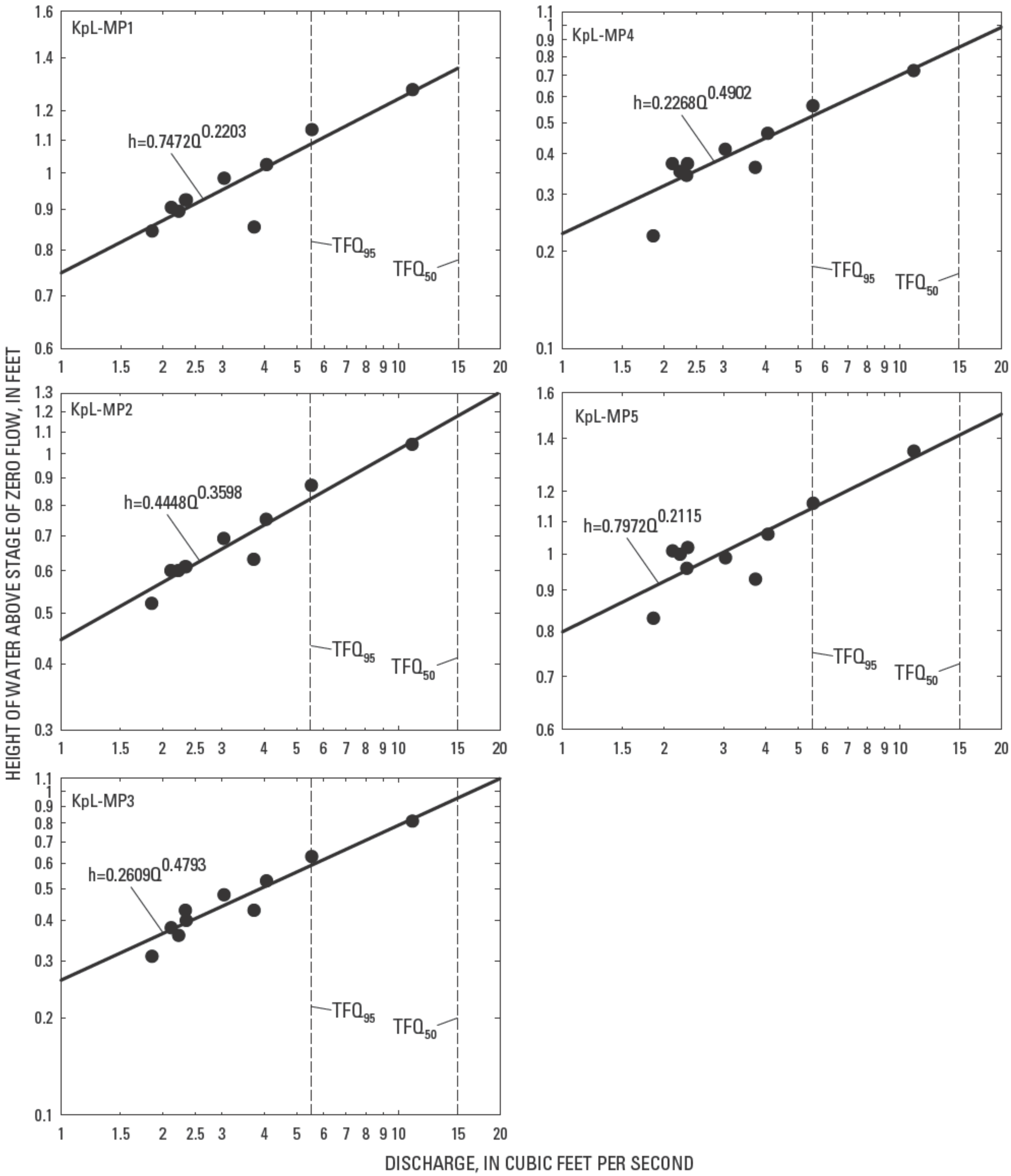

Figure B6. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Kopiliula lower habitat site, northeast Maui, Hawaii.

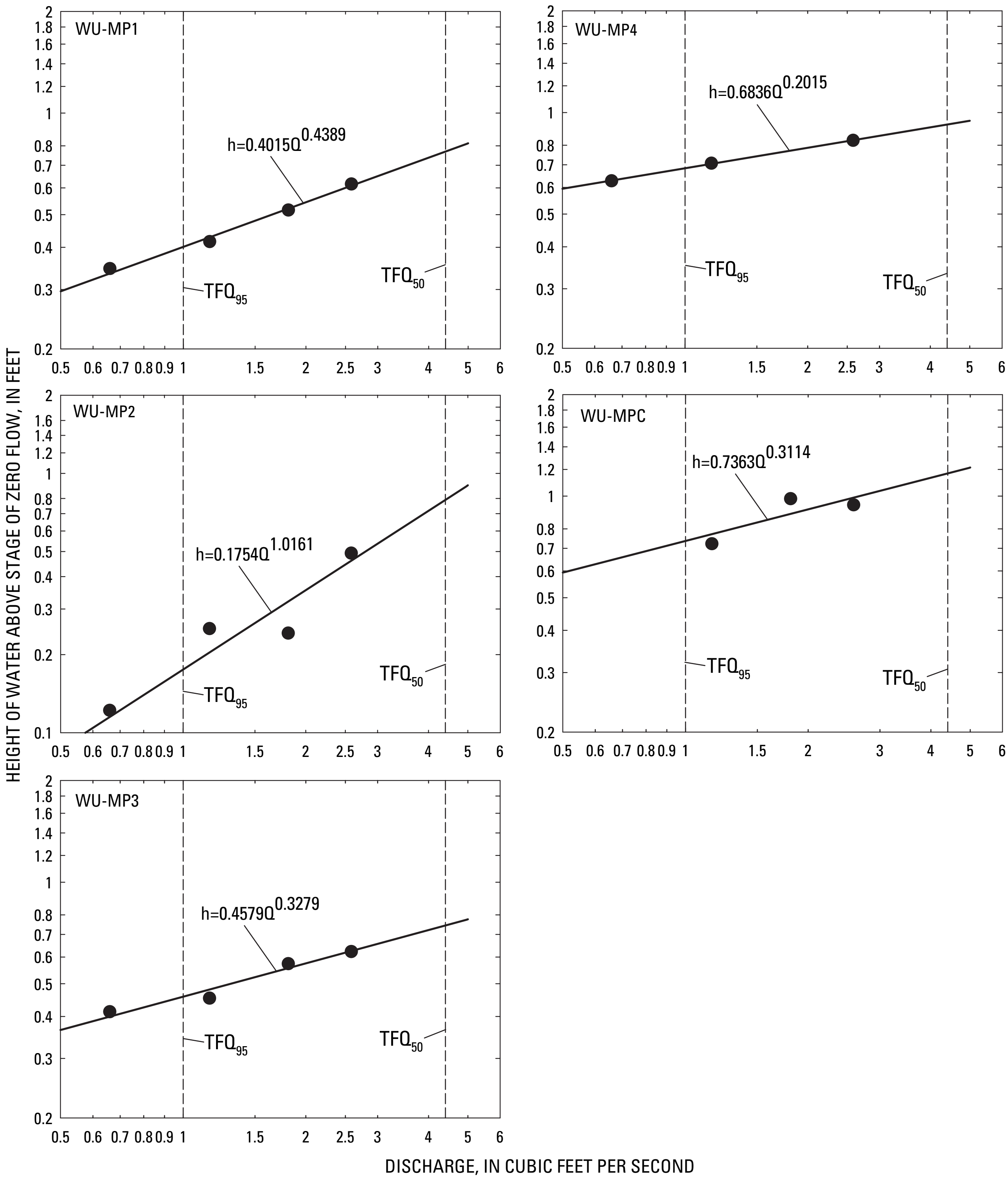

Figure B7. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Wailuanui upper habitat site, northeast Maui, Hawaii.

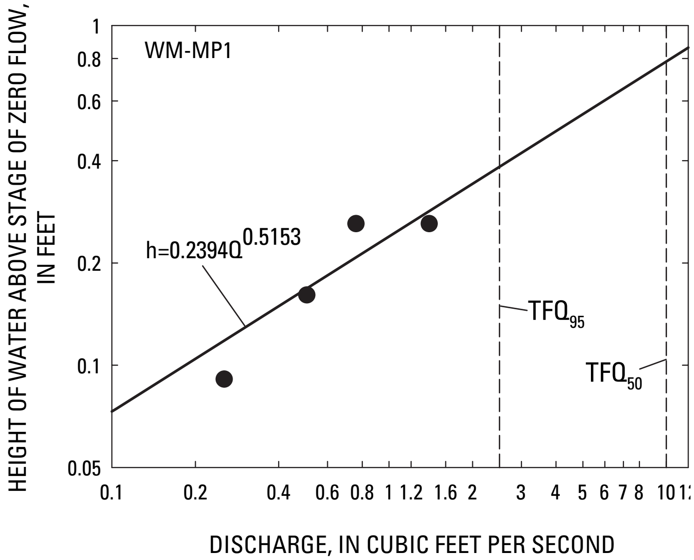

Figure B8. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Wailuanui middle habitat site, northeast Maui, Hawaii.

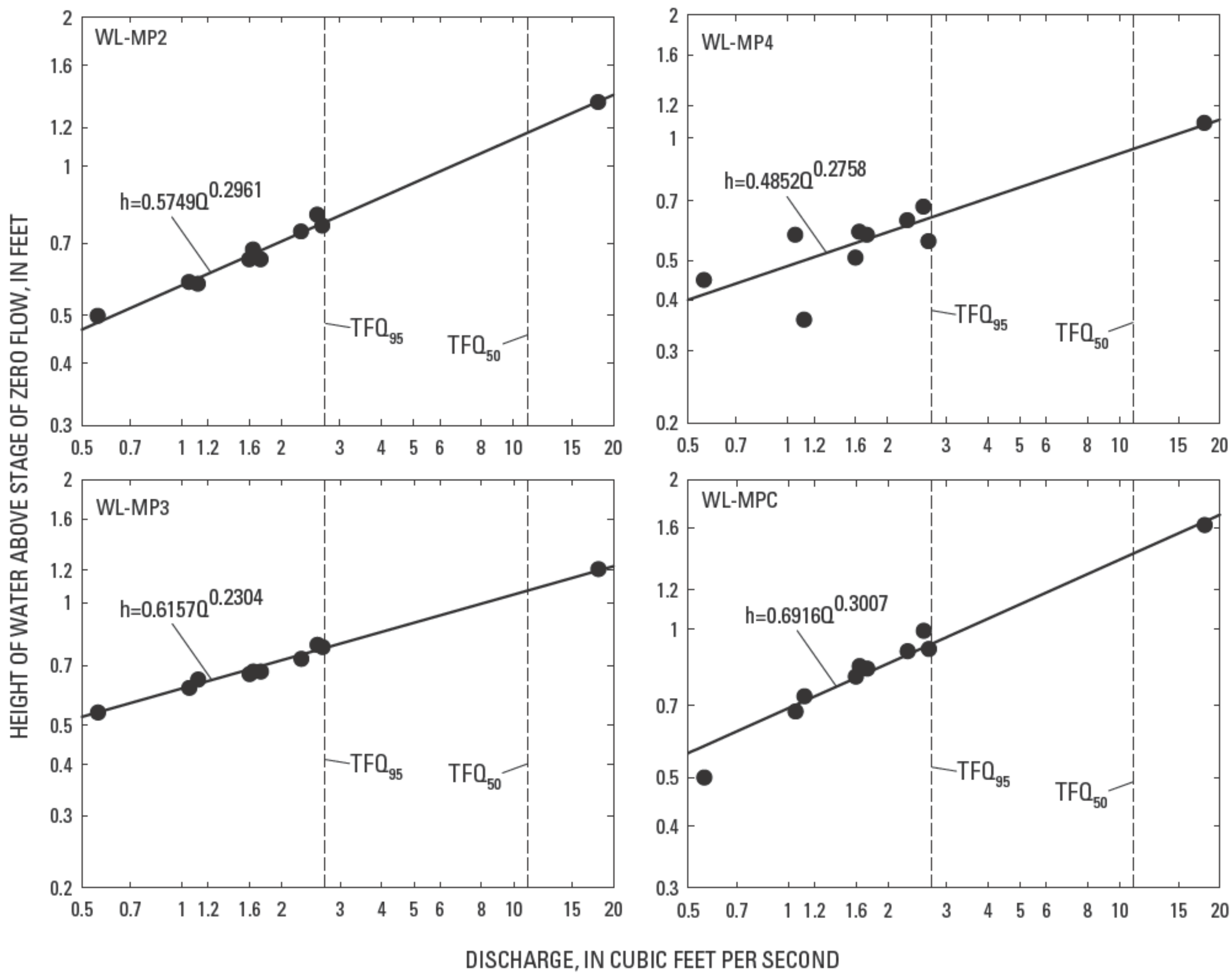

Figure B9. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Wailuanui lower habitat site, northeast Maui, Hawaii.

