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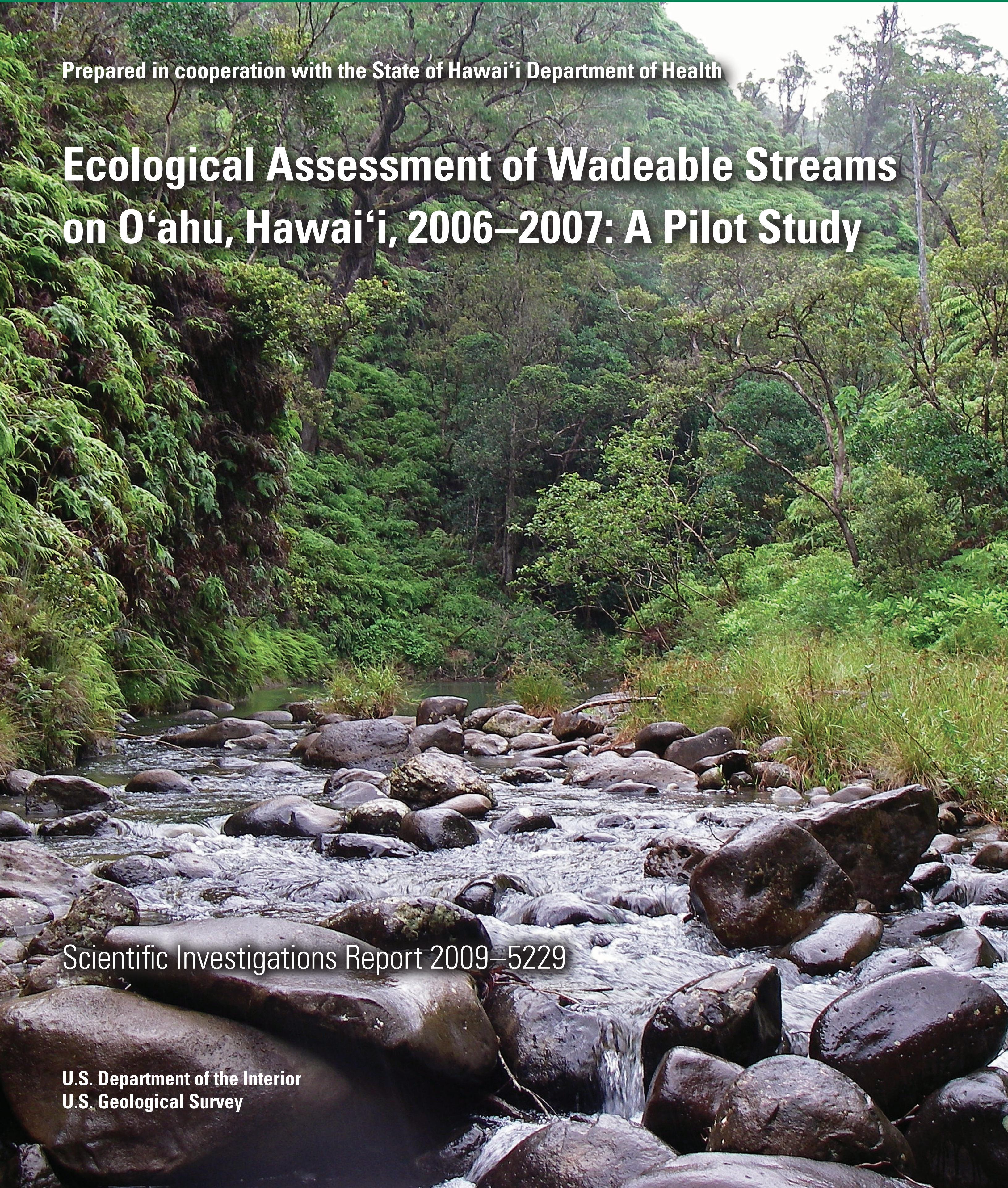
Ecological Assessment of Wadeable Streams on O‘ahu, Hawai‘i, 2006–2007: A Pilot Study



Scientific Investigations Report 2009–5229

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

Cover: Photograph of the Wadeable Stream Assessment study site on the North Fork of Kaukonahua Stream. (Photograph by Reuben H. Wolff, U.S. Geological Survey)

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By Reuben H. Wolff and Linda A. Koch

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Executive Summary

This ecological assessment presents results of a first-ever, statistically valid survey of the biological condition of wadeable, perennial streams on the island of Oʻahu, Hawaiʻi. The U.S. Geological Survey (USGS) Pacific Islands Water Science Center (PIWSC) conducted this assessment in cooperation with the Hawaiʻi State Department of Health (HDOH) using the U.S. Environmental Protection Agency (USEPA) Wadeable Streams Assessment (WSA) sampling design and protocols. The USEPA designed the WSA to answer questions such as: Is there a water-quality problem? How extensive is the problem? Does the problem occur in “hotspots” or is it widespread? Which environmental stressors affect the water quality of streams, and which are most likely to be detrimental?

The information presented in this report fills an important gap in meeting the requirements of the Clean Water Act. The purpose of this WSA pilot study is fourfold:

1. Collect biological, chemical, and physical habitat information from randomly selected perennial stream sites on the island of Oʻahu.
2. Describe the ecological condition of these streams using benthic invertebrate assemblages.
3. Identify and rank the relative importance of chemical and physical stressors (disturbances) affecting the biological condition.
4. Enhance the capacity of the HDOH to include these design and measurement tools in their water-quality monitoring programs so that assessments will be ecologically and statistically comparable, both regionally and nationally (USEPA, 2006a).

To accomplish the assessment, chemical, physical, and biological data were collected at 40 wadeable, perennial stream sites to determine the biological condition of these waters and the primary stressors affecting their quality (fig. ES1; appendix A). Sampling sites were chosen using a statistical design to ensure representative results. The WSA standardized protocols were adhered to at all field sites to ensure comparable results. A rigorous quality-control program

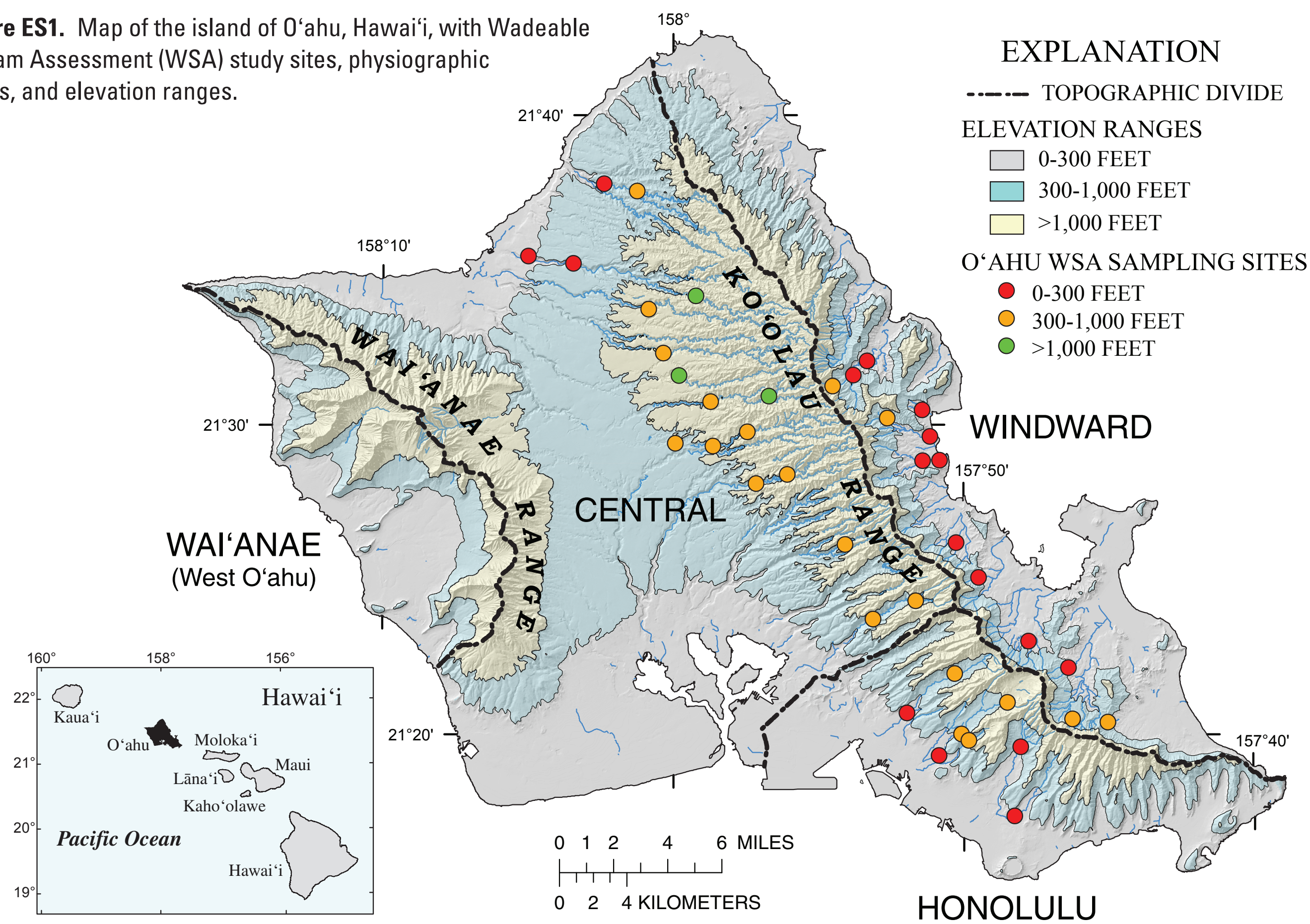


Figure ES1. Map of the island of Oʻahu, Hawaiʻi, with Wadeable Stream Assessment (WSA) study sites, physiographic zones, and elevation ranges.

was followed that included annual training of all field crews, auditing field crews and labs, a 2–person review of each field datasheet, and resampling the macroinvertebrate assemblages at 10 percent of the sites. The sampling was completed in 2006–07. The results of this pilot study provide a comprehensive assessment of the biological condition of wadeable, perennial streams on O‘ahu, as well as within three major geographic regions and two elevation ranges.

Probabilistic Design

Many surveys use probabilistic methods to make statistically valid inferences. The basic design is to sample a small but unbiased, probability-based, sample of a larger population. One of the best known uses of probabilistic sampling is the Nielsen rating. The Nielsen Media Research company uses a representative sample of about 12,000-17,000 homes, from all 50 states, across a broad range of demographic categories, proportional to their presence in the population at large, to estimate what the country's 114.5 million television households are watching. It would be extremely difficult to call all 114.5 million households during a program and it would be economically impractical to sort through 114.5 million television diaries. The smaller representative sample provides a practical, manageable, and economical way to estimate what the larger population is watching. The Nielsen ratings cannot tell you who watched what program, but it can estimate the number of households that watched a particular program and by using the demographic data, it can also estimate the percentage of those households who are of a particular group characterized by age, ethnicity, or income level. The system can also narrow the population of interest to the local broadcasting region. In the same way, it would be economically impractical to sample every site on every stream in a State. The WSA study design requires representative samples in proportion to the abundance of each category of stream class. The stream class categories (like the Nielsen ratings' demographic data) represent the various stream geographic, hydrologic, geomorphic, geologic, topographic, and (or) elevation attributes. Each random site (like the Nielsen sample homes) represents a percentage of the larger population (that is, all households) of streams in the study area.

Ecological Condition

As part of the WSA, benthic macroinvertebrate samples were collected, preserved, and taxonomically sorted, identified, and tallied. This WSA study examined a number of elements of the macroinvertebrate assemblages that could be used as indicators of the ecological condition of streams on O‘ahu (appendix B). Benthic macroinvertebrates are stream animals without backbones that are larger than 0.02 inches (0.5 mm), such as adult and larval shrimp, snails, insects, and worms, that live all or part of their lives in a stream. This large group

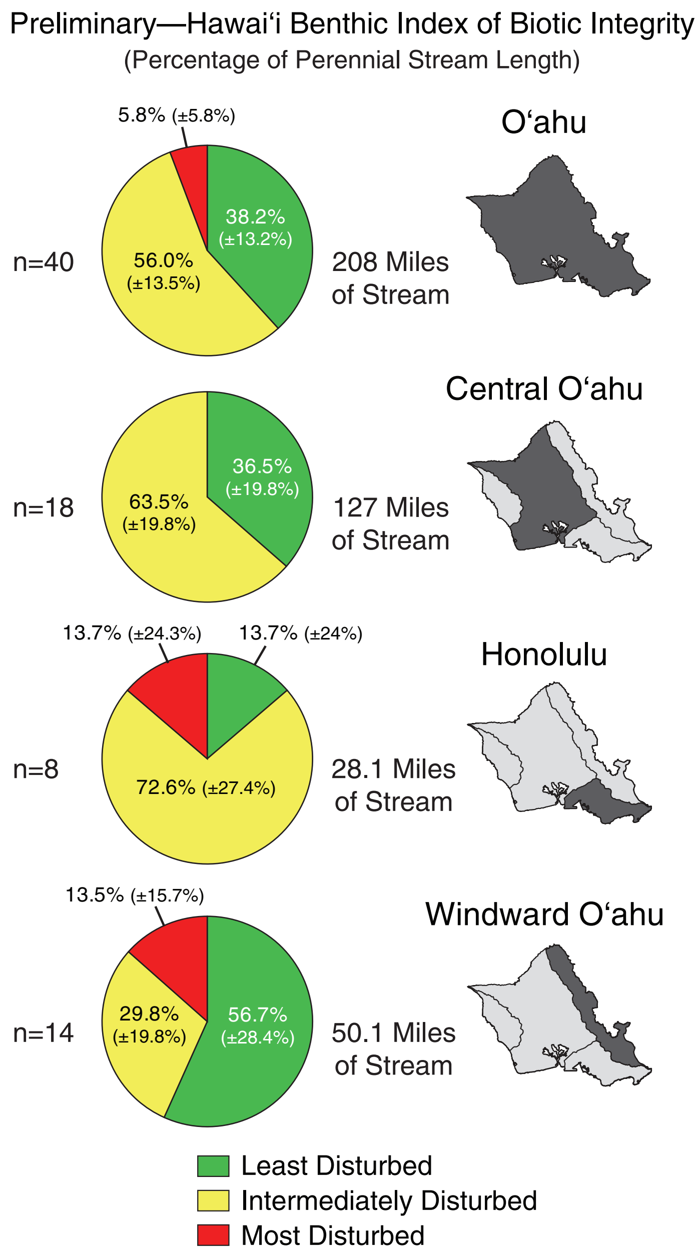


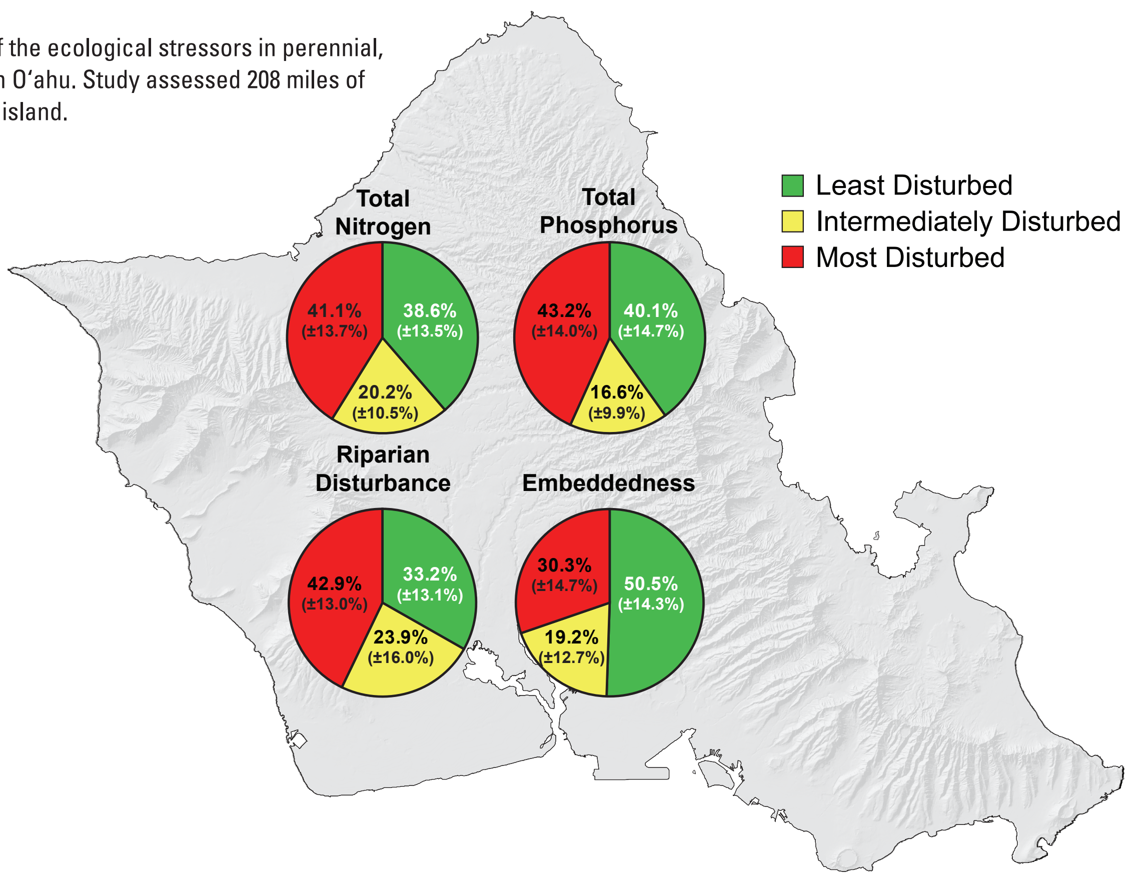
Figure ES2. Ecological condition of wadeable streams on O‘ahu and three regions based on an analysis of macroinvertebrate assemblage data using the Preliminary-Hawaiian Benthic Index of Biotic Integrity. (n = number of sites) of diverse organisms is commonly used in evaluating the condition of aquatic ecosystems. The analyses of the macroinvertebrate data was performed using the Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) developed by Wolff (2005). The P–HBIBI is an index based on a core set of metrics that score parameters of the benthic macroinvertebrate community. This macroinvertebrate index is in an early stage of development and requires further investigation and improvement. The results of the P–HBIBI analysis presented in this report should be considered provisional and may change with future revisions of the P–HBIBI. However, the current version of the P–HBIBI represents the best available measure for assessing benthic macroinvertebrate assemblages on O‘ahu and was therefore used in this report to estimate the ecological conditions.

The O‘ahu WSA study estimated that for the total of 208 miles of accessible, perennial, wadeable stream on the island, 5.8 ± 5.8 percent (12 mi) of the islands’ stream length is in most disturbed biological condition, 56 ± 13.5 percent (116.6 mi) is in intermediately disturbed biological condition, and 38.2 ± 13.2 percent (79.6 mi) is in least disturbed biological condition, based on the P–HBIBI (fig. ES2). Of the three geographic regions discussed in this report (by chance, the random selection process picked no streams in Wai‘anae), streams in the Honolulu region were the most stressed, with 13.7 ± 24 percent (3.8 mi) of stream length in most disturbed biological condition and 72.6 ± 27.4 percent (20.4 mi) in intermediately disturbed condition. Windward O‘ ahu had the highest percentage (56.7± 20.8 percent; 28.4 mi) of stream length in least disturbed biological condition. The central O‘ahu region had 63.5 ± 19.82 percent (80.7 mi) of stream length in intermediately disturbed condition and none in most disturbed condition. It should be noted that the estimates for the geographic regions were based on a smaller number of sites than was desirable. As a result of having <20 sites, the 95-percent confidence intervals, a measure of the uncertainty of the estimate, were often relatively large. Because of the considerable uncertainty, the results for these regions should not be used to infer the actual conditions and are intended only to demonstrate the possible uses and benefits of the probabilistic design. In future probabilistic studies, the desired number of sites within these subregions needs to be addressed during the design stage.

Ecological Stressors

There are many factors that can cause stress to aquatic biological communities. This WSA study examined a number

Figure ES3. Extent of the ecological stressors in perennial, wadeable streams on O‘ahu. Study assessed 208 miles of stream length on the island.



of chemical and physical habitat parameters that have been previously identified as potential stressors (appendixes C and D). Results of this study show that the nutrients nitrogen and phosphorus have elevated concentrations, as compared to reference sites, in more than 40 percent of the stream length on O‘ahu (fig. ES3). Riparian disturbance, a physical habitat index that measures human influence on and adjacent to the stream bank, was estimated to be most disturbed in almost 43 ± 13 percent (89.3 mi) of the stream length. The results for the habitat parameter embeddedness, a measure of the amount of fine sediment in streambeds, indicated about 30.3 ± 14.7 percent (63.1 mi) of stream length was in most disturbed condition and more than 50 ± 14.3 percent (105.2 mi) was in least disturbed condition.

The information in this report is the first attempt in Hawai‘i to assess the islandwide ecological condition of wadeable, perennial streams on O‘ahu using the USEPA WSA probabilistic design. This study has demonstrated that such an assessment is practical and that it can provide the information necessary to assess the current baseline ecological condition and can be used, with future WSA studies, to measure the positive or negative changes in those conditions and the effectiveness of management efforts to protect, restore, and maintain Hawai‘i’s aquatic environment. However, there are some constraints that must be considered, including the large length of inaccessible streams, the compatibility of sampling methods, and the feasibility of implementing a similar approach on the other islands.