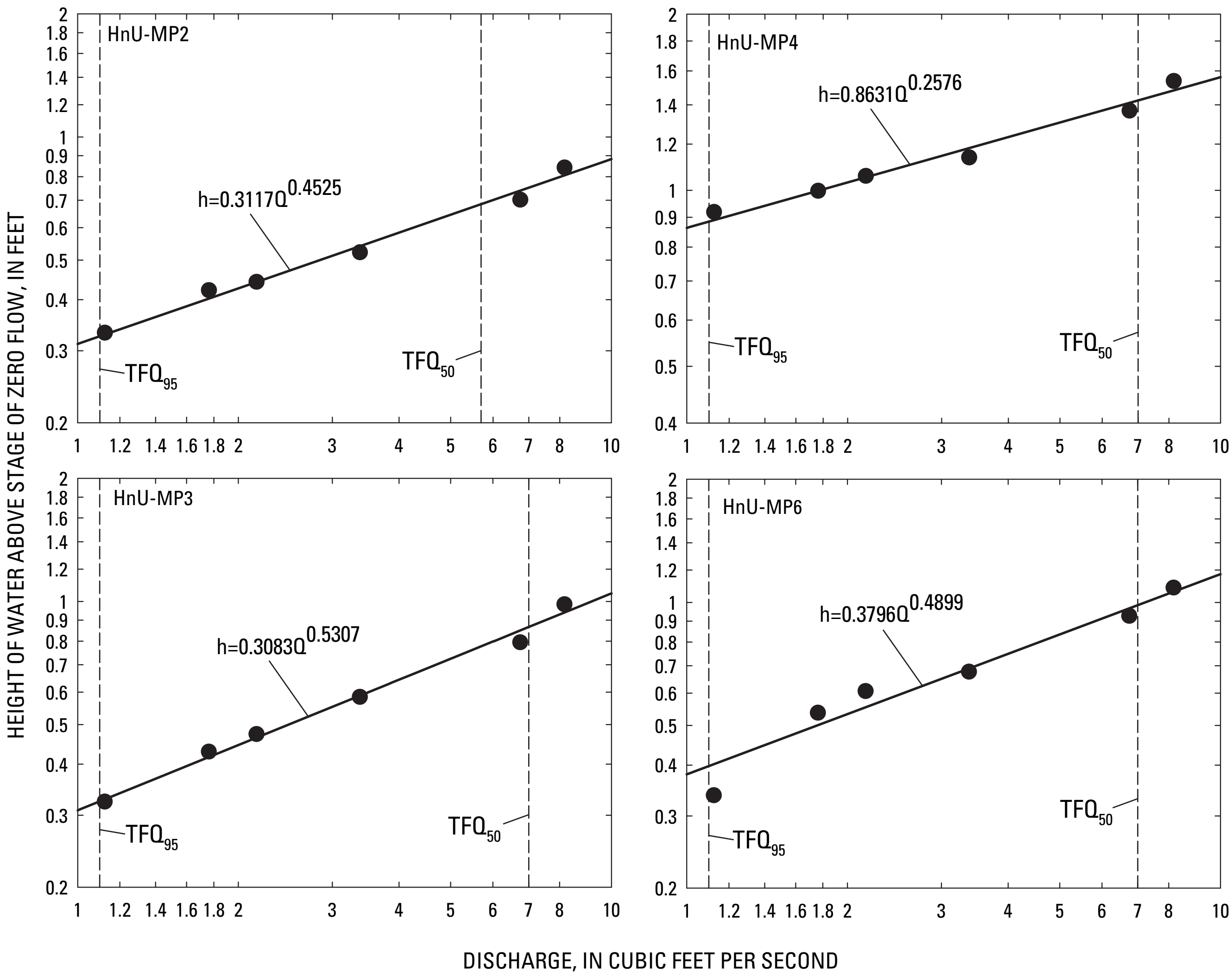

Figure B10. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Honomanu upper habitat site, northeast Maui, Hawaii.

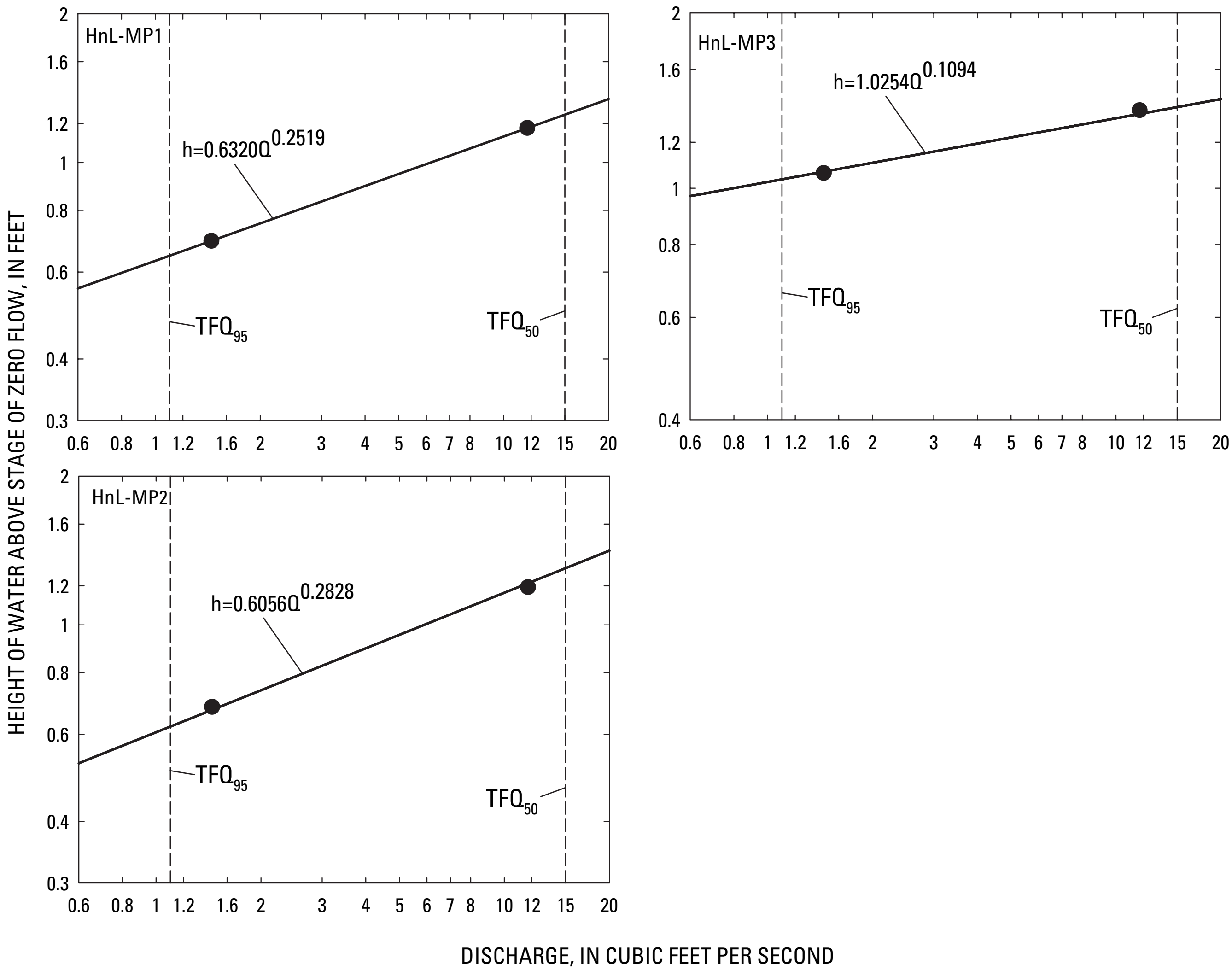

Figure B11. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Honomanu lower habitat site, northeast Maui, Hawaii.

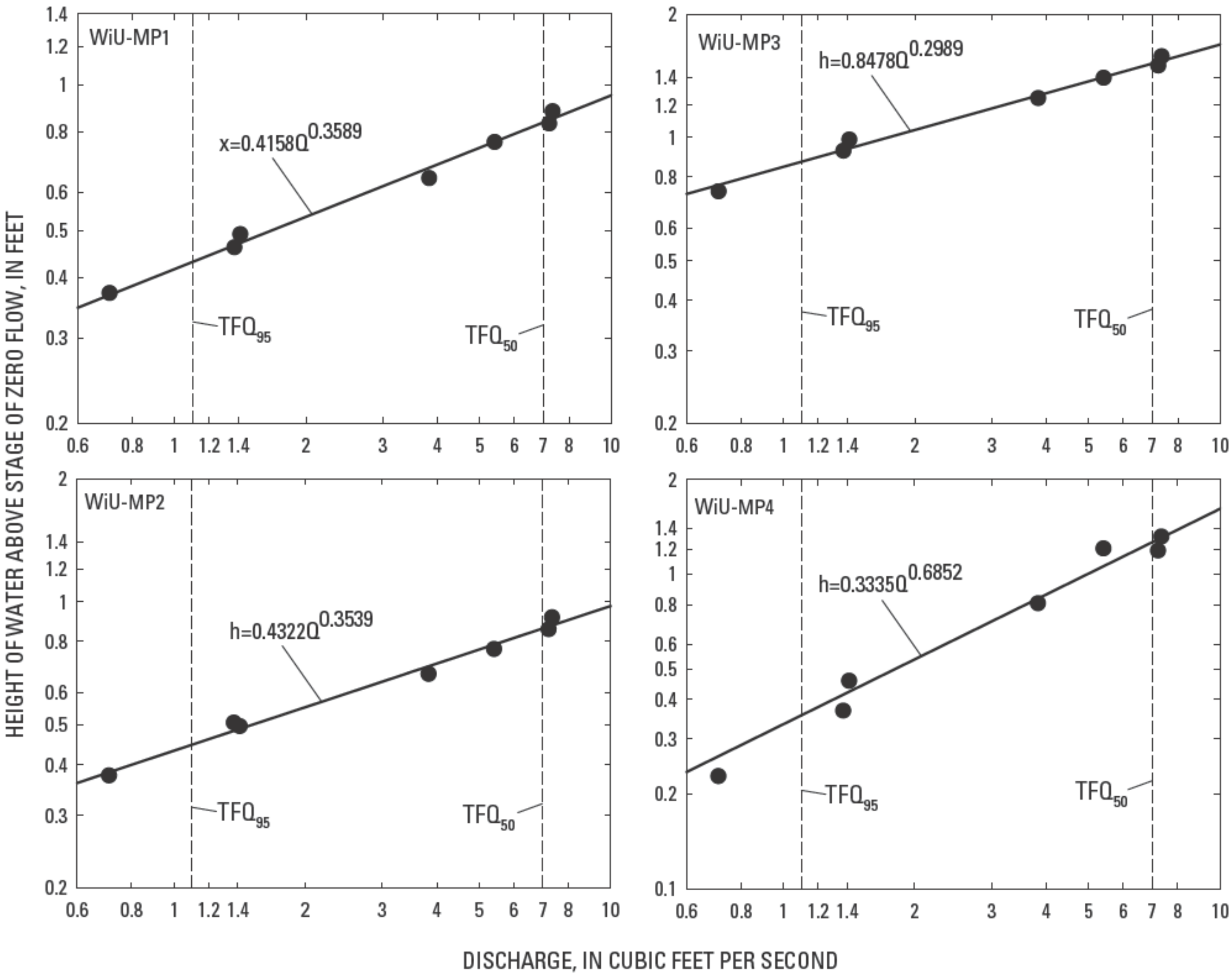

Figure B12. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Waikamoi upper habitat site, northeast Maui, Hawaii.

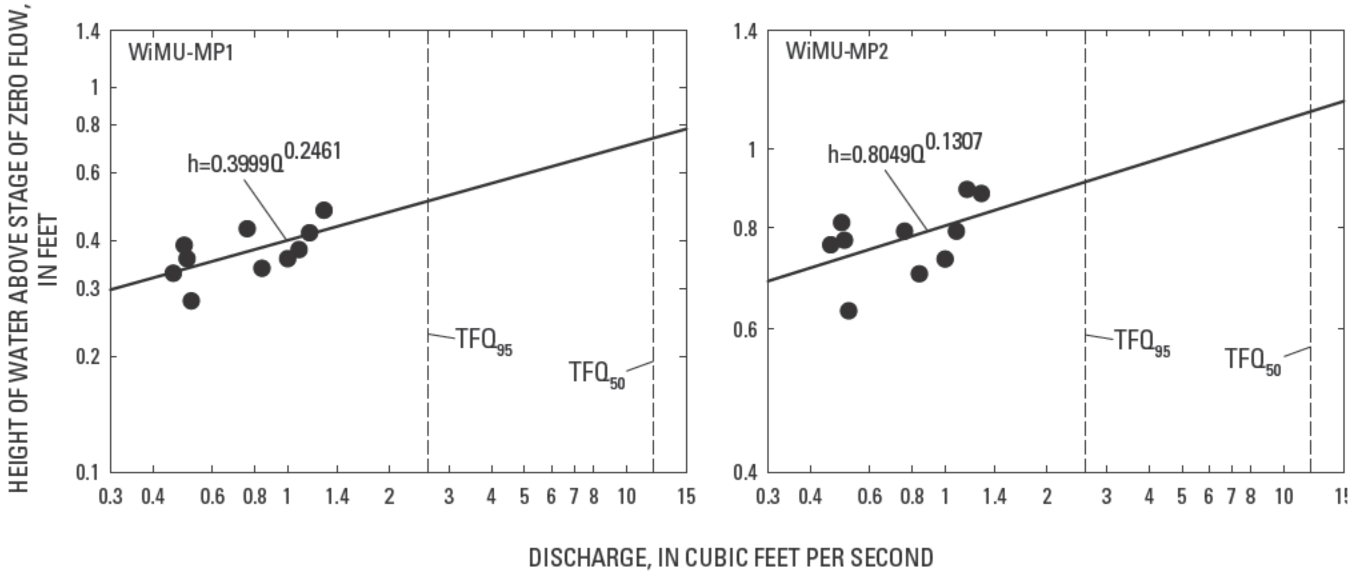

Figure B13. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Waikamoi middle-upper habitat site, northeast Maui, Hawaii.

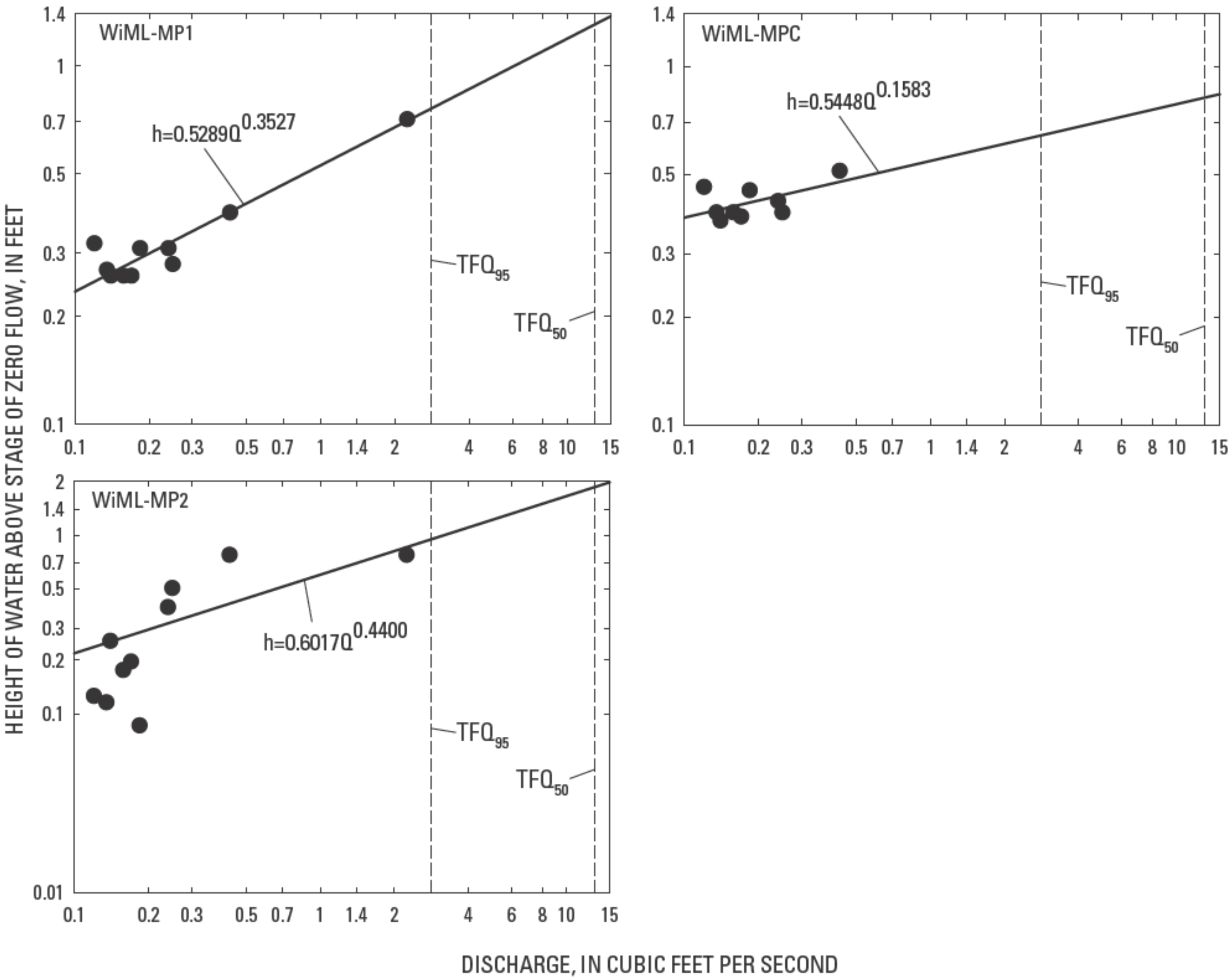

Figure B14. Stage-discharge measurements, best-fitting lines, and median (TFQ_{50}) and Q_{95} (TFQ_{95}) flow for selected reaches of the Waikamoi middle-lower habitat site, northeast Maui, Hawaii.

Appendix C: Development and Testing of Species Habitat Suitability Criteria

Development of Species Habitat Suitability Criteria

The biological and habitat data measured at each stream transect were compiled for each stream reach to determine habitat availability and habitat utilization. Habitat availability was defined as the proportion of the habitat type at each site in each interval, regardless of the presence or absence of any macrofauna. Habitat utilization for each site was defined as the proportion of each species occupying each habitat type interval. Frequency distributions for each species and age class were generated for each habitat variable at the various sites. Habitat availability and utilization data for the habitat variables were grouped into uniform intervals for analysis.

The size data for the native fish species *Lentipes concolor* (oopu alamoo), *Awaous guamensis* (oopu nakea), and *Sicyopterus stimpsoni* (oopu nopili) were converted from the total lengths into size class categories (adult, juvenile, and fry) following the approach of Kinzie and others (1984). The habitat variables velocity and depth data were combined and expressed as Froude number using

$$Fr = V_m / (gd)^{1/2} \quad , \qquad (1)$$

where:

- Fr is the Froude number,
- V_m is the mean flow velocity, in ft/s,
- g is gravitational acceleration, 32.2 ft/s^2, and
- d is the flow depth, in ft.

A Fr <1 is subcritical or calm flow, Fr =1 is critical flow, and Fr >1 is supercritical or torrential flow (Newbury, 1996). Froude number provides an objective way to classify and analyze the flow regimes of riffle, run, and pool. Substratum data were arranged into categories based on the most abundant substrate type in each cell. Where two or more substrate categories were equally dominant, the largest type was used.

To demonstrate preference for a particular habitat type, it must be shown that the frequency distribution of habitat utilization is statistically dissimilar to the distribution of the habitat availability; otherwise, the habitat utilization could simply be a random function proportional to the habitat availability. To test this hypothesis, the Kolmogorov-Smirnov two-sample goodness-of-fit (KS-gof) test (SAS Institute Inc., 1989) was used with the Froude number calculated for the available and utilized data (table C1). Kinzie and others (1984) and Kinzie (1988) used the same test but on the depth and velocity separately. The procedure is a nonparametric statistical analysis that computes, using the empirical distribution function (EDF), the Kolmogorov-Smirnov test statistic, D, for two samples. This statistic tests the null hypothesis that the true distribution functions of both samples are equal. If the null hypothesis is rejected, the distributions of available and utilized habitat are different and therefore, preference is indicated.

After the habitat availability and utilization distributions were tested, habitat criteria were created for Froude number and substrate for each species and size class at each site using nonparametric tolerance limits (Gosse, 1982; Bovee, 1986). Kinzie and others (1986) recommend that utilization curves be developed with nonparametric tolerance limits at the 90-percent confidence level. This method of developing curves from small databases is conservative and is not highly influenced by internal variations in the frequency distribution (Kinzie and others, 1986). Utilization and availability criteria were developed using the table of nonparametric tolerance limits developed by Somerville (1958). This table provides, for a given sample size (n), an ordered value for the 50-, 75-, 90-, 95-, and 99-percent proportions. Using half of the ordered value for each proportion, P, the lower boundary (counting up from the minimum value) ranked value and the upper boundary (counting down from the maximum value) ranked value (Remington and Schork, 1970; Bovee, 1986) are obtained. The normalized weighting factors of Gosse (1982) were used to normalize the criteria to values between 0 and 1. The normalized suitability index (NSI) was derived as:

$$NSI = 2(1 - P) \quad . \qquad (2)$$

For example, if n = 55 and P = 0.50, then the ordered value from the table = 28 and half the ordered value = 14. Therefore the 14th ranked value and the 41st ranked value would be the lower and upper boundaries, and the NSI = 2(1-0.5) = 1.0. Nonparametric tolerance limits for values of n that were not included in the table were interpolated. Figure C1 is an example of a non-parametric utilization curve that includes a plot of available and utilized habitat data that were used to determine the final curve. Figures C2 to C8 show the final criteria for adult and juvenile alamoo, adult and juvenile nopili, adult nakea, opae, and hihiwai.

Transferability of Species Habitat Suitability Criteria to Unsampled Streams in Study Area and Other Study Sites in Hawaii

After the utilization and availability criteria were developed, the utilization criteria were used to test the transferability of the habitat criteria to unsampled streams in the study area and to other sites in Hawaii where studies were conducted. The U.S. Fish and Wildlife Service provided data from previous studies conducted in Hawaii during 1984–1989. Copies of the original field data sheets and field notes were used to compile the historical data for comparative purposes. These studies included two sites on Nanue Stream on the island of Hawaii, seven sites on Hanakapiai Stream and two sites on the Wainiha River on the island of Kauai, seven sites on Hanawi Stream and two sites on Puaaluu stream on Maui, and one site each on Kawainui, Lanipuni, and Pilipililau Streams on the island of Molokai (table C2). Habitat availability data were collected at only five of these 22 study sites. In addition, the criteria generated from this study were compared to data from Waikolu and Pelekunu Streams on Molokai (Brasher, 1996; Brasher, 1997). The data sets that included habitat availability were used to verify the transferability of the habitat preference criteria generated from this USGS study.