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Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C=(°F-32)/1.8
Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).
Altitude, as used in this report, refers to distance above the vertical datum.
Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).
Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Ecological Assessment of Wadeable Streams on O‘ahu, Hawai‘i, 2006–2007: A Pilot Study

By Reuben H. Wolff and Linda A. Koch[1]

Abstract

In 2006–07, the U.S. Geological Survey (USGS) Pacific Islands Water Science Center (PIWSC), in cooperation with the Hawai‘i Department of Health (HDOH), conducted a pilot study as a participant in the U.S. Environmental Protection Agency's (USEPA) Wadeable Streams Assessment (WSA) program. Forty randomly selected sites on perennial streams on O‘ahu, Hawai‘i, were surveyed for habitat characteristics, water chemistry, and benthic macroinvertebrate assemblages. Of the original sampling frame of approximately 505.2 miles of perennial stream, roughly 96.7 ± 30.7 miles were found to be nonperennial or estuarine and another 200.5 ± 64.7 miles were judged to be inaccessible. The scope of this report presents an assessment of the remaining 208 ± 57.6 miles of accessible, wadeable, perennial stream length on O‘ahu.

Benthic macroinvertebrate assemblages were used to determine the ecological condition at each site. Components of the benthic macroinvertebrate assemblages were assessed using the multimetric Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) developed by Wolff (2005). Based on the P–HBIBI scores, an estimated 5.8 ± 5.8 percent of the island's total stream length is in most disturbed condition, 56 ± 13.5 percent is in intermediately disturbed condition, and 38.2 ± 13.2 percent is in least disturbed condition. Windward O‘ahu had the highest percentage of stream length in least disturbed biological condition at 56.7 ± 20.8 percent. Using the relative abundance of insects, one of the core metrics that make up the P–HBIBI, 43.4 ± 14.2 percent of the islandwide stream length was classified in the most disturbed condition—52 ± 31.2 percent of the Honolulu region stream length and 51.4 ± 23.3 percent of the windward O‘ahu stream length.

An analysis of total nitrogen (N) estimated approximately 41.1 ± 13.7 percent of the stream length on O‘ahu was in most disturbed condition. Regionally, the Honolulu region had the largest proportion, 61.3 ± 28.6 percent, of most disturbed stream length in terms of total N. An analysis of total phosphorus (P) classified approximately 43.2 ± 14 percent of the stream length on O‘ahu as most disturbed. Regionally, windward O‘ahu had the largest proportion, 78.4 ± 19.5 percent, of stream length classified as most disturbed. An analysis of embeddedness classified 30.3 ± 14.7 percent of O‘ahu's stream length as most. Regionally, windward O‘ahu had the largest proportion, 43.3 ± 17.1 percent, of stream length classified as most disturbed as compared to the reference condition. An analysis of riparian disturbance, an index of the in-channel, riparian, and near-stream human activities, classified 43 ± 13 percent of stream length on O‘ahu as most disturbed. The Honolulu region had the largest proportion of stream length, 86.3 ± 13.7 percent, classified as most disturbed.

The information in this report is the first attempt in Hawai‘i to assess the islandwide ecological condition of wadeable, perennial streams on O‘ahu using the USEPA WSA probabilistic design. This study has demonstrated that such an assessment is practical and that it can provide information that may help the USEPA and HDOH in determining the status of aquatic ecosystems on O‘ahu, Hawai‘i. This study provides a baseline assessment of the current islandwide ecological condition and identifies potential environmental stressors. It can be used, with future WSA studies in Hawai‘i, to measure the changes in those conditions and the effectiveness of management efforts to protect, restore, and maintain Hawai‘i's aquatic environment.

Introduction

In response to a growing public awareness and concern for controlling water pollution, the Federal Water Pollution Control Act of 1948 was extensively amended in 1972 by the U.S. Congress. As amended again in 1977, the law became commonly known as the Clean Water Act (CWA). The objective of the Clean Water Act (CWA) is to protect, restore, and maintain the surface water resources of the United States. This includes maintaining the chemical, physical, and biological integrity of the nation's waters. The CWA set the policy for regulating water pollution in the rivers, lakes, wetlands, and coastal waters of the United States. The CWA regulates point- and nonpoint-source pollution from municipal wastewater treatment plants, industrial facilities, agricultural activities, and other activities.

Under section 305 of the CWA, each State is required to prepare and submit biennial reports to the U.S. Environmental Protection Agency (USEPA) with an analysis detailing their efforts to protect and restore the Nation's surface waters. The reports provide an evaluation of whether these conservation efforts have, or will eventually, achieve the desired goals, which include: the protection and propagation of a balanced

[1]State of Hawai‘i Department of Health, Environmental Planning Office

population of shellfish, fish, and wildlife; the safety of recreational activities in and on the water (305(b) Report); and a list of Water Quality-Limited Segments (WQLS) for surface waters that are exceeding or will likely exceed State Water Quality Standard (303(d) List of Impaired Waters)(CWA Section 305). The USEPA, in turn, provides this information to the U.S. Congress and to the American public.

A critical evaluation of the USEPA and the States' reporting was noted in 2000, when it was determined that the information provided by these agencies could not be used to make statistically valid inferences about water quality at a state, ecoregion, or national level and that agencies lacked sufficient data to develop specific management strategies (USEPA, 2006a; Shapiro and others, 2008). Further criticisms were made with regard to the State and Federal agencies' failure to collect adequate environmental data needed to assess ecosystem status and trends and the lack of a nationally consistent data-collecting program. Traditional surface water monitoring focuses on targeted monitoring to investigate the relationships between water-quality conditions and the natural and anthropogenic factors that cause those conditions. Targeted monitoring sites are purposely selected because they are sites known to be affected by human activities, environmental conditions, and (or) hydrologic conditions. Targeted monitoring is successful at identifying impaired waters and at monitoring compliance with regulatory point- and nonpoint-source pollution restrictions. Targeted monitoring is also a valuable method for identifying the effects of various land uses, such as agricultural, industrial, and urban, on local surface waters and aquatic biota. However, the results of targeted monitoring studies cannot be used to extrapolate to the larger populations of streams in a State, region, or nationally. Targeted monitoring cannot answer questions about the spatial extent of a water quality problem.

In response to these criticisms, the USEPA, in a collaborative effort with other Federal agencies, States, and tribes, developed the Wadeable Streams Assessment (WSA) program, with a nationally consistent, comprehensive, and scientifically defensible probabilistic monitoring strategy designed to assess the environmental status and trends for the entire Nation's aquatic ecosystems (USEPA, 2002; Paulsen and others 2008). The WSA also provides States with funding and expertise that enhances their ability to monitor and assess the quality of their waters (USEPA, 2006a). WSA probabilistic monitoring differs from targeted monitoring in that the monitoring sites are randomly selected; therefore every spot along every accessible, wadeable perennial stream within the area of interest has an equal and known probability of being selected. By using a random or stratified random sampling design, the results can be extrapolated from the set of sampled sites to a larger target population (or subpopulation, such as a watershed, region, or State). The WSA utilizes biological assemblages (benthic macroinvertebrates, fish, and (or) periphyton) as indicators of ecological conditions, and evaluates water chemistry (nutrients, salinity, and acidification) and physical habitat data to identify and estimate the extent of potential stressors. The goal of the WSA probabilistic monitoring is not to identify any specific impaired stream but to estimate the percentage (or relative extent) of all streams, within the area of interest, that are subject to an ecological stressor and to rank the relative severity of each investigated stressor.

The goal of the USEPA's WSA program is to assess the water quality of the Nation's wadeable streams. The WSA program focuses on "wadeable" streams, small and shallow enough to sample without a boat, and has projects in all 50 States, Puerto Rico, and Guam and investigations at both a national and ecoregional scale (Boward and others, 1999; Herlihy and others, 2000; Hughes and others, 2000; Hayslip and others, 2004; Stoddard and others, 2005b; Robinson and others, 2006; USEPA, 2006a; Herger and others, 2007). The USEPA's National Health and Environmental Effects Research Laboratory (NHEERL), Western Ecology Division (WED) has published WSA comprehensive field and laboratory manuals available on the USEPA website at: http://www.epa.gov/owow/monitoring/wsa/materials.html (accessed 02/09). These protocols were designed to standardize the methods of collecting and processing of data relevant to the ecological condition of stream resources, allowing the data to be combined to produce a nationally consistent assessment. The main objectives of the WSA program are to (from Paulsen and others, 2008):

1. Report on the ecological condition of all wadeable perennial streams of the U.S.;

2. Focus on direct measures of biological assemblages in assessing ecological condition;

3. Assess risks to the environment, assess the current environmental conditions of the Nation's streams and rivers, and assess changes in those conditions over time;

4. Identify and rank the relative importance of potential stressors affecting the Nation's streams and rivers, using supplemental measures of chemical, physical, and biological habitat;

5. And influence how States design their monitoring programs and how they assess and report on the condition of their streams and rivers.

The WSA was intended to benefit from existing State agency expertise and knowledge of aquatic resources. WSA background materials, including the field methods manual and quality assurance plan are available on the USEPA website at: http://www.epa.gov/owow/monitoring/wsa/materials.html (accessed 02/09). A USEPA national synthesis report titled 'Wadeable Streams Assessment: A Collaborative Survey of the Nation's Streams' was published in 2006 and is available on the USEPA website at: http://www.epa.gov/owow/streamsurvey/index.html (accessed 02/09). A number of State and regional WSA reports have been published and are available on the USEPA website at: http://www.epa.gov/emap/html/pubs/docs/geographic.html (accessed 02/09)).

Previous work using probabilistic sampling in Hawai‘i includes a pilot study of estuarine resources in the Hawaiian Islands. This study was conducted as part of the USEPA's National Coastal Assessment (NCA) Environmental Monitoring and Assessment Program (EMAP). The NCA surveys the condition of the Nation's coastal resources. The assessment of the ecological condition of Hawaiian estuaries was conducted in 2002 (Nelson and others, 2007). The statistical summary of this study is available at: http://www.epa.gov/wed/pages/publications/authored.htm (accessed 02/09).

The Hawai‘i State Department of Health (HDOH) seeks to gain insight into the health and biological integrity of the State's freshwater streams by utilizing the consistent and repeatable field operations and bioassessment methods of the WSA. The WSA, including the specific methodologies, provides the necessary quality assurance for establishing scientifically defensible data and decisions. The WSA enables States and tribes to utilize the greater resources of the USEPA to develop methods that are acceptable for a multitude of purposes, including baseline studies, trend analyses, impact monitoring, and enforcement responsibilities of the various regulating authorities to provide information on aquatic organisms and their habitats. Many States and agencies have participated in State and regional studies providing data for the assessment of the Nation's waters.

The general concept of probabilistic design enables the development of a monitoring strategy, which employs statistical survey methods that allow large geographical areas to be assessed by a relatively small subsample. These subsamples then can be used to make valid statements about the condition of the resources in general. With continuing resource limitation, the HDOH expects to utilize probabilistic designs to evaluate larger geographical areas of fresh and marine waters with fewer resources. While HDOH recognizes the problems of oversimplification in making general statements, the monitoring strategy currently under development will use the information of these random sites to target specific sites within the region or watershed of interest. In short, the random design will act as a tier 1 starting point that can trigger a more selective targeted sampling effort within streams determined to be under stress. The HDOH may eventually include aquatic-community-based biocriteria into the State water quality standards to assist in determining the condition of various waterbodies. These improved methods will enable the State to make better decisions in the protection of Hawai‘i's aquatic resources.