Utilization criteria from sites that had high abundances of a species and the greatest range of habitat availability were selected to test transferability. These criteria were overlain on the habitat utilization and availability distributions from other sites that had greater than 20 individuals of the same species and size class. The predicted percentage of habitat utilization for each interval, $P_i^{\%}$, was calculated as the product of the percent habitat availability (*A*) multiplied by the maximum *NSI* value (NSI_{max}, given a minimum value of 0.20 encompassing 90 percent of the conditions that the individuals are likely to inhabit) for each interval (*i*).

$$P_i^{\%} = A_i (NSI_{max})_i \quad . \qquad (3)$$

The results were normalized to 1 by dividing each interval by the sum of all of the intervals.

$$\frac{P_i^{\%}}{\sum P_i^{\%}} \quad . \qquad (4)$$

The predicted number of observations at each interval, $P_i^{\%}$, was calculated as the total number of observations (*n*) at the second site multiplied by the predicted proportion of habitat utilization for each interval:

$$P_i^{obs} = nP_i^{\%} \quad . \qquad (5)$$

To test the fit of the predicted number of observations, the KS-gof test was used to compare the distribution of the actual observations with the distribution of the predicted observations. Because the intervals represent a range of values, all the values for the predicted number of observations for a given interval were assigned the value of the midpoint of that interval. To allow comparisons, the values of the actual observations were also converted to the value of the interval midpoint. The measure of achievement of the transferability of the criteria was interpreted as not disproving the null hypothesis that the distributions, actual and predicted, were equal. Comparisons of the predicted and observed number of individuals for each interval were also examined graphically (figs. C9-C13).

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Table C1. Results of Kolmogorov-Smirnov two-sample goodness-of-fit tests for within-sites comparison of Froude number utilization and availability for taxa and size class, northeast Maui, Hawaii.

[Abbreviations: n, number of observations; D, test statistic; nd, not determined; test results that are significant at *p*-value less than or equal to 0.05 are shown in **bold** and indicate preference; <, less than]

Taxa	Study sites	*n* Utilized	*n* Available	D	*p*-value
Lentipes concolor (alamoo)					
Adult	Hanawi middle	151	252	0.18	**0.003**
Adult	Palikea	30	177	.22	.179
Fry	Hanawi middle	49	252	.13	.477
Juvenile	Hanawi middle	113	252	.21	**.002**
Juvenile	Palikea	43	177	.22	.077
Neritina granosa (hihiwai)					
nd	Hanawi lower	255	316	.14	**.006**
nd	Kopiliula lower	265	306	.40	**< .0001**
nd	Kopiliula lower replicate	244	306	.25	**< .0001**
nd	Wailuanui lower	35	144	.46	**< .0001**
Juvenile Oopu (hinana)					
Fry	Hanawi lower	243	316	.23	**< .0001**
Fry	Kopiliula lower	31	306	.40	**.000**
Awaous guamensis (nakea)					
Adult	Hanawi lower	28	316	.23	.134
Adult	Kopiliula lower	42	306	.25	**.017**
Adult	Kopiliula lower replicate	23	306	.32	**.028**
Juvenile	Kopiliula lower	31	306	.34	**.003**
Juvenile	Kopiliula lower replicate	28	306	.12	.868
Sicyopterus stimpsoni (nopili)					
Adult	Hanawi lower	57	316	.23	**.011**
Adult	Kopiliula lower	58	306	.47	**< .0001**
Adult	Kopiliula lower replicate	52	306	.39	**< .0001**
Adult and Juveniles	Hanawi lower	117	316	.15	**.034**
Juvenile	Hanawi lower	60	316	.15	.219
Juvenile	Kopiliula lower	22	306	.35	**.012**
Atyoida bisulcata (opae)					
nd	Hanawi middle	354	252	.11	.075
nd	Hanawi Upper	215	182	.31	**< .0001**
nd	Honomanu Upper	587	184	.10	.109
nd	Kopiliula Upper	258	172	.16	**.008**
nd	Waikamoi Upper	467	152	.13	**.046**
nd	Wailuanui Upper	15	51	.27	.364

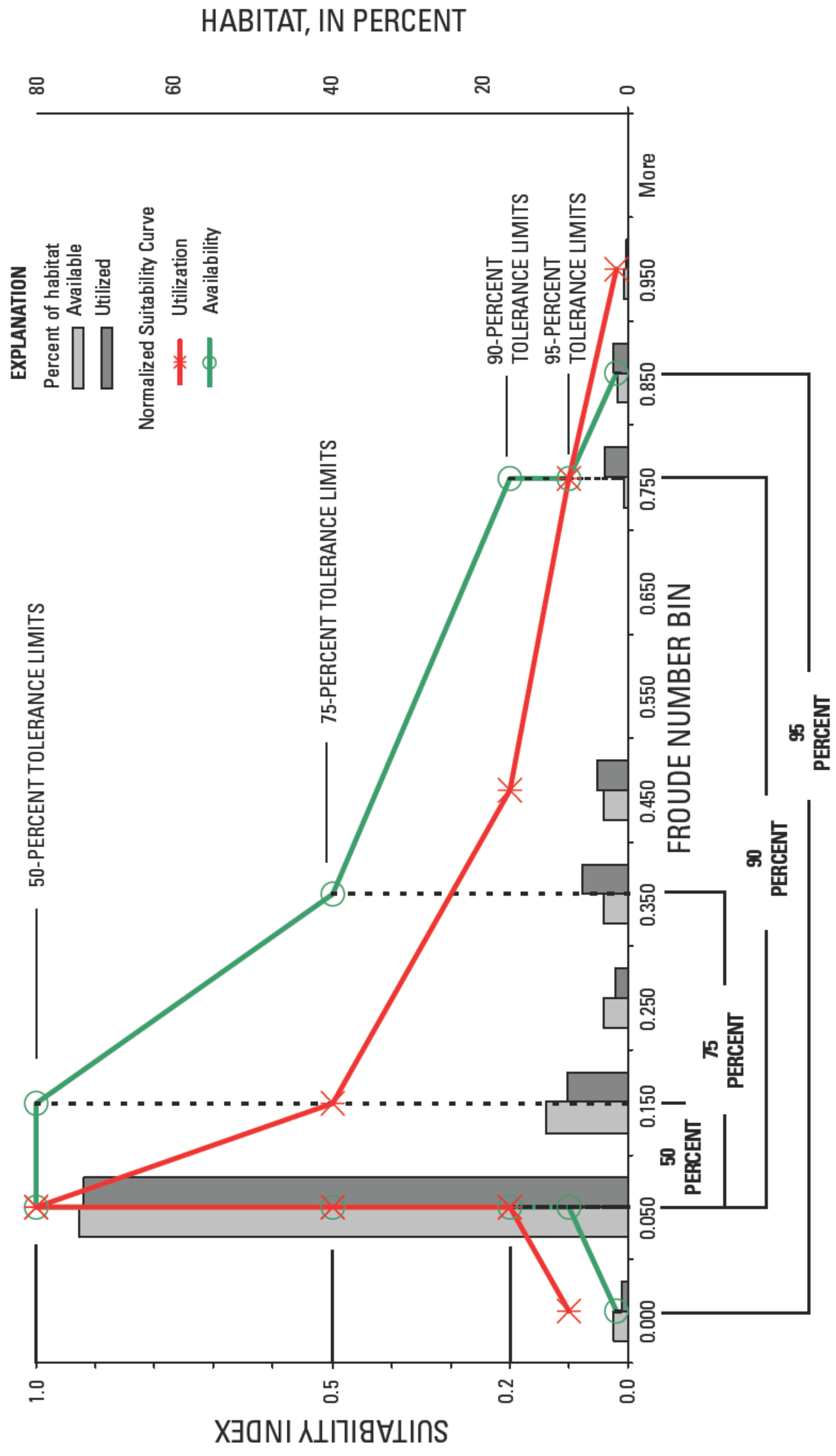

Figure C1. Example of non-parametric habitat utilization curve for Froude number.

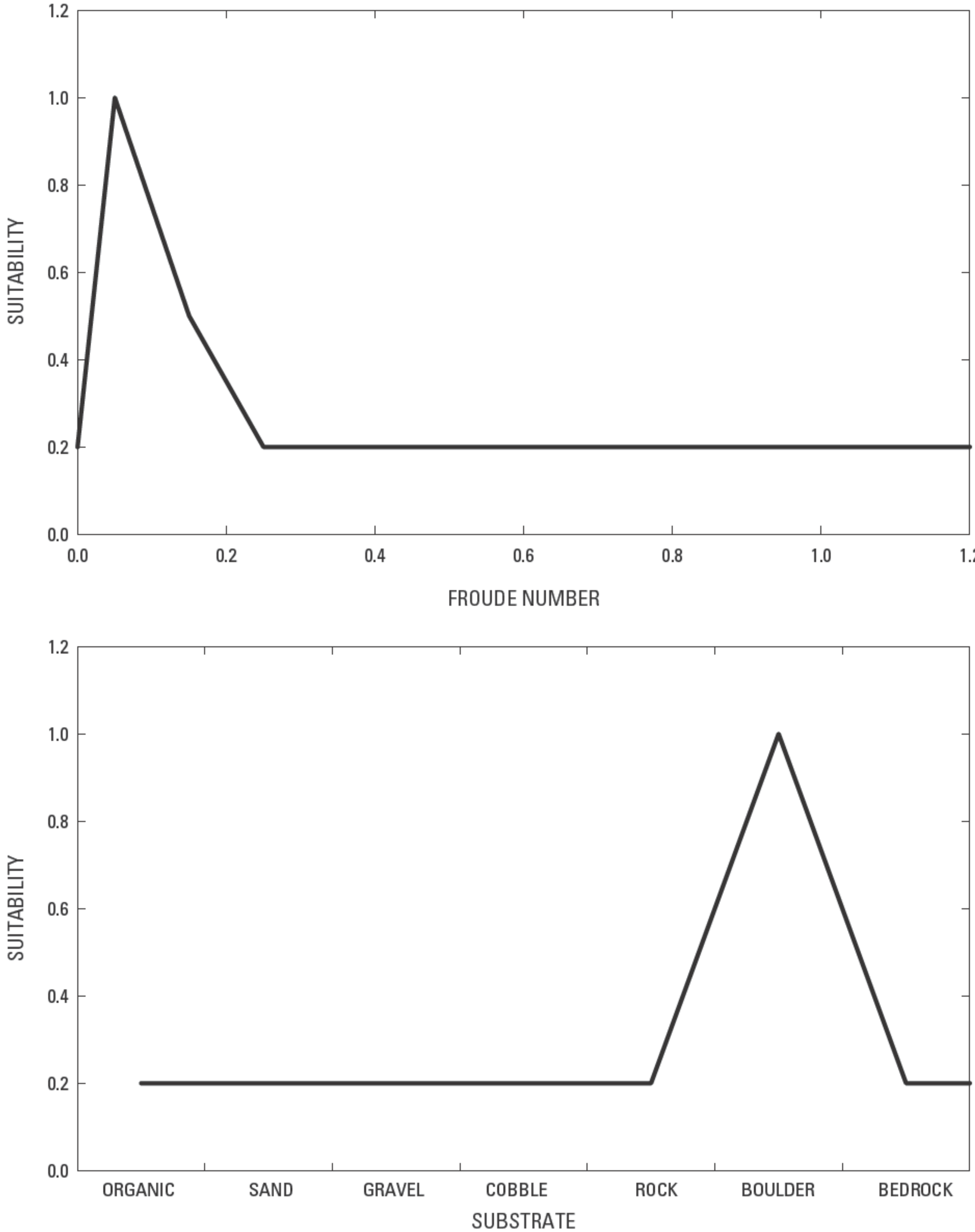

Figure C2. Non-parametric Froude number and substrate utilization criteria for adult alamoo.

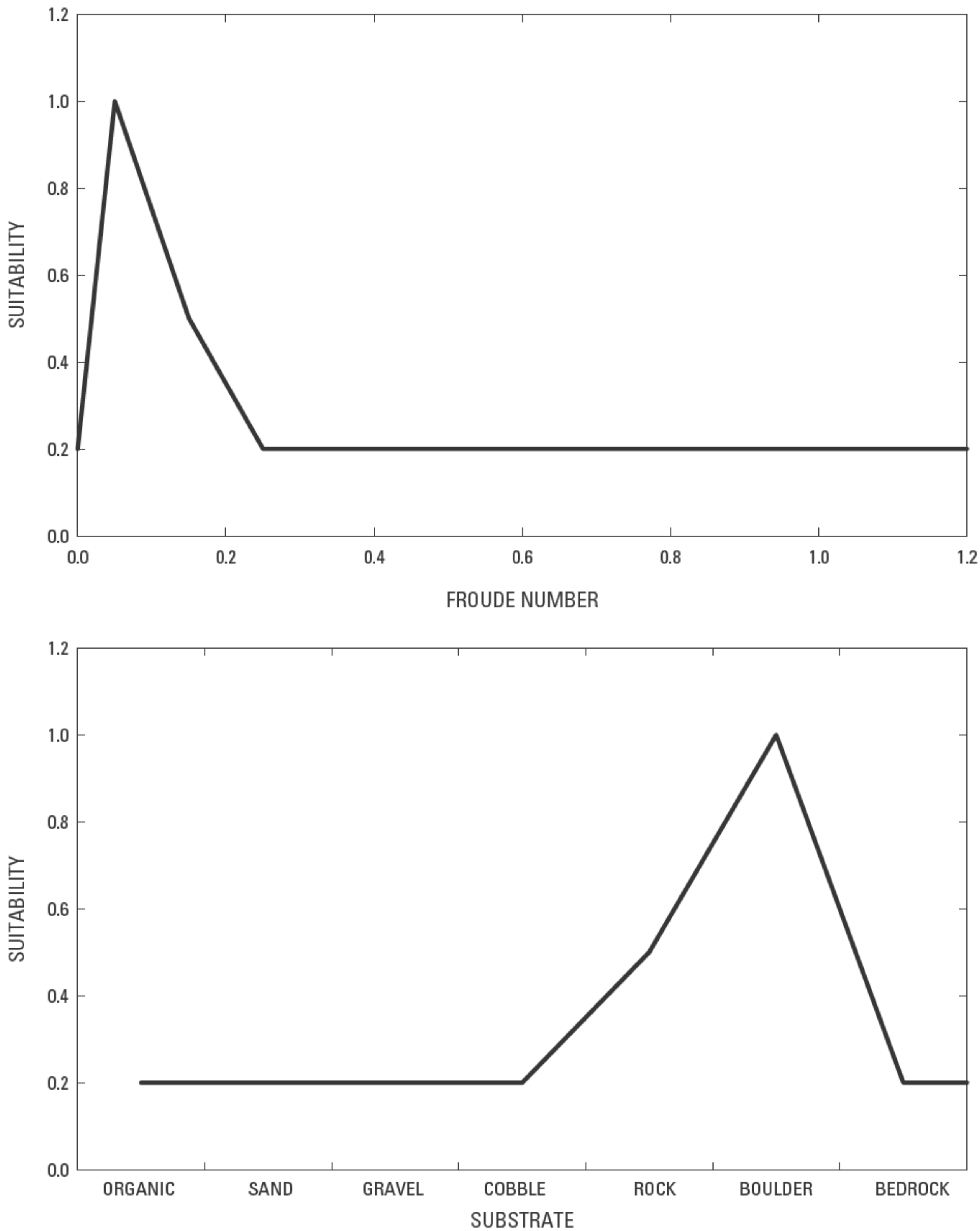

Figure C3. Non-parametric Froude number and substrate utilization criteria for juvenile alamoo.

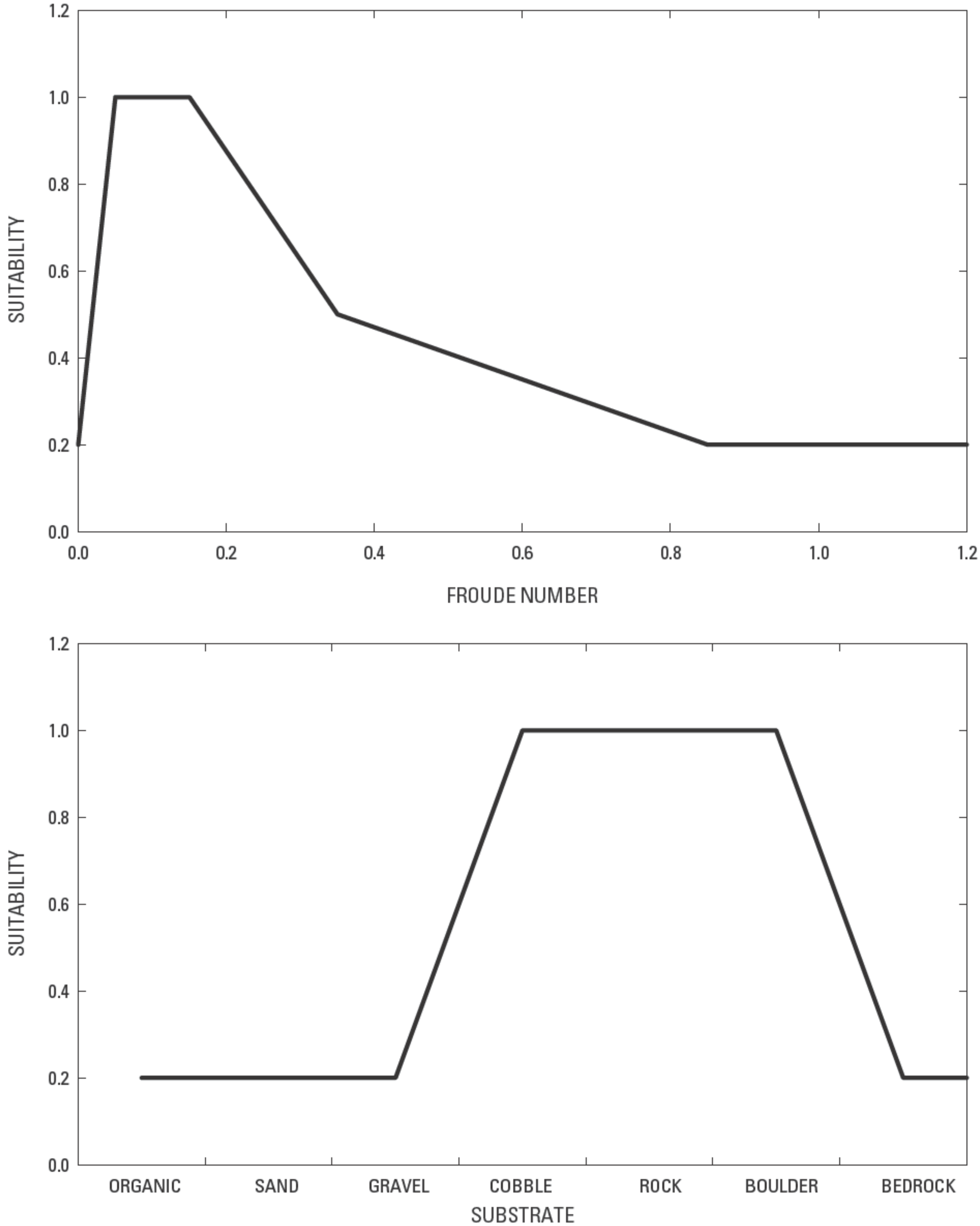

Figure C4. Non-parametric Froude number and substrate utilization criteria for adult nopili.

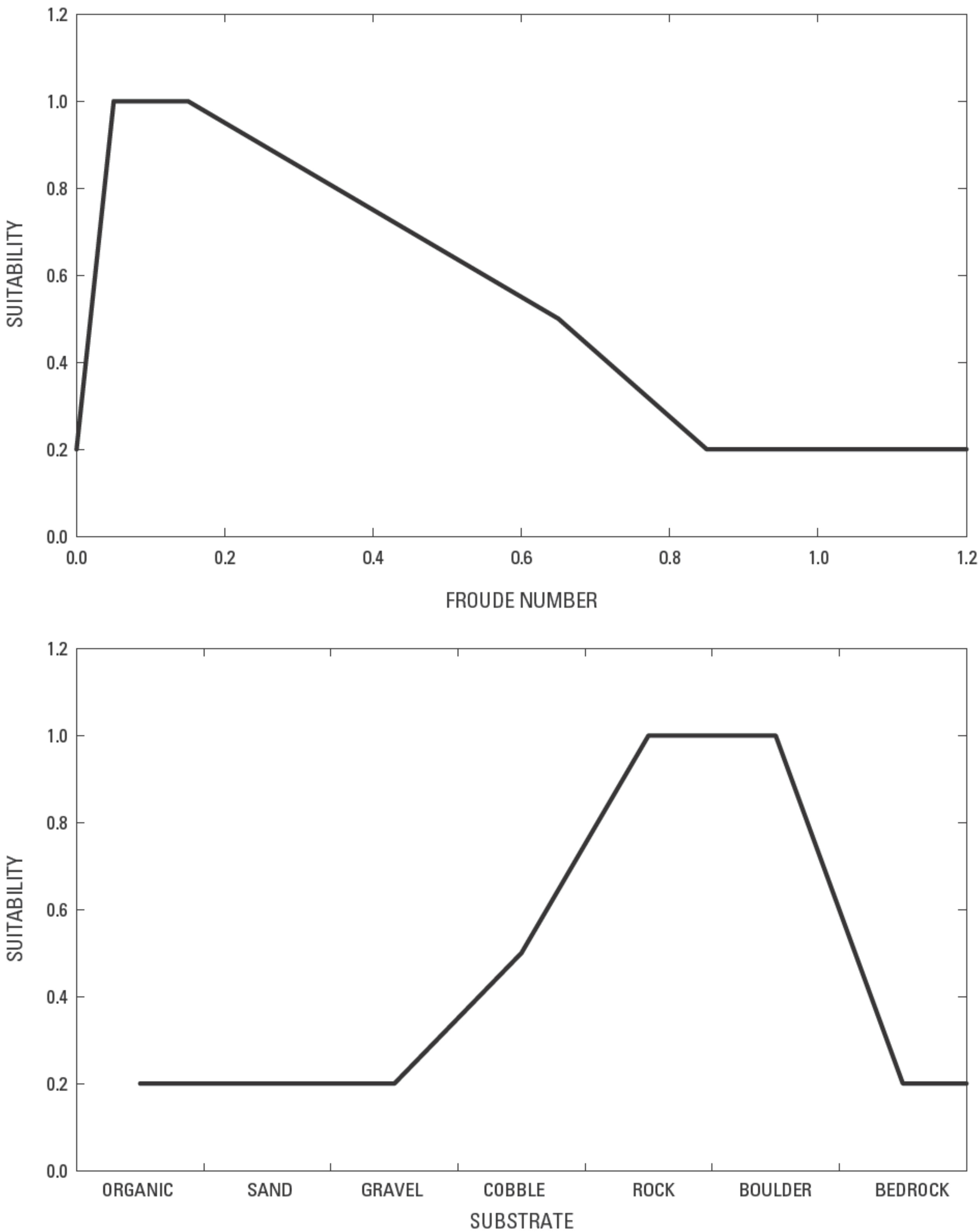

Figure C5. Non-parametric Froude number and substrate utilization criteria for juvenile nopili.