In 2006, the U.S. Geological Survey (USGS) Pacific Islands Water Science Center (PIWSC) and the HDOH began a 2-year cooperative pilot study in collaboration with the USEPA, under the USEPA's WSA program. The primary goal of this pilot study was to use the WSA probabilistic design and sampling methodologies to assess the ecological condition of wadeable perennial streams on the island of O‘ahu, Hawai‘i. A second objective was to provide the HDOH and other State agencies with a constructive demonstration and support to enable them to conduct their own probabilistic monitoring and assessments and to possibly incorporate these methods into their standard protocols. A third objective was to use the benthic macroinvertebrate data collected during the study to expand the USGS PIWSC benthic macroinvertebrate dataset for future refinement of the Preliminary–Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) developed in 2005 (Wolff, 2005).

Using a statistically unbiased, probability-based sampling design, 40 sites on wadeable, accessible, perennial streams on O‘ahu were randomly selected and surveyed for physical habitat characteristics, water chemistry, and benthic macroinvertebrate assemblages following the standard WSA protocols (USEPA, 2004a). Twenty sites were sampled during the spring and summer of 2006, and 20 sites were sampled during the spring and summer of 2007. An additional benthic macroinvertebrate sample was collected at each of the 40 sites following the USGS National Water Quality Assessment (NAWQA) program protocol for sampling the Richest Targeted Habitat (RTH) (Cuffney and others, 1993; Fitzpatrick and others, 1998). These additional samples were collected in order to be consistent with the sampling methods used during previous USGS benthic macroinvertebrate sampling efforts in Hawai‘i.

This report was intended to demonstrate an application of the WSA probabilistic sampling methodology and to provide agencies in Hawai‘i with a conceptual view of its potential relevance. One relevant aspect demonstrated in this report was an examination of smaller areas within O‘ahu described in this report as physiographic regions (windward, central, Honolulu, and Wai‘anae) and elevation regions (0 to 300 ft, 300 to 1,000 ft, and >1,000 ft). Because the study was limited to 40 sites to cover the entire island, these individual regions did not have that many sites. As a result of having <20 sites, the 95-percent confidence intervals, a measure of the uncertainty of the estimate, were often relatively large. Because of the considerable uncertainty, the results for these regional subpopulations should not be used to infer the actual conditions and are intended only to demonstrate this aspect of the probabilistic design. In future WSA studies in Hawai‘i, the number of sites required within each designated region needs to be addressed during the design stage of the study.

Assessment Objectives

The assessment objectives of this study included: (1) estimate the extent of streams on O‘ahu (based on the National Hydrography Dataset (NHD) perennial stream coverage accessed at http://nhd.usgs.gov/ February 2005) that are wadeable, perennial, and accessible, (2) assess the ecological condition of these wadeable perennial streams on O‘ahu using components of the benthic macroinvertebrate assemblage, (3) estimate the extent of wadeable perennial streams on O‘ahu affected by potential stressors associated with water chemistry and physical habitat, and (4) estimate the extent of the ecological condition of wadeable perennial streams within physiographic and elevation regions on O‘ahu in regard to water chemistry, physical habitat characteristics, and benthic macroinvertebrate assemblages.

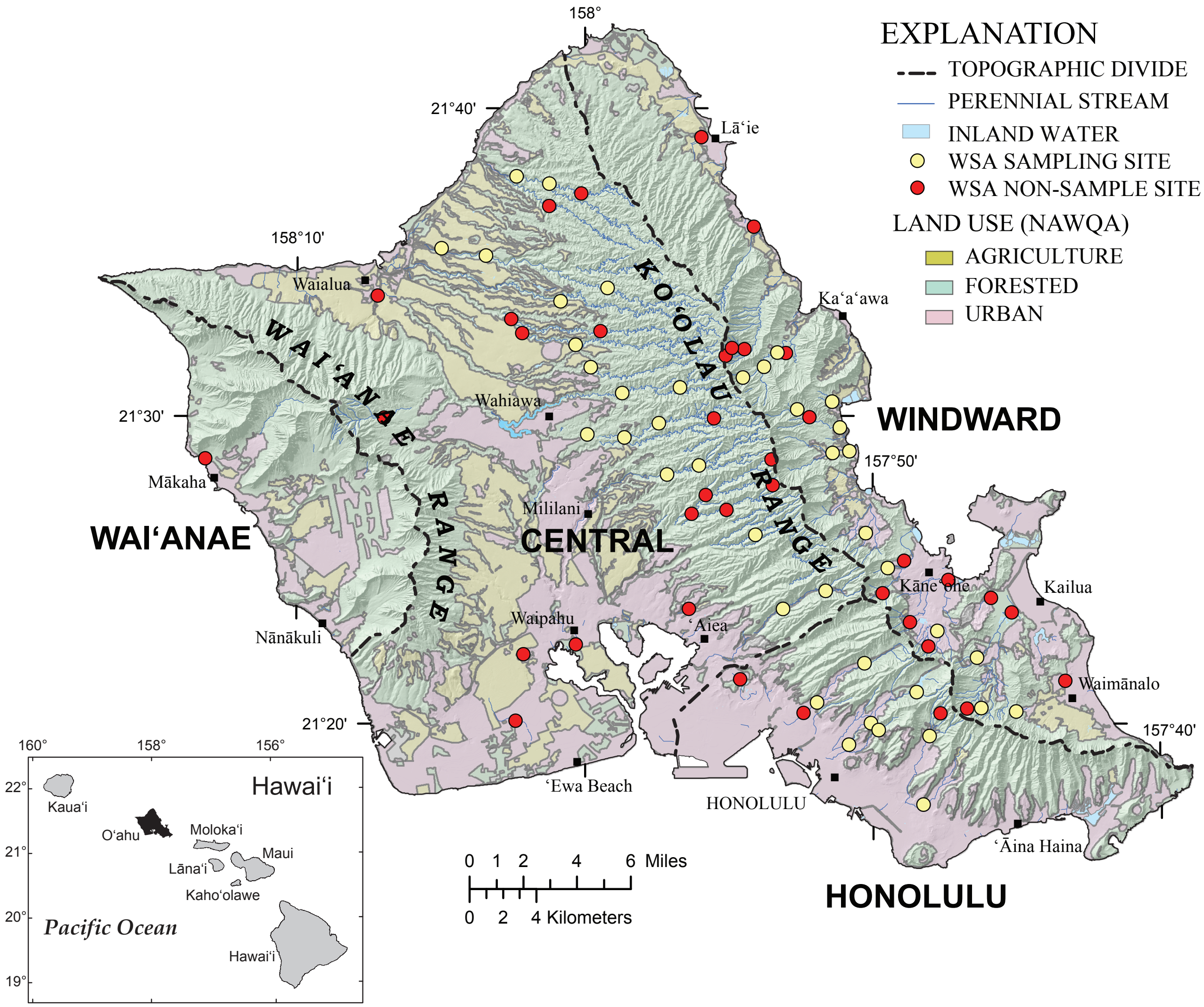

Figure 1. Land use and Wadeable Stream Assessment (WSA) sampling sites on the island of Oʻahu, Hawaiʻi. WSA non-sample sites includes sites that were evaluated as non-target sites and sites that were inaccessible. (Modified from Klasner and Mikami, 2003).

Purpose and Scope

This report provides an analysis of the results of a cooperative pilot study by the USGS PIWSC, the HDOH, and the USEPA on Oʻahu, Hawaiʻi as part of the USEPA's WSA program. The purpose of this report is to demonstrate an application of the WSA probabilistic sampling methodology to assess the ecological condition of wadeable perennial streams on Oʻahu, Hawaiʻi. Data on physical habitat, water chemistry, and benthic macroinvertebrate assemblages collected for this study at 40 randomly selected sites in 2006–07 are used to assess the ecological condition of perennial streams on Oʻahu. Reference-site conditions are used to assess and estimate the extent of ecological indicators islandwide and within predefined geographic and elevation regions. This report does not identify individual streams or stream sections with water quality or physical habitat challenges or stressed biological assemblages. Instead, the probabilistic approach used in this study provides information on the ecological condition of wadeable perennial streams for the entire island.

Acknowledgments

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This study could not have been completed without the dedicated fieldwork of Chiu Yeung, Crystal Hammer, John Engott,

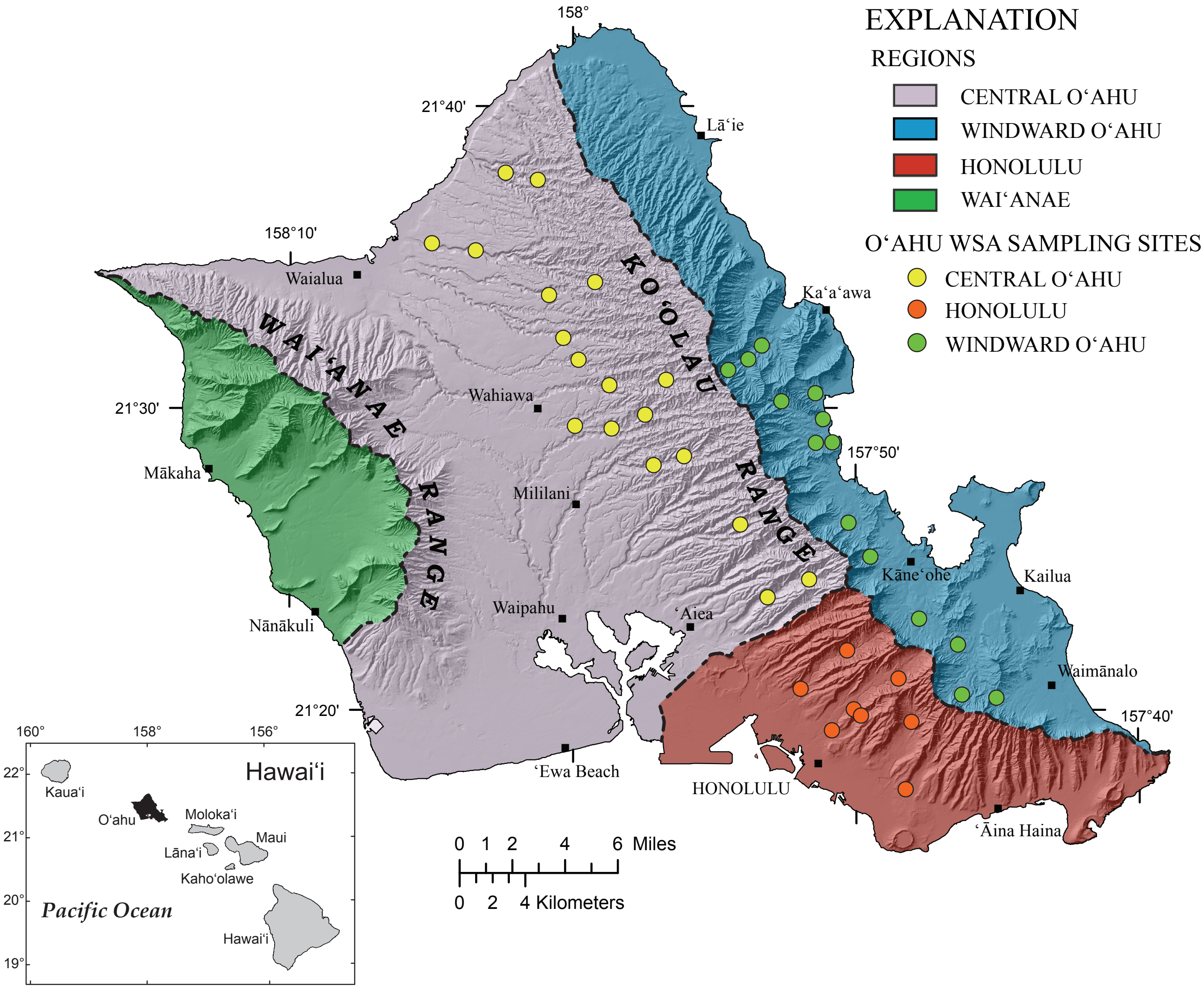

Figure 2. Geographic regions and WSA sampling sites on the island of Oʻahu, Hawaiʻi.

and Guy Foster of the USGS, PIWSC, and Monica Furness, Momi Wheeler, Katie Kamelamela, and Stephanie McDowell.