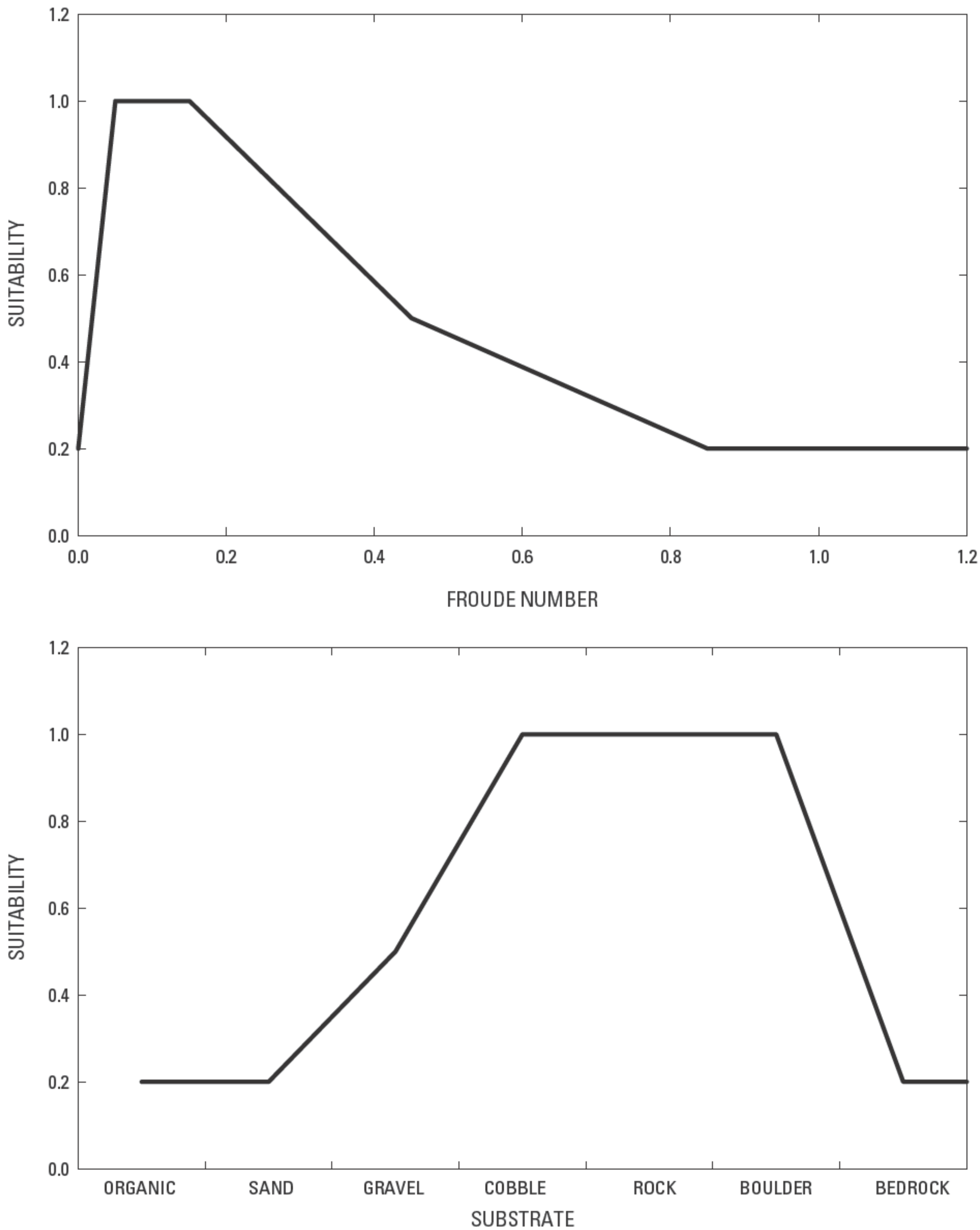

Figure C6. Non-parametric Froude number and substrate utilization criteria for adult nakea.

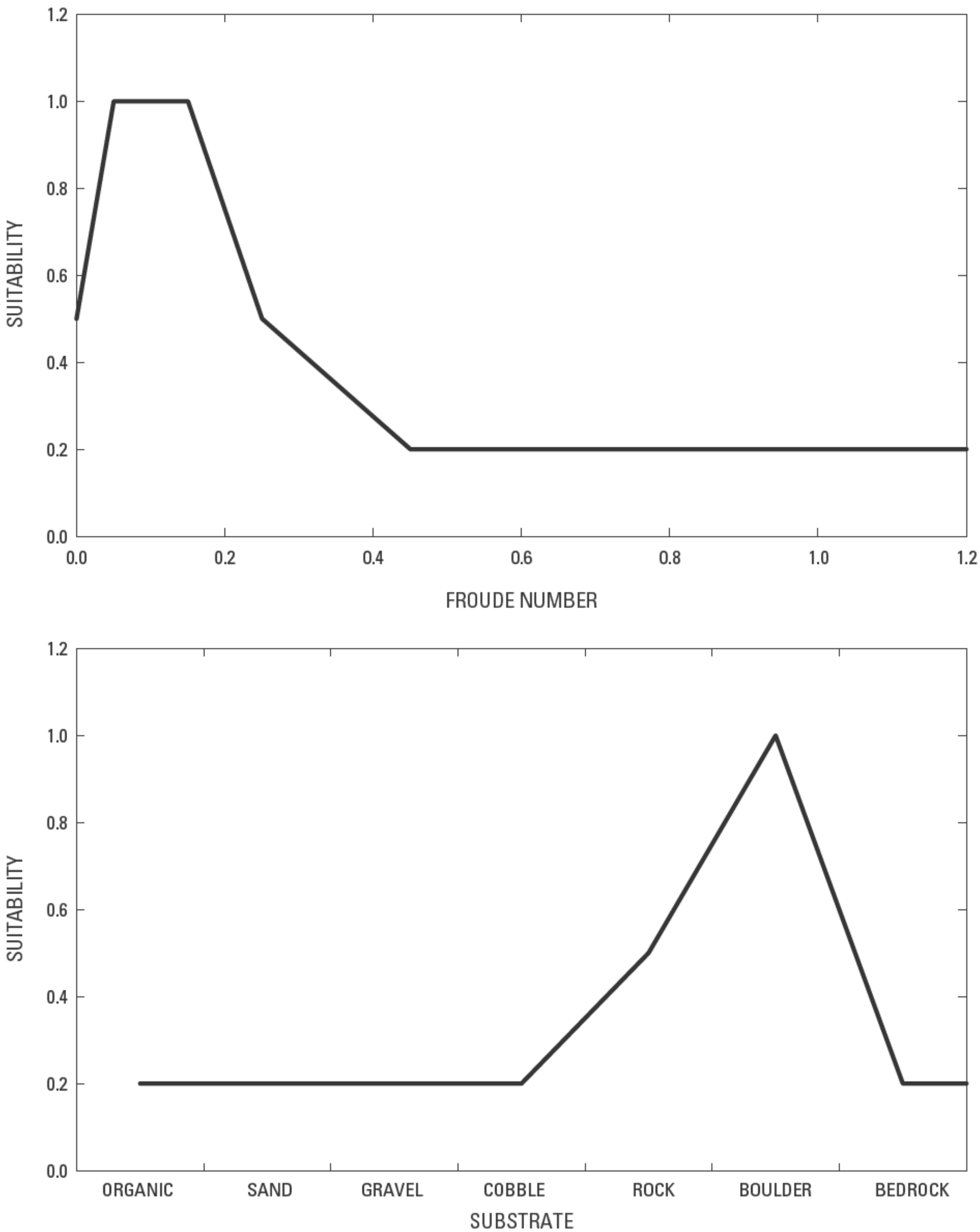

Figure C7. Non-parametric Froude number and substrate utilization criteria for opae.

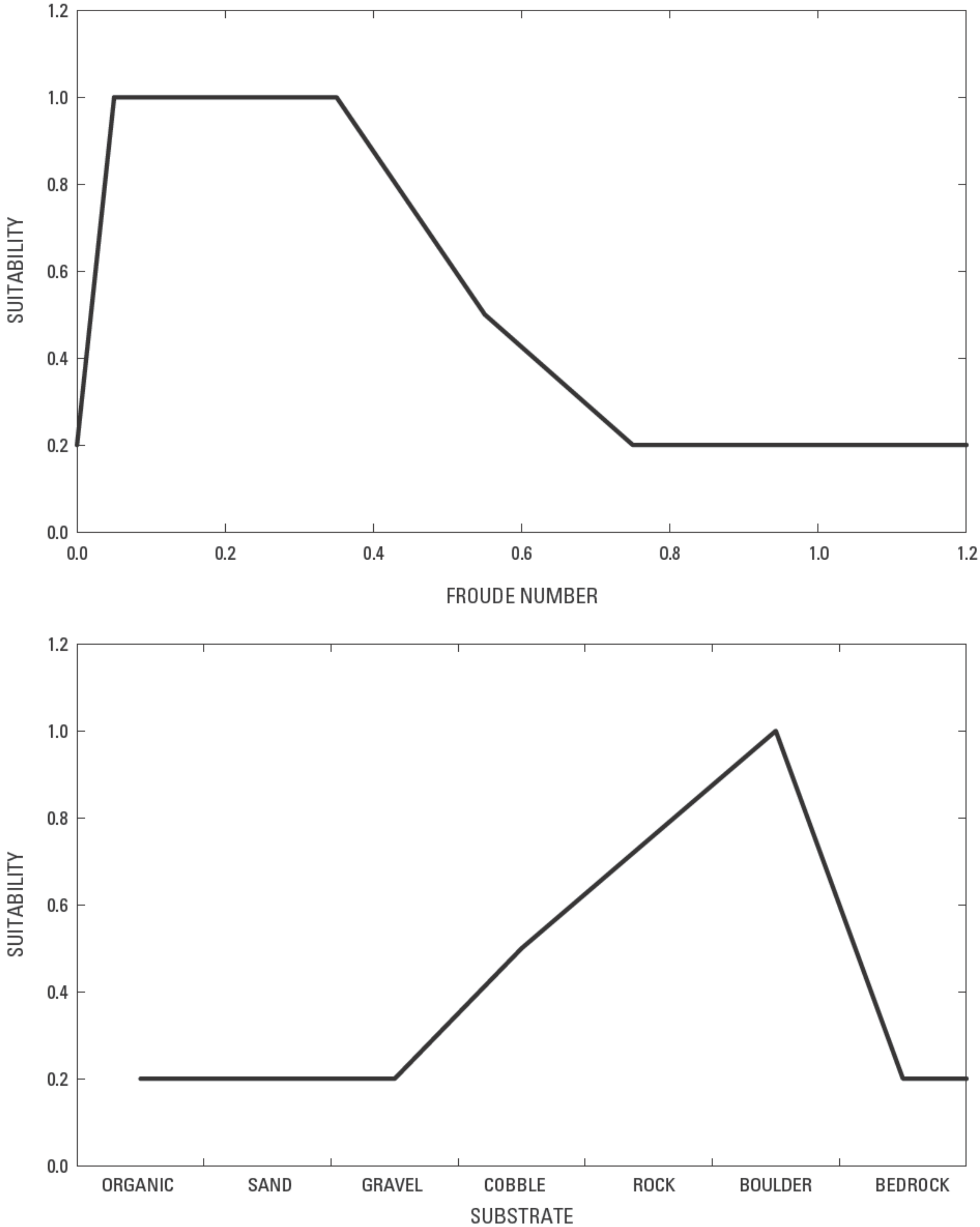

Figure C8. Non-parametric Froude number and substrate utilization criteria for hihiwai.

Table C2. Selected previous habitat studies conducted in Hawaii.

[Sites in **bold** include habitat availability data; data from Thomas R. Payne & Associates were interpreted from published frequency histograms]

Agency	Island	Stream name	Site name	Date
U.S. Fish and Wildlife Service	Hawaii	Honolii	Honolii1	6/20/1989
			Honolii-below	6/20/1989
			Honolii-Upper	6/26/1989
		Nanue	**Nanue-Middle**	12/15/1985
			Nanue-Upper	10/19/1985
	Kauai	Hanakapiai	Hanakapiai1160	1/7/1984
			Hanakapiai20	2/17/1984
			Hanakapiai30	2/18/1984
			Hanakapiai400	1/6/1984
			Hanakapiai50	1/9/1984
			HanakapiaiMouth	2/17/1984
			HanakapiaiUnc	1/8/1984
		Wainiha	Wainiha-End	2/19/1984
			Wainiha-IFIM	4/28/1985
	Maui	Hanawi	Hanawi165	3/9/1984
			Hanawi25	4/6/1984
			Hanawi40	8/20/1984
			Hanawi400	4/7/1984
			HanawiAbove	4/7/1984
			HanawiBS	8/23/1984
		Puaaluu	Puaaluu20	3/10/1984
			Puaaluu-Above	4/8/1984
	Molokai	Kawainui	Kawainui	4/17/1988
		Lanipuni	Lanipuni	4/16/1988
		Pilipililau	Pilipililau	4/17/1988
Thomas Payne & Associates	Kauai	Lumahai	Lumahai-Lower	8/19/1986
			Lumahai-Middle	8/19/1986
			Lumahai-Upper	8/19/1986
	Maui	East Wailuaiki	East Wailuaiki	10/5/1987
National Park Service	Molokai	Pelekunu	P20	1994-95
			P100	1994-95
			P500	1994-95
			P600	1994-95
			P4400	1994-95
			FP500	1994-95
		Waikolu	W200	1994-95
			W1000	1994-95
			W2300	1994-95
			W3000	1994-95
			W3400	1994-95
			W4000	1994-95

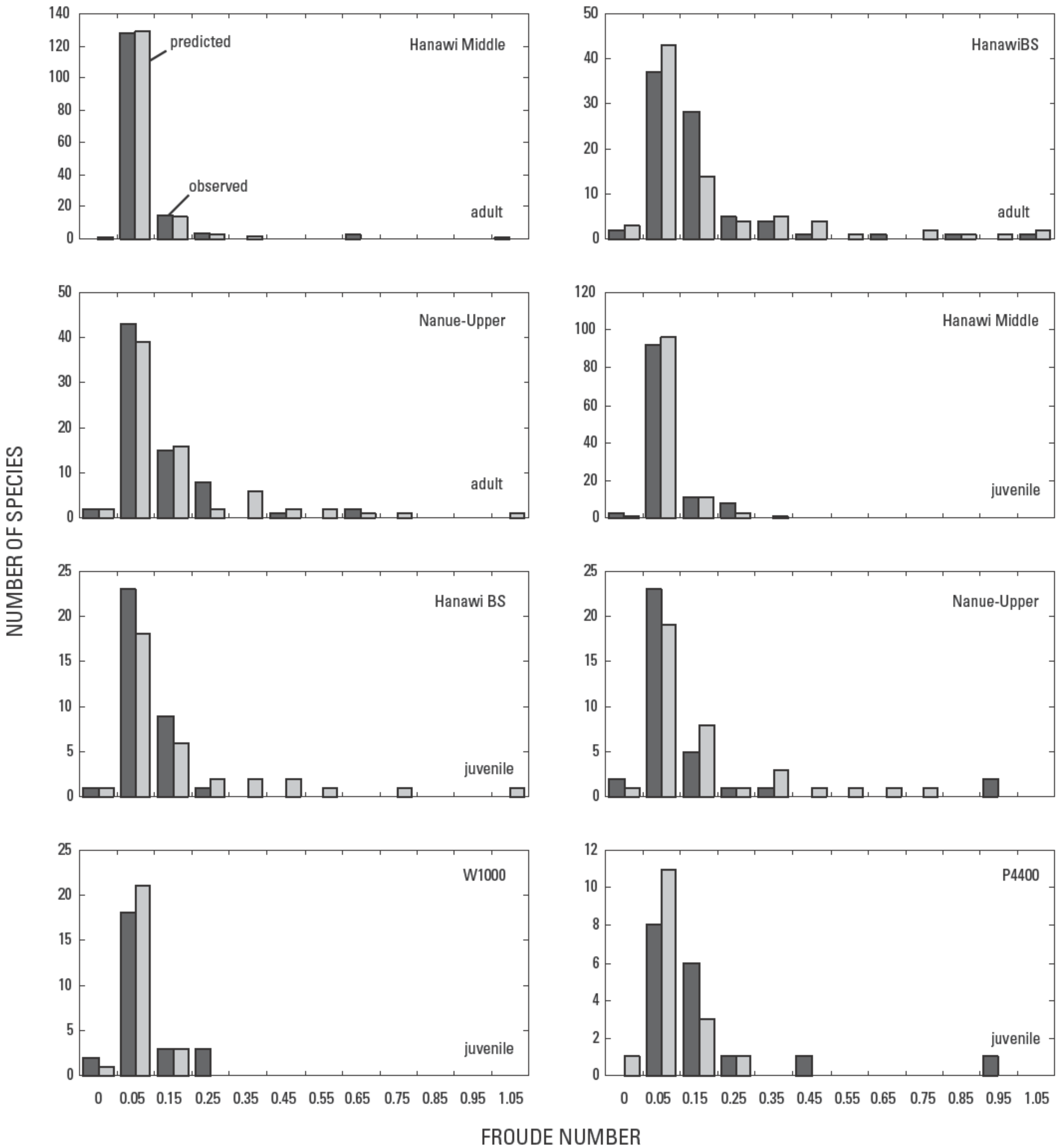

Figure C9. Observed and predicted abundances of adult and juvenile alamoo using the non-parametric tolerance limits developed from the Hanawi middle site for sites in this study and other studies in Hawaii.

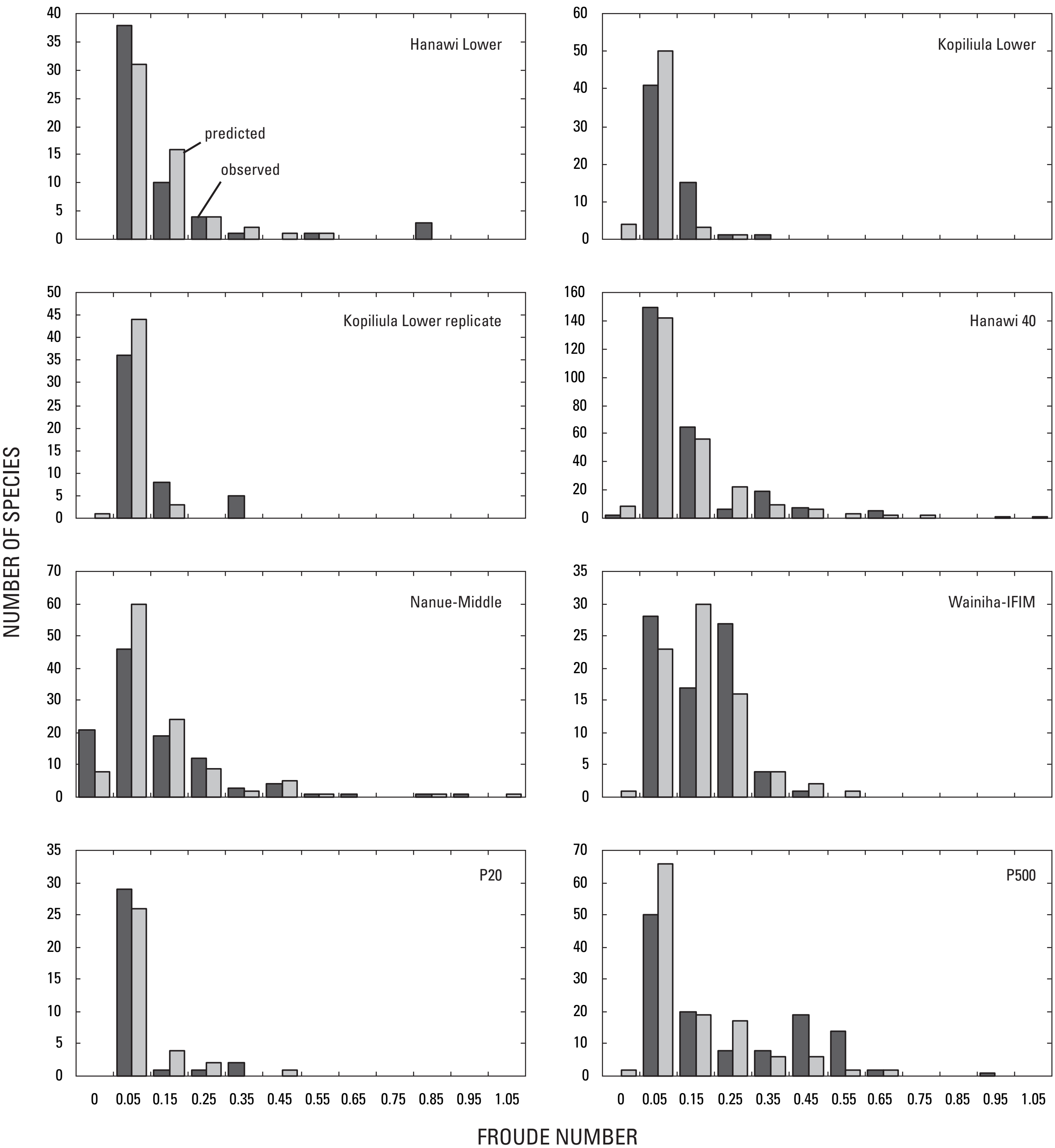

Figure C10. Observed and predicted abundances of adult nopili using the non-parametric tolerance limits developed from the Hanawi lower site for sites in this study and other studies in Hawaii.

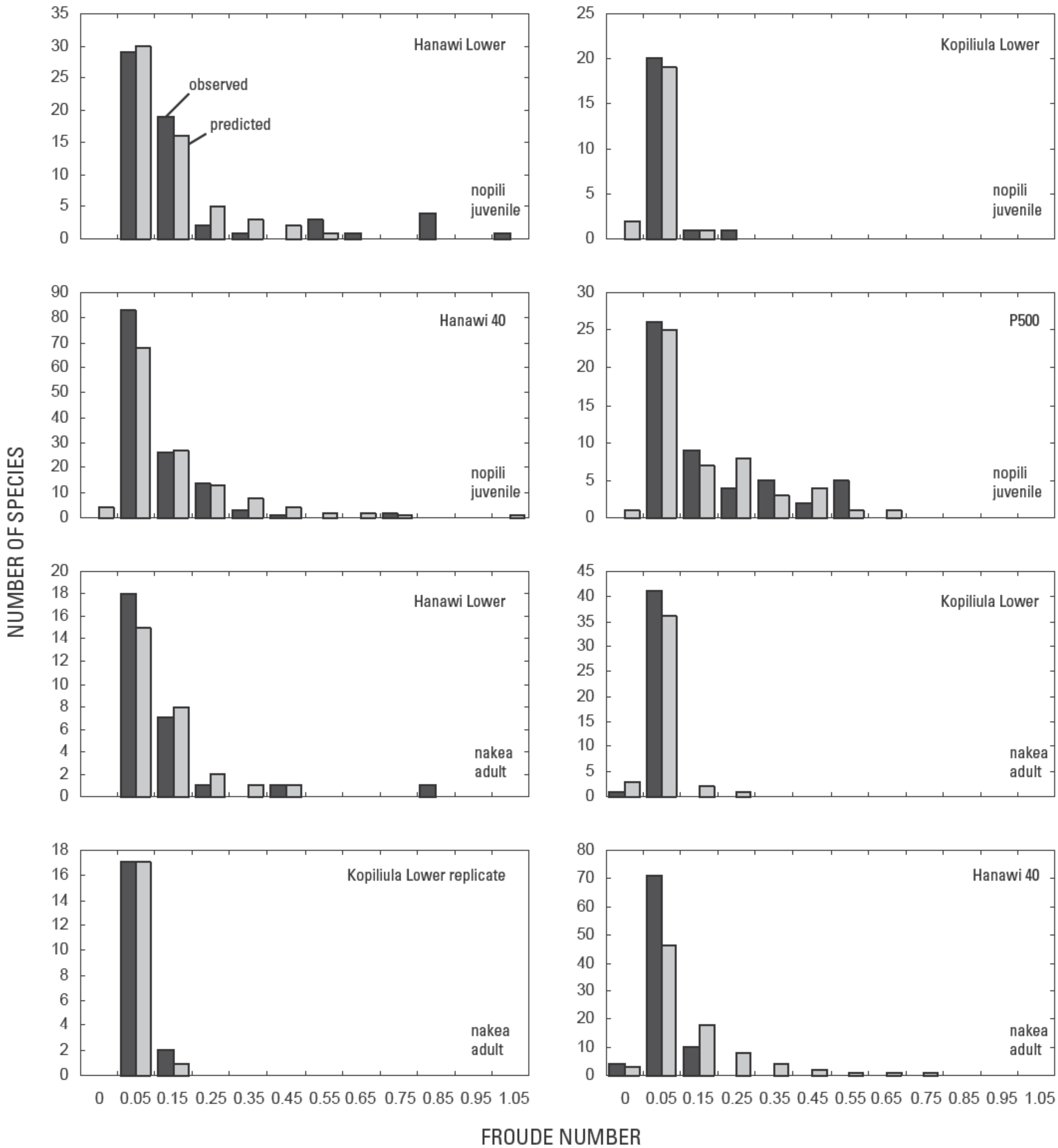

Figure C11. Observed and predicted abundances of juvenile nopili and adult nakea using the non-parametric tolerance limits developed from the Hanawi lower site for sites in this study and other studies in Hawaii.