The authors also thank Phil Kaufman, Dave Peck, Tony Olsen, and Tom Kincaid from the USEPA's NHEERL, WED, for their help and guidance throughout this project. The authors send a special thanks to Gordon Smith of the USFWS and Matthew Burt of the U.S. Army Garrison Hawaiʻi, Directorate of Public Works, Environmental Division.

Description of the Study Area

The island of Oʻahu is the third largest island of the State of Hawaiʻi and is located between longitude 158°20'W and 157º35'W and between latitude 21°15'N and 21°45'N (fig. 1). The landscape of Oʻahu ranges from a broad coastal plain, surrounding much of the island, to steep interior mountains. Oʻahu can be divided into two primary physiographic regions, windward and leeward, which relate to the exposure of these areas to the northeasterly trade winds and orographic rainfall. In general, the windward side has smaller drainage basins, higher rainfall, and perennial streams, while the leeward side has larger drainage basins, lower rainfall, and intermittent streamflow (Oki and Brasher, 2003). The leeward area can be further subdivided into the physiographic regions of Honolulu, central, and Waiʻanae (west) areas (fig. 2) (Oki and Brasher, 2003).

The climate of Oʻahu is characterized by mild temperatures, which vary by few degrees between seasons. The small temperature difference between the warmest and coolest months is largely attributable to the influence of the surrounding ocean, the persistence of cool trade winds, and the small seasonal variation in solar radiation (Blumenstock and Price, 1967; Sanderson, 1993). Topography and the location of the north Pacific anticyclone relative to the island primarily control the climate of Oʻahu. During the dry season the stability of the north Pacific anticyclone produces persistent northeasterly trade winds that blow 80 to 95 percent of the time (Oki and Brasher, 2003). Daylight hours also change little from season to season. The length of the longest day and the shortest day of the year vary only by a few hours. This lack of seasonality in temperature and day length is reflected in the reduction of seasonality in the invertebrate life cycles compared to temperate continental streams.

A rainy season occurs on O‘ahu from October through April and a dry season from May through September. However, high rains and storm flows can occur throughout the year (Blumenstock and Price, 1967; Sanderson, 1993; Giambelluca and Schroeder, 1998). During heavy storms, 24-hour rainfall can exceed 10 in. over coastal areas and 20 in. over the mountainous interior of the Ko‘olau Range (Giambelluca and others, 1984). The windward (northeastern) side of the island is wettest. This pattern is controlled by the orographic lifting of moisture-laden northeasterly trade winds along the windward slope of the Ko‘olau Range (Giambelluca and Schroeder, 1998; Oki and Brasher, 2003).

Drainage basins on O‘ahu are generally small, compared to continental drainages, mainly because the distance between the headwaters and mouths of streams is short and adjacent streams are closely spaced (Oki and Brasher, 2003). In most of the windward area, drainage basins generally are smaller, shorter, and wider than those in central O‘ahu, and drainage basins in the Honolulu area are intermediate in size and shape. Main courses of streams generally follow the consequent drainage pattern established on the original domed surfaces of the shield volcanoes. Numerous lower order tributaries commonly join the main courses. Streambed slopes are steep in the mountainous interior, where rainfall is high, and flatter near the coast. Steep terrain and steep stream gradients cause water to run off rapidly following precipitation. As a result, streamflow is characteristically flashy, with high flood peaks and little baseflow. Some streams flow perennially throughout their entire course. Other streams are naturally or artificially interrupted with dry stretches, flowing perennially over parts of their course (Polhemus and others, 1992). The remaining intermittent streams flow during only parts of the year throughout their entire course. Streams commonly flow perennially in the interior, dike-intruded areas, where the groundwater table is intersected and where rainfall is persistent, or near the coast, where the water table is higher than the stream level; however, few streams on O‘ahu are perennial

Table 1. Land use for O‘ahu, Hawai‘i, by region and elevation.

[Based on NAWQA land use coverage (Klasner and Mikami, 2003)]

Region	Elevation range (feet)	Land use								Row total	
		Agriculture		Barren		Developed		Other (forested)			
		Acres	Percent of row	Acres	Percent of row	Acres	Percent of row	Acres	Percent of row	Acres	Percent of region
Central	0–300	16,495	29.99	750	1.36	27,311	49.66	10,437	18.98	54,992	26.24
	300–1,000	26,930	32.72	97	0.12	14,050	17.07	41,229	50.09	82,305	39.27
	>1,000	4,426	6.13	54	0.07	2,380	3.29	65,406	90.51	72,266	34.48
	Total	47,851	22.83	901	0.43	43,741	20.87	117,071	55.86	209,563	
Honolulu	0–300	97	0.34	–	–	23,850	84.11	4,408	15.55	28,356	50.89
	300–1,000	155	0.99	–	–	3,538	22.49	12,041	76.53	15,735	28.24
	>1,000	3	0.02	–	–	340	2.93	11,281	97.05	11,624	20.86
	Total	255	0.46	–	–	27,729	49.77	27,731	49.77	55,715	
Wai‘anae	0–300	2,421	15.26	252	1.59	7,097	44.73	6,095	38.42	15,865	40.75
	300–1,000	124	1.21	–	0.00	976	9.53	9,143	89.26	10,244	26.31
	>1000	–	0.00	–	0.00	21	0.16	12,807	99.84	12,828	32.95
	Total	2,545	6.54	252	0.65	8,094	20.79	28,045	72.03	38,936	
Windward	0–300	8,195	19.04	215	0.50	18,040	41.92	16,582	38.53	43,032	54.12
	300–1,000	350	1.47	154	0.65	1,060	4.44	22,304	93.45	23,868	30.02
	>1,000	–	0.00	–	0.00	1	0.01	12,607	99.99	12,608	15.86
	Total	8,545	10.75	369	0.46	19,101	24.02	51,493	64.76	79,509	
O‘ahu	—	59,197	15.43	1,522	0.40	98,665	25.71	224,339	58.46	383,724	100

Table 2. Land use for Oʻahu, Hawaiʻi, by elevation range

[Based on NAWQA land use coverage (Klasner and Mikami, 2003)]

Elevation range (feet)	Land Use								Elevation Range Total	
	Agriculture		Barren		Developed		Other (forested)			
	Acres	Percent of row	Acres	Percent of row	Acres	Percent of row	Acres	Percent of row	Acres	Percent
0–300	27,208	19	1,217	0.9	76,299	54	37,522	26	142,245	37
300–1,000	27,560	21	251	0.2	19,624	15	84,717	64	132,152	34
>1,000	4,429	4	54	0.05	2,742	3	102,101	93	109,326	28

Table 3. Land use for Oʻahu, Hawaiʻi, by physiographic region.

[Based on NAWQA land use coverage (Klasner and Mikami, 2003)]

Region	Land Use								Region total	
	Agriculture		Barren		Developed		Other (forested)			
	Acres	Percent of row	Acres	Percent of row	Acres	Percent of row	Acres	Percent of row	Acres	Percent
Central	47,851	22.83	901	0.43	43,741	20.87	117,071	55.86	209,563	55
Honolulu	255	0.46	—	—	27,729	49.77	27,731	49.77	55,715	15
Waiʻanae	2,545	6.54	252	0.65	8,094	20.79	28,045	72.03	38,936	10
Windward	8,545	10.75	369	0.46	19,101	24.02	51,493	64.76	79,509	21

over their entire length (Nichols and others, 1996). These conditions nearly rule out surface-water development on Oʻahu and lead to heavy reliance on ground water (Nichols and others, 1996). A total of 57 streams on Oʻahu have been classified as perennial in all or part of their courses (Hawaiʻi Cooperative Park Service Unit, 1990).

Descriptions of the surface-water resources and flow characteristics associated with Oʻahu's streams include those for the windward (Hirashima, 1962, 1963, 1965; Takasaki and others, 1969), north-central (Rosenau and others, 1971), northern (Takasaki and Valenciano, 1969), southeastern (Takasaki and Mink, 1982), and southern (Mink, 1962; Hirashima, 1971; Shade, 1984) parts of the island. In general, drainage basins on Oʻahu are small and streams are flashy as compared to continental drainages. However, streamflow characteristics are highly variable, both spatially and temporally.

The island of Oʻahu is approximately 383,724 acres (table 1). Land use on Oʻahu was mapped by the U.S. Geological Survey in 1998 (Klasner and Mikami, 2003). Estimated land use is 15.4 percent agricultural, 25.7 percent developed (nonagricultural), 0.4 percent barren-mining (mining in Hawaiʻi is defined as the extraction, collection, and storage of aggregate and fill materials such as soil, sand, gravel, rock, and dredge spoils), and 58.5 percent other (including conservation, forest reserve, natural areas, wetlands, water, barren-nonmining, and unmanaged vegetation) (fig. 1). The category 'other' will be referred to as 'forest' for purposes of this report. The higher elevations (>1,000 ft) of the island are predominantly forested (93 percent) (table 2; fig. 3). The mid elevations (300-1,000 ft) are less dominated by forest (64 percent), with 21 percent agricultural and 15 percent developed land use. Lower elevation land use is dominantly developed (54 percent), with subordinate forest (26 percent) and agriculture (19 percent). Agriculture and urbanization on Oʻahu have resulted in substantial stream habitat alteration. An extensive study, conducted in the 1970s, showed that 57 percent of the streams on the island of Oʻahu had been channelized, 58 percent had water exported from them, and all had roads crossing over them (Timbol and Maciolek, 1978).

Windward Oʻahu

Windward Oʻahu accounts for about 21 percent (79,509 acres) of the land area of Oʻahu (table 3). The windward side of the island is the wettest, with maximum mean annual rainfall near the topographic crest of the Koʻolau Range exceeding 275 in. (Giambelluca and others, 1986). Land use on windward Oʻahu consists primarily of forest (65 percent), followed by developed (24 percent) and agriculture (10.8 percent) (table 1). Land use in the upper (>1,000 ft) and mid elevations (300–1,000 ft) of the windward region consists almost entirely of forested land (99.9 percent and 93.5 percent, respectively) (table 2). Low elevation (<300 ft) windward land use comprises developed land (41.9 percent), forest (38.5 percent), and agriculture (19 percent).

Central Oʻahu

Central Oʻahu is the largest region of leeward Oʻahu, accounting for about 55 percent of the island (209,563 acres) (table 3). The central area is becoming increasingly urbanized, although large-scale plantation agriculture and diversified agriculture also exist, and contains the largest drainage basins on the island. Land use in central O‘ahu consists of forest (55.9 percent), agriculture (22.8 percent), and developed (20.9 percent). Upper elevation land use is primarily forest (91percent), with some agriculture (6.1 percent) and developed (3.3 percent). Mid-elevation land use consists of forest (50 percent), agriculture (32.7 percent), and developed (17 percent). The low-elevation land use consists primarily of developed land (50 percent), with agriculture (30 percent) and forest (19 percent).

Honolulu

The Honolulu region accounts for about 15 percent (55,715 acres) of the area of O‘ahu (table 3). The Honolulu area is highly urbanized in the coastal areas and generally undeveloped in the mountainous interior areas, and it contains large U-shaped valleys (Stearns and Vaksvik, 1935; Oki and Brasher, 2003). Land use in the Honolulu region consists of forest (49.8 percent) and developed (49.8 percent), with modest agriculture (0.5 percent). Upper elevation land use is dominantly forest (97 percent). Mid-elevation land use is mostly forest (76.5 percent), with some developed land (22.5 percent). Low-elevation land use is mostly developed (84 percent), with some forest (15.6 percent).

Wai‘anae

Wai‘anae, or west O‘ahu, makes up about 10 percent (38,936 acres) of the area of O‘ahu (table 3). The rain shadow effect, caused by the Wai‘anae Range, results in lower rainfall and fewer perennial streams in the western region. The upper and mid-elevation land use is predominantly forest (99.8 percent and 89.3 percent, respectively). The lower elevation land use is developed (44.7 percent), forest (38.4 percent), and agriculture (15.3 percent).

Site Selection

A probability-based survey design was used to select sampling sites in order to get an unbiased representation of aquatic resource condition across this large geographic area. The principal characteristics of probability-based designs are that: (1) the population being sampled is clearly described, (2) every element in the population has the opportunity to be sampled with a known probability, and (3) sample selection is carried out by a random process. This approach allows statistical confidence levels to be placed on the estimates and provides the potential to detect changes and trends in condition with repeated sampling (Robinson and others, 2006; Olsen and Peck, 2008).

The geographic information system (GIS) sampling frame of perennial streams for the island of O‘ahu, Hawai‘i was created from USGS vector digital hydrography data at 1:24,000-scale from the USGS Hawai‘i Data Clearinghouse website available at http://hawaii.wr.usgs.gov/oahu/data.html (accessed 02/2005). The target population consisted of all perennial streams on island of O‘ahu, Hawai‘i. Sampling sites were randomly generated by Tony Olsen of the USEPA NHEERL, Western Ecology Division (Stevens and Olsen, 1999). A Generalized Random Tessellation Stratified (GRTS) survey design for a linear stream resource was used (Stevens and Olsen, 2003). The GRTS design generates a spatially balanced random sample from a geographic area. The sample design used three ‘multi-density’ categories based on elevation: 0 to 300 ft, 300 to 1,000 ft, and >1,000 ft, with an unequal probability of selection emphasizing sites to be selected from the two lower elevation ranges (fig. 3). This design was utilized in an effort to limit the time spent investigating higher elevation sites that would prove to be unsampleable because of the precipitous nature and inaccessibility of a large percentage of the higher elevation stream reaches (fig. 4). The output data supplied by the USEPA consisted of two sets of sites, a base set and an oversample set. The base set of sites was the primary list of possible sampling sites. The oversample set of sites was provided as substitute sampling sites for when a site from the base set was evaluated to be unsampleable (USEPA, 2004e). To maintain the integrity of the spatially balanced design, sites were selected from the base set in the order provided. When a site was judged unsampleable, a replacement site was selected, in the order provided, from the oversample set (USEPA, 2004e). Each site was associated with an unequal probability weighting factor determined for each ‘multi-density’ elevation category. The weighting factor is a measure of stream length represented by each site. When base sites were replaced by substitute sites from the oversample site list, the survey design weights were adjusted accordingly (Olsen and Peck, 2008)) (appendix A).

Geospatial Methods

Maps of O‘ahu were created delineating the physiographic regions (modified from Oki and Brasher, 2003) and the 300-ft and 1,000-ft elevation contours (figs. 2–3). These delineated areas were used to define subpopulations of streams for analysis in this report. These maps were used to calculate the total perennial stream length within each outlined area. These maps were also used to calculate the acreage of level 1 landuse types (agricultural, barren, developed, and forested) within each outlined area using the O‘ahu NAWQA landuse coverage (tables 1–3) (Klasner and Mikami, 2003). Mapping and geospatial analysis was performed using ESRI® ArcMap™ 9.2 and ArcToolbox™. The physiographic regions (windward, central, Honolulu, and Wai‘anae) were modified from Oki and Brasher (2003). These physiographic regions were converted from lines to polygons and used to clip the Klasner and Mikami (2003) land-use coverage, the NOAA

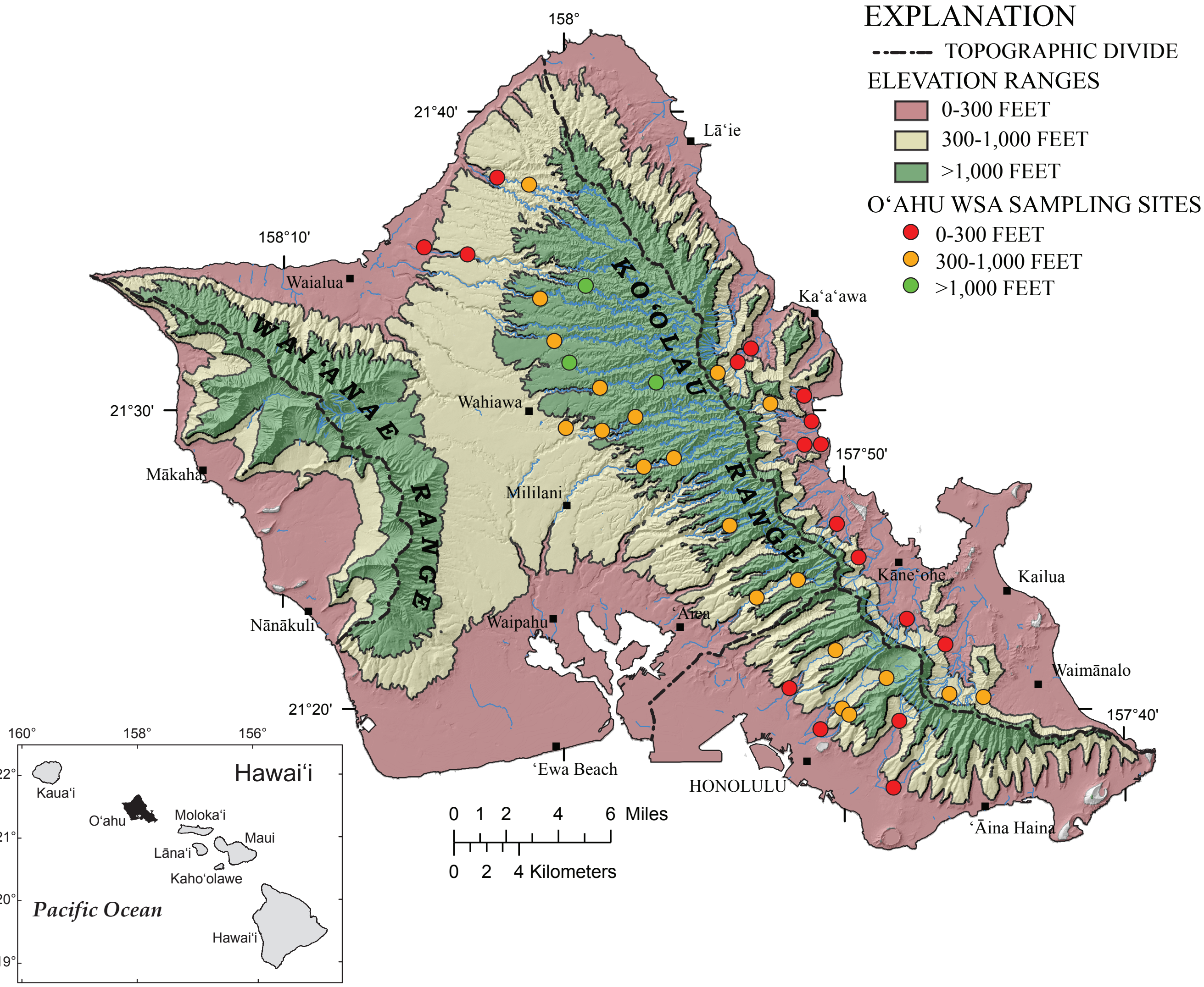

Figure 3. Elevation ranges and WSA sampling sites on the island of O‘ahu, Hawai‘i.

C-CAP O‘ahu land-cover coverage, and the NHD perennial stream layer (Analysis Tools » Extract » Clip). A USGS 10-meter Digital Elevation Model (DEM) was used to calculate the 3-dimensional surface length, following the elevation contour of the watershed, of the perennial streams on O‘ahu and within each physiographic and elevation region (3D Analyst Tools » Functional Surface » Surface Length). The areal extents of land-use and land-cover type class polygons were recalculated within each physiographic and elevation region (Spatial Statistics Tools » Utilities » Calculate Areas).