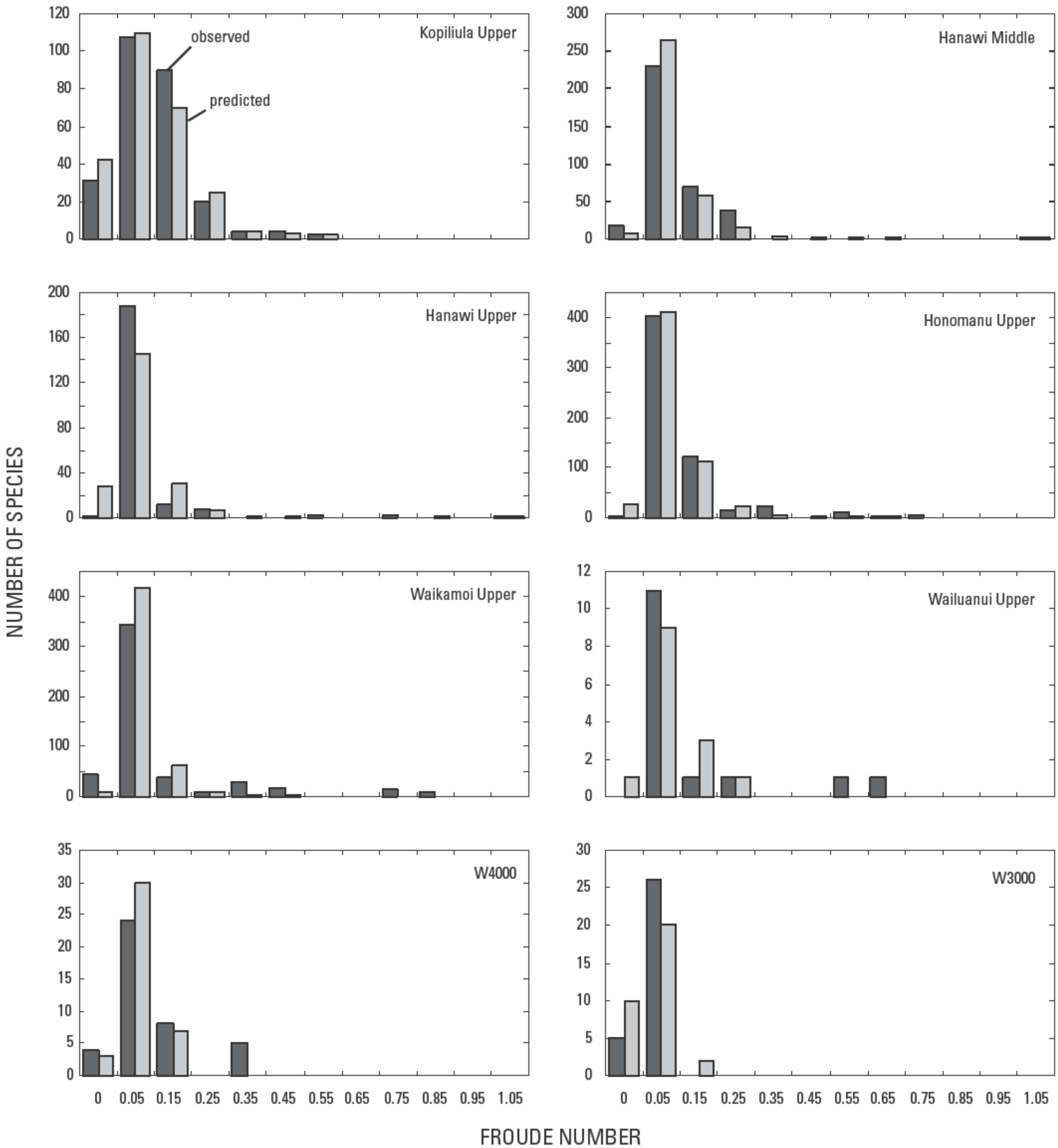

Figure C12. Observed and predicted abundances of opae using the non-parametric tolerance limits developed from the Kopiliula upper site for sites in this study and other studies in Hawaii.

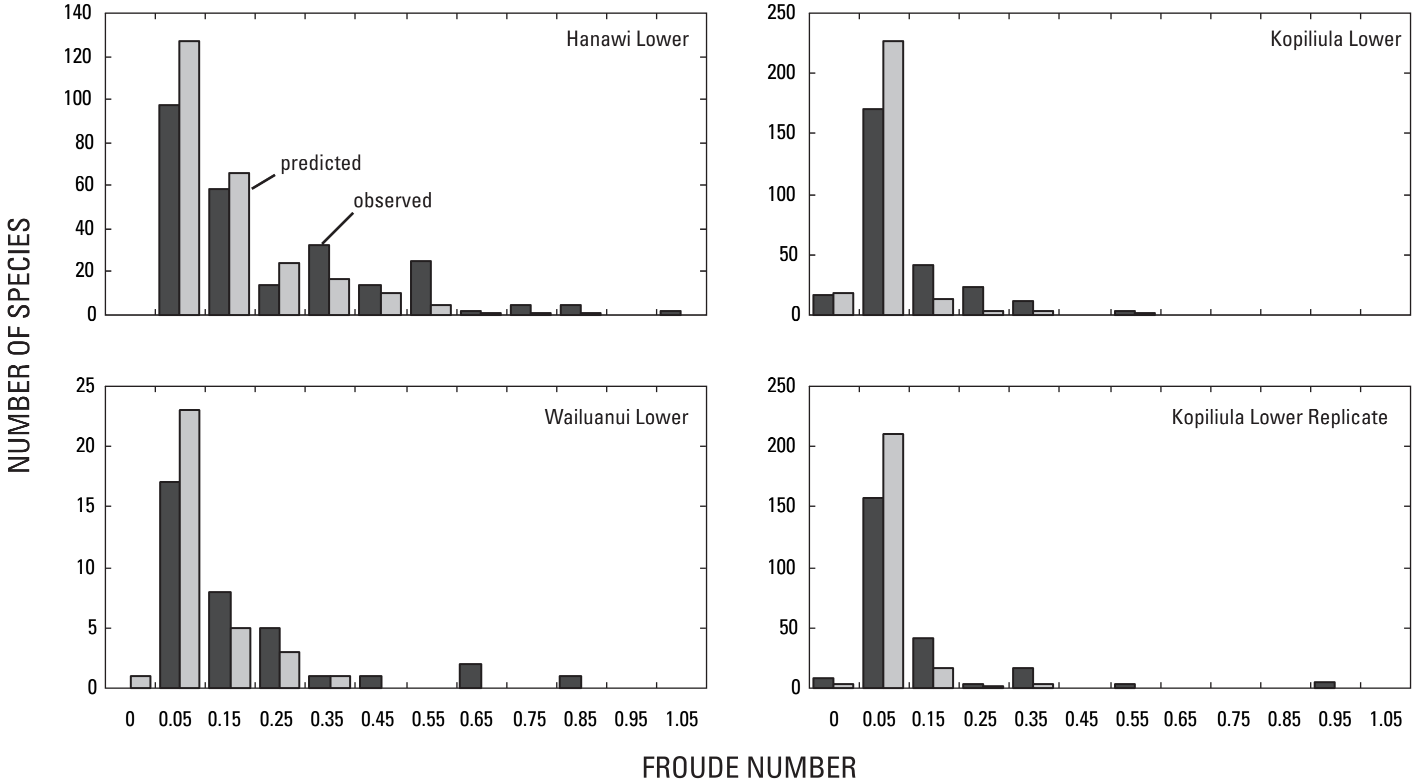

Figure C13. Observed and predicted abundances of hihiwai using the non-parametric tolerance limits developed from the Hanawi lower site for sites in this study and other studies in Hawaii.

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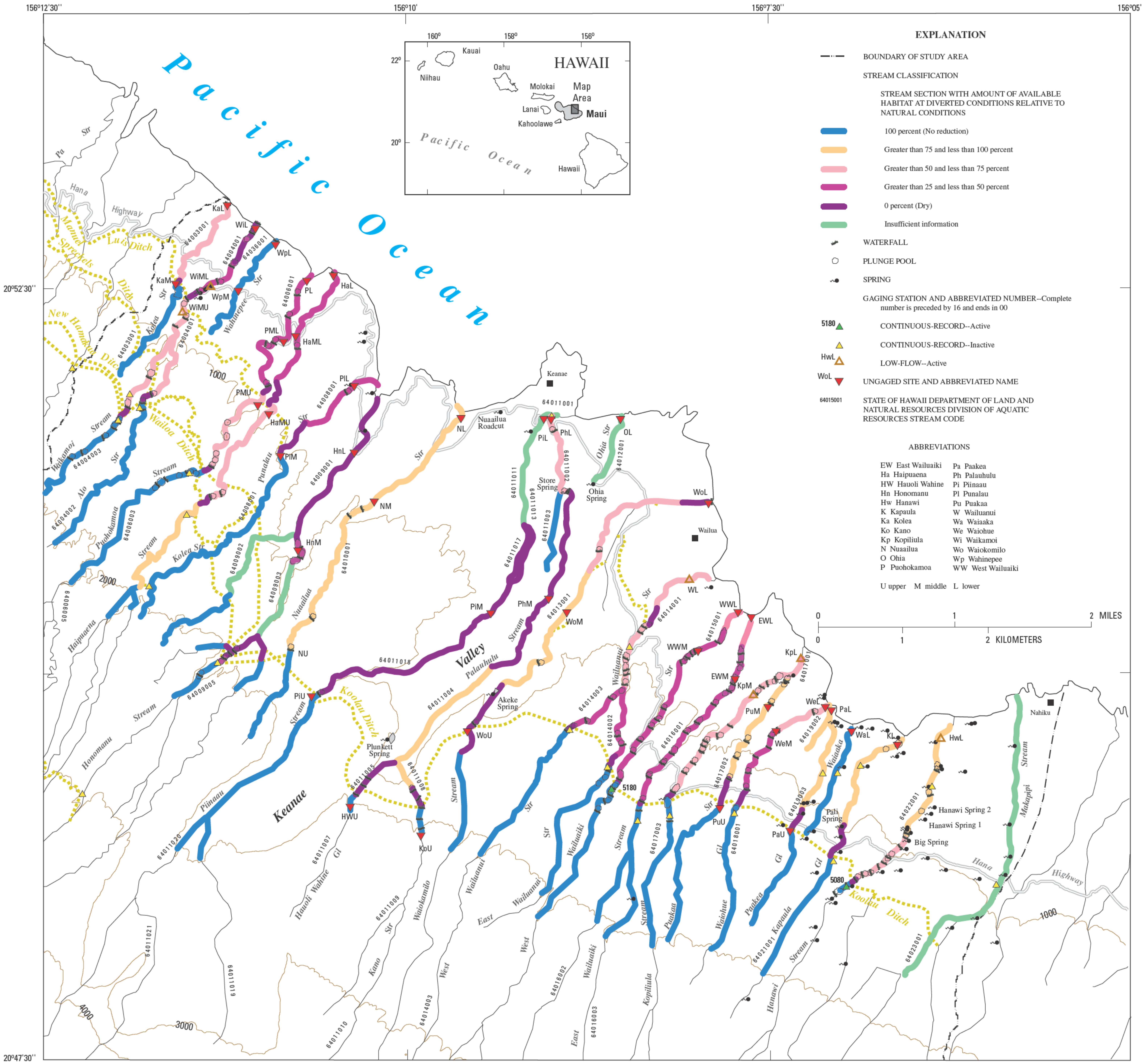

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ESTIMATED HABITAT RELATIVE TO NATURAL CONDITIONS FOR STUDY AREA STREAMS, NORTHEAST MAUI, HAWAII

by
Stephen B. Gingerich and Reuben H. Wolff

2005