Reference Condition

To assess the current ecological condition of the wadeable streams on O‘ahu, benchmarks or *thresholds* for each of the ecological indicators needed to be established. In today’s world, genuine pristine, untouched habitats, unaffected by human activities, do not exist even in the most remote areas. Therefore, these reference condition threshold values were based on the *least disturbed condition* (LDC). The LDC sites are ideally the highest quality physical, chemical, and biological habitat sites available. For this pilot study, the thresholds were developed using data from a subset of the 10 least disturbed sampling sites selectively screened from the original 40 sites (see appendix A) (Stoddard and others, 2006; Herlihy and others, 2008). This set of reference sites provided a range of values, for each ecological indicator, representing what would be expected in areas least affected by human influence. The subset of sites was determined from the initial 40 sampling sites using a series of screening procedures. The sites were first screened using the on-site evaluations of the field crew by means of the WSA *Stream Assessment* and *Rapid Habitat Assessment* field forms and secondly using objective criteria developed from the water chemistry and physical habitat

Figure 4. Photograph of the Ko‘olau Range on the windward side of O‘ahu. Much of the higher elevations of this range are very steep

parameters (Whittier and others, 2007). The *Stream Assessment* and *Rapid Habitat Assessment* field forms are qualitative summaries, based on a consensus of the expert opinions of the team leaders and field crew, of the overall site condition (Gibson, 1996; USEPA, 2004a). The starting point for the screening process was a consensus-based characterization of each study site on a scale of 1 to 5, from *highly disturbed* to *pristine*. Only those sites agreed upon as *mostly pristine* to *pristine* (scored as 4 or 5) with completely forested upstream watersheds were selected for further screening. These sites were also screened using the WSA version of the Rapid Bioassessment Protocols (Plafkin and others, 1989; Barbour and others, 1999) based on a consensus-based scoring of stream habitat visual observations. The remaining sites were then screened using the water chemistry data. The resulting values for each of 18 water chemistry parameters were ranked in order from lowest value to greatest value, with higher values indicative of increasing disturbance. Values greater than or equal to the 95th percentile were flagged as ‘High’. The sites with the fewest number of ‘High’ flags were selected. This process was repeated using a set of relevant variables from the physical-habitat characteristics dataset. The final set of reference sites were selected from the different regions around the island. Eight of the sites were from the central region and 2 were from the windward region (7 sites between 300 and 1,000 ft, 2 sites below 300 ft, and 1 site above 1,000 ft) to account for the some of the ecological variability across the island. Given that the reference site thresholds for water chemistry and physical habitat variables will be used to assess the ecological impact on the aquatic biota, the biological data were not used to screen the reference sites.

For each ecological indicator, a single set of thresholds was established for all of the wadeable reaches of streams on O‘ahu (table 4). For variables where higher values indicate worse conditions, the upper threshold values were the 95th percentile and the lower threshold values were the 75th percentile; for variables where lower values indicate worse conditions, the upper threshold was the 5th percentile and the lower threshold was the 25th percentile of the reference sites (Stoddard and others, 2005b; Robinson and others, 2006; Herger and others, 2007). The thresholds values defined the ecological condition as either ‘*least disturbed’* (for values below the lower threshold), ‘*intermediate’* (between the lower and upper thresholds), or ‘*most disturbed’* (equal to or above the upper threshold).

This pilot study had a limited number of sampling sites and practical limitations that precluded sampling at targeted reference sites. It was therefore necessary to use a greater percentage of the sampling sites to establish the reference conditions than was desirable. A minimum of 10 of the 40 sites was needed to establish the reference thresholds, making it necessary to use 25 percent of the sampling sites (Herger and others, 2007). Because all of the sampling sites were selected at random, it was left up to chance as to what ecological conditions would be present at each site and whether or not any of the sites would be in *least disturbed* areas. Therefore some of the sites included as reference condition sites may not in fact be *least disturbed* sites but are the best available sites. An increase in the number of randomly selected sampling sites or the use of targeted sites would increase the probability of selecting sites in truly *least disturbed* areas, but because of the time and budget constraints of this pilot study this desired goal could not be met. The limited number of sites within each physiographic and elevation region made it impractical to calculate discrete thresholds for each region, resulting in a single set of thresholds for the entire island, which may or may not be an accurate measure for the different regions.

Field Methods

The fieldwork for this report was conducted over a two-year period, 2006–07. In 2006, sampling began in late April and ran through July. Sampling in 2007 began in mid-May and ran through mid-August. These months are commonly considered to be the dry season in Hawai‘i and a time when perennial streams in Hawai‘i, in general, have lower flows (Wong, 1994; Oki and Brasher, 2003). These months are also consistent with other aquatic macroinvertebrate sampling efforts in Hawai‘i (McIntosh and others, 2002; Brasher and others, 2004; Wolff, 2005). Although it has been shown that some nonnative aquatic invertebrates have adapted to the tropical conditions by being reproductively active year round (Kondratieff and others, 1997), they tend to be most active during the spring and summer months (Wolff, 2000). In 2006, the month of March was marked by heavy rains and flooding on O‘ahu, culminating in a large flood event at the end of the month. Although habitat measurements were collected during low-flow conditions at the end of April and in early May, the macroinvertebrate and water chemistry sampling was done later in May and in June to allow the streams to recover, biologically, from the flooding (appendix A).

Study Reaches

The study reaches were established by locating the x-y coordinates or ‘target-site,’ provided in the sampling frame, using topographic maps and hand-held GPS units. The length of each study reach was calculated as 40 times the channel wetted width, determined as the average wetted width of 5 measurements taken within 5 channel widths upstream and downstream of the target-site on the day of the survey, with a minimum reach length of 492 feet (150 meters). In most cases, the reach was established using the target-site as the center point (transect ‘F’), although in some circumstances the reach was adjusted in relation to the X-site because of physical constraints. Each study reach was divided by 11 equally spaced cross-sectional transects, with the downstream end of the reach labeled transect ‘A’ and the upstream transect labeled transect ‘K’.

Physical Habitat Characteristics

All physical habitat characteristics were determined in accordance with the WSA Field Operations Manual (USEPA, 2004a; Lazorchak and others, 1998; Peck and others, 2006). Data were recorded on field data sheets and later transferred into a Microsoft® Access relational database. The field data sheets were reviewed for accuracy prior to leaving each study site. The database data entries were reviewed in conjunction with the field data sheets for transcription errors. A brief description of the field method is provided below. For more detailed descriptions of the field method, please refer to the Field Operations Manual (USEPA, 2004a).

Thalweg Profile.—A longitudinal survey along each sampling reach was conducted determining the maximum depth, habitat class, presence of soft/fine sediment, and presence of off-channel habitat at equally spaced intervals. A tally of large woody debris was also conducted over the entire study reach.

Channel Dimensions.—Measurements were taken at each of the 11 transects, including the wetted width, bankfull height and bankfull width, undercut bank distance, and bank angles.

Table 4. Threshold values from reference sites used to determine levels of disturbance.

[Macroinvertebrate thresholds were taken from the Preliminary Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) in Wolff (2005); >, greater than; <, less than; ≤, less than or equal to; %, percent; mg/L, milligrams per liter; m^2, square meters; *, denotes terms used in Stoddard and others, 2005a]

Parameter	Most disturbed		Least disturbed	
	Threshold	Percentile	Threshold	Percentile
Macroinvertebrate P-HBIBI Score	>22	P-HBIBI	≤14	P-HBIBI
Percentage of Insects	≤75%	P-HBIBI	>90%	P-HBIBI
Macroinvertebrate Abundance (per m^2)	≤700	P-HBIBI	>3,000	P-HBIBI
Abundance of Non-Native Mollusks (per m^2)	>90	P-HBIBI	0	P-HBIBI
Total Nitrogen	>0.14 mg/L	95th	<0.106 mg/L	75th
Total Phosphorus	>0.013 mg/L	95th	<0.008 mg/L	75th
Total Suspended Solids	>1.0 mg/L	95th	<0.8 mg/L	75th
Sulfate	>2.862 mg/L	95th	<2.22 mg/L	75th
Percent Embeddedness (*xembed)	>40.2%	95th	<35.3%	75th
Relative Bed Stability (*lrbs_bw5)	<-0.92	5th	>-0.57	25th
Riparian Vegetation (*xcmg)	<0.67	5th	>0.81	25th
Riparian Disturbance (*w1_hall)	>0.49	95th	0	75th

Channel Gradient and Sinuosity.—The water-surface slope and channel sinuosity of each stream reach were determined using a clinometer and a surveyor's rod by measuring the slope and angle between adjacent pairs of transects. Supplemental measurements were made when the sinuosity or other obstructions blocked the line of site between transects.

Channel Substrate Size and Embeddedness.—Substrate size, estimated percentage of embeddedness, and water depth were recorded for 5 locations along each of the 11 transects (left bank, ¼ wetted-width, ½ wetted-width, ¾ wetted width, and right bank).

Habitat Complexity and Cover.—Visual estimates of the percentage of cover of potential fish habitat were conducted for filamentous algae, aquatic macrophytes, large woody debris, brush and small woody debris, in-channel live trees or roots, overhanging vegetation, undercut banks, boulders, and artificial structures.

Discharge.—Stream discharge was measured using a SonTek® FlowTracker Handheld Acoustic Doppler Velocimeter (ADV) consistent with USGS methodology (Rantz and others, 1982). Discharge measurements were typically taken directly downstream of the downstream-most transect (A). The ADV data used to calculate discharge was independently reviewed for quality control.

Riparian Measurements.—Riparian vegetation cover and structure were visually estimated, on both the right and left banks, of an area approximately 32.8 ft (10 m) long by 32.8 ft (10 m) wide at each transect. Estimates were made of the percentage of cover at three cover classes including ground cover, less than 1.64 ft (0.5 m) high, mid-layer understory, 1.64–16.4 ft (0.5–5 m) high, and canopy greater than 16.4 ft (5 m) high. Anthropogenic alterations to the riparian zone were visually estimated for influences such as walls, buildings, pavement, roads, pipes, trash, maintained lawns and ornamental plantings, row crops, pastures, and other modifications.

Indices and Metrics

Statistical analyses were performed on the physical habitat data prior to using the data in the WSA report. These analyses were used to compile the raw data and calculate indices and metrics representing the ecological condition at each site. The statistical methods and guidance described in this section were provided by the USEPA.

The array of qualitative and quantitative physical habitat data that was collected during the course of this project was used to calculate indices and metrics of stream size and gradient, sinuosity, substrate size and stability, habitat complexity and cover, woody debris size and abundance, residual pool (pools that retain water even when there is no flow) dimensions and frequency, riparian vegetation cover and structure, anthropogenic disturbances, and channel-riparian interaction (anthropogenic activities, channel sinuosity, incision, and morphometric complexity) for each site. Guidance for these calculations was provided in the USEPA report Quantifying Physical Habitat in Wadeable Streams (Kaufmann and others, 1999). The data were analyzed using SAS/STAT® software with SAS computer codes provided by Phil Kaufmann and Curt Seeliger of NHEERL WED. The SAS codes were modified to handle the O‘ahu WSA data and were used to perform: (1) data verification and validation procedures and (2) index and metric calculations. The data verification and validation codes checked the structure of the WSA physical habitat data files and flagged erroneous and missing values. The reachwide indices and metrics that were calculated included simple statistics such as mean, standard deviation, and quartiles, as well as more complex calculations of areal cover, proximity-weighted estimates (weighting each observation according to its nearness to the stream), woody debris abundance, residual pool characteristics, and bed stability (median substrate diameter/average substrate diameter of substrate mobilized at bankfull flow).

Water Chemistry

A 1.057-gal (1 liter) cubitainer® and two 0.135-oz (60 milliliter) syringes of stream water were collected in the middle of the channel at each site (USEPA, 2004a). The syringes were sealed with a Luer-lock valve to prevent gas exchange. Syringes are used to seal off the samples from the atmosphere because the pH and dissolved inorganic carbon (DIC) concentrations will change if the streamwater equilibrates with atmospheric CO_2. All samples were placed in a cooler on ice for overnight transport to the analytical laboratory at the USEPA's NHEER Laboratory, WED in Corvallis, Oregon. Upon receipt at the laboratory, the syringe samples were analyzed for pH and, DIC and the cubitainer samples were split into aliquots and preserved (filtration and (or) acidification)—usually within 48 to 72 hours of collection (USEPA, 2004c). Streamwater from the cubitainers was used to measure the major cations and anions, nutrients, turbidity, and color.

Detailed information on the analytical methods, detection limits, and quality assurance and quality control procedures can be found in the USEPA's Water Chemistry Laboratory Manual (USEPA, 2004c). In brief, sulfate (SO_4^{2-}), nitrate (NO_3^-,), and chloride (Cl^-) concentrations were determined by ion chromatography; dissolved organic carbon (DOC) concentrations by persulfate oxidation and a carbon analyzer; turbidity by nephelometer; dissolved silica (SiO_2) and ammonium (NH_4^+) concentrations by colorimetry, and total nitrogen (N) and phosphorus (P) concentrations by persulfate oxidation and colorimetry (USEPA, 2004c).

Benthic Macroinvertebrates

Two sampling methods were used to collect benthic macroinvertebrates from each study site. The first method adhered to the WSA protocol for a reachwide (RW) sample as described in the Wadeable Streams Assessment Field Operations Manual (USEPA, 2004a; Klemm and others, 1990). This protocol utilized a 0.0197-in. (500-µm) mesh D-frame kick net with a 1-ft-wide opening. A sample was collected from 3.28 ft

(1 m) downstream of each of the 11 cross-section transects at an assigned sampling point (left, right, or center). The first of these points was assigned at random and successive points were assigned in order. Replacement points were selected when the sampling points were too deep to wade. The kick net was placed on the streambed and a 1-ft^2 quadrat of substrate in front of the net was delineated by eye. Coarse substrate particles within the quadrat were scrubbed to dislodge organisms into the net and then placed outside the quadrat. The quadrat was then disturbed by foot for 30 seconds. The 11 transect samples were cleaned of extraneous inorganic and plant material and combined into a single composite sample for each sampling site. The samples were stored in a 70-percent ethanol solution until they were shipped to the analytical laboratory, EcoAnalysts Inc. in Moscow, Idaho, for identification and enumeration as discussed below.

The second method followed the NAWQA protocol for Richest Targeted Habitat (RTH) (Cuffney and others, 1993). These samples were collected from the faunistically richest community of benthic invertebrates, which typically (also in Hawaiian streams) is located in coarse-substrate riffle habitats (Moulton and others, 2002; Brasher and others, 2004). Samples were collected from five riffles using a modified Surber sampler (Slack sampler) with a 0.0167-in (425-µm) mesh net (Cuffney and others, 1993). The five sampling sites were selected using the criteria that: (a) a sufficient number of riffles were present; (b) the substrate was natural and mostly coarse grained (small to large cobbles); (c) the flow was in the main channel; and (d) the net could be properly positioned. Sampling sites were ultimately determined by the project aquatic biologist, relying on professional experience, particularly in streams with less than optimal sampling conditions, with an emphasis on maintaining consistency in the sampling efforts. If riffles were not present, RTH sampling sites were positioned in the fastest flowing water. RTH samples were not collected from seven sites that had only pool habitat and from two sites that were entirely concrete-lined channels. All substrate within a 2.69-ft^2 (0.25-m^2) area in front of the net was gently dislodged and thoroughly scrubbed to remove all organisms, until nothing except immoveable or fine-grained substrate remained. Five RTH samples were collected at each sampling reach, cleaned of extraneous inorganic and plant material, and then combined to produce a single composite sample. The samples were stored in a 70-percent ethanol solution until they were shipped to the analytical laboratory, EcoAnalysts Inc. in Moscow, Idaho, for identification and enumeration as discussed below.

Macroinvertebrate Analytical Procedures

The sorting, identification, and enumeration of all the macroinvertebrate samples was conducted by the contract laboratory, EcoAnalysts Inc. of Moscow, Idaho. Expert laboratory personnel picked through the samples, sorting out the macroinvertebrates from the bits and pieces of plant and inorganic material using standard procedures as discussed in Barbour and others (1999). Both sample types, RW and RTH, were processed in the same manner. Each sample was spread evenly in a sorting tray of known dimensions, marked with crisscrossing grid lines. The sorting was conducted incrementally by randomly selecting, removing, and sorting individual grids of material until a fixed count of 500 organisms were counted from each sample. The number of grids of material that were picked through from each sample was compared to the total number of grids of the whole sample to determine the percentage of each sample that was needed to reach the 500-organism threshold. This percentage is called the subsample factor. The subsample factor was then used to estimate the total number of organisms in each whole sample. For example, if 6 out of 12 total grids (50 percent) of a sample produced 500 organisms, the subsample factor would be $12 \div 6$, or 2, and the whole sample would be estimated to contain 500×2, or 1,000 organisms. The sorted organisms were identified to the lowest taxonomic level possible, usually to the genus or species level. Damaged organisms were more difficult to identify and were usually determined at the family or class level. Aquatic worms were identified at the class Oligochaeta level. Quality-control procedures included a second sort of the material of each sample by a second laboratory taxonomist until a 90-percent or better sorting efficacy was attained. Further quality-control measures were conducted on 10 percent of the samples to verify the taxonomic identifications by the original taxonomist. A second taxonomist independently examined and identified the sorted organisms until a 90-percent or better similarity was attained between the two taxonomists.

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

Quality Assurance

Quality assurance and quality control activities for WSA are described in a quality assurance project plan (USEPA, 2004d). All of the WSA protocols are described in detail in USEPA publications, including the field methods, benthic laboratory methods, water chemistry laboratory methods, physical habitat data processing, and statistical analyses methods (USEPA, 2004a, b, c, d; Kaufmann and others, 1999; Kincaid, 2006). The appropriate protocols were followed by each member of the field crew, the benthic macroinvertebrate laboratory, EcoAnalysts, Inc., the USEPA water chemistry laboratory at the NHEER Laboratory in Corvallis, Oregon, and the project chief. The field crew was personally instructed prior to each sampling season by USEPA personnel who coauthored the field manual.

Extent Calculations

The WSA probabilistic sampling design presupposes that the results from the smaller number of sampling sites can be extrapolated to the larger population of target streams. The percentage of the total stream length, or ‘extent’, of the stream resource and the percentage of the target population and subpopulations of stream length, or ‘relative extent,’ of the ecological stressors were extrapolated from the data collected at the sampling sites. These extrapolations allow for inferences to be made about the entire stream network from the smaller number of streams that were actually sampled. The foundation for these extrapolation calculations comes from the weighting factors assigned to the sampling sites during the site selection process explained earlier in this report. Each site represents a length of stream such that the sum of the stream lengths equals the total population of stream length. For more information on the WSA survey design and extent estimate calculations see Olsen and Peck (2008). For more information on the methods used to calculate the confidence intervals see Stevens and Olsen (2003).

In this pilot study, the USEPA NHEERL, WED provided a base set of 150 randomly selected sites. Each of these sites was representative of a larger number of stream lengths on O‘ahu such that the entire base set of 150 sites represented all the wadeable, perennial stream length on the island. To numerically characterize the amount of stream length represented by each site, each site was assigned an initial weighting factor representing a length of stream, in miles, such that the sum of the 150 weights was equal to the 505.2 miles of stream on O‘ahu. For example, a site with an initial weight of 2.27 represented 2.27 miles of stream length. Additionally, for this study, the USEPA was requested to use three categories, based on elevation (0 to 300 ft, 300 to 1,000 ft, and >1,000 ft), with a greater emphasis for sites to be selected from the two lower elevation ranges (40:40:20) because of the precipitous nature and inaccessibility of the higher elevation stream reaches. This required that the initial weighting factors be different for each elevation category and that the sum of the site initial weights within each elevation range equal the sum of the stream lengths within each category.

The initial weighting factors calculated for the base set of sampling sites needed to be adjusted after the final set of sampling sites had been determined (appendix A) (Stoddard and others, 2005a; Olsen and Peck, 2008). These adjustments were necessary because: (1) 24 sites were judged to be ‘non-target’ (not perennial or estuarine) sites and were removed and replaced by sites from the oversample set of sites—these oversample sites were selected in the order provided and did not necessarily replace sites of equal initial weight, (2) 15 target sites were considered inaccessible and were also replaced by oversample sites, and (3) only 40 sites were actually sampled and used for the final extrapolations. The non-target and inaccessible sites are identified in figure 1 as WSA non-sample sites. Adjusted weights were calculated as:

$$W_{adj} = W_{init} \times (\mathrm{SF} \div \Sigma W_{init}),$$

where W_{adj} is the adjusted site weight, W_{init} is the initial site weight, SF is the stream length from the original sample frame, and ΣW_{init} is the sum of initial site weights for all evaluated sites (Olsen and Peck, 2008). The adjusted weights were calculated on the basis that the sum of the weights of the 79 evaluated sites should equal the total stream length of the original sampling frame (505.2 mi), the sum of the weights of the 40 targeted sample sites equal the target population of streams (208 mi), and the sum of the weights of the sites within each elevation category was equal to the stream length within each category. For more detailed information on these procedures and calculations see Olsen and Peck (2008).

Once the weighting factors were adjusted for the actual sampling sites, the stream length of the resource was calculated as the sum of the weights of the sites within the resource category (Non-target, Physical Barrier (inaccessible), or Targeted Sample) and population (O‘ahu, physiographic region, or elevation range) and the extent of the resource was calculated by dividing by the total stream length of the population (fig. 5). Estimates of condition (biological indicators) and extent of stressors (stressor indicators) were calculated similarly by summing the weights of the sites within each condition type (least disturbed, intermediate, and most disturbed) and population and dividing by the total assessed stream length for the population.

Cumulative Distribution Functions

Plots of the cumulative distribution functions (CDFs) were created for each ecological indicator, including the water chemistry variables, the physical habitat metrics and indices, and the macroinvertebrate metrics (appendixes B, C, and D). These CDFs were used to describe the estimated proportions of stream length, from the target population of streams, represented by values of the indicator of interest, along with the 95-percent confidence bounds (Diaz-Ramos and others, 1996). The datasets, including the physical habitat metrics and indices, water chemistry, and benthic macroinvertebrates, were analyzed using the S-Plus® statistical program with software developed by Thomas Kincaid and Tony Olsen for the USEPA WSA (Kincaid, 2006). The files included in psurvey.analysis_2.12.S-PLUS 6&7.zip and StreamAnalysis S-PLUS.zip (example analyses) were downloaded on June 18, 2008, from the internet at http://www.epa.gov/nheerl/arm/analysispages/software.htm. This software processes R-language functions for the analysis of probability surveys. These functions re-calculate adjusted weights for each site based on the use of the oversample sites. The S-Plus® scripts were modified from examples provided by Olsen and Kincaid and from Silvanima and others (2008) to process the O‘ahu WSA data sets.

Results

Extent of Resource

The sampling frame used to select the sites for the WSA O‘ahu sampling was created from a perennial stream coverage provided from the USGS Hawai‘i Data Clearinghouse website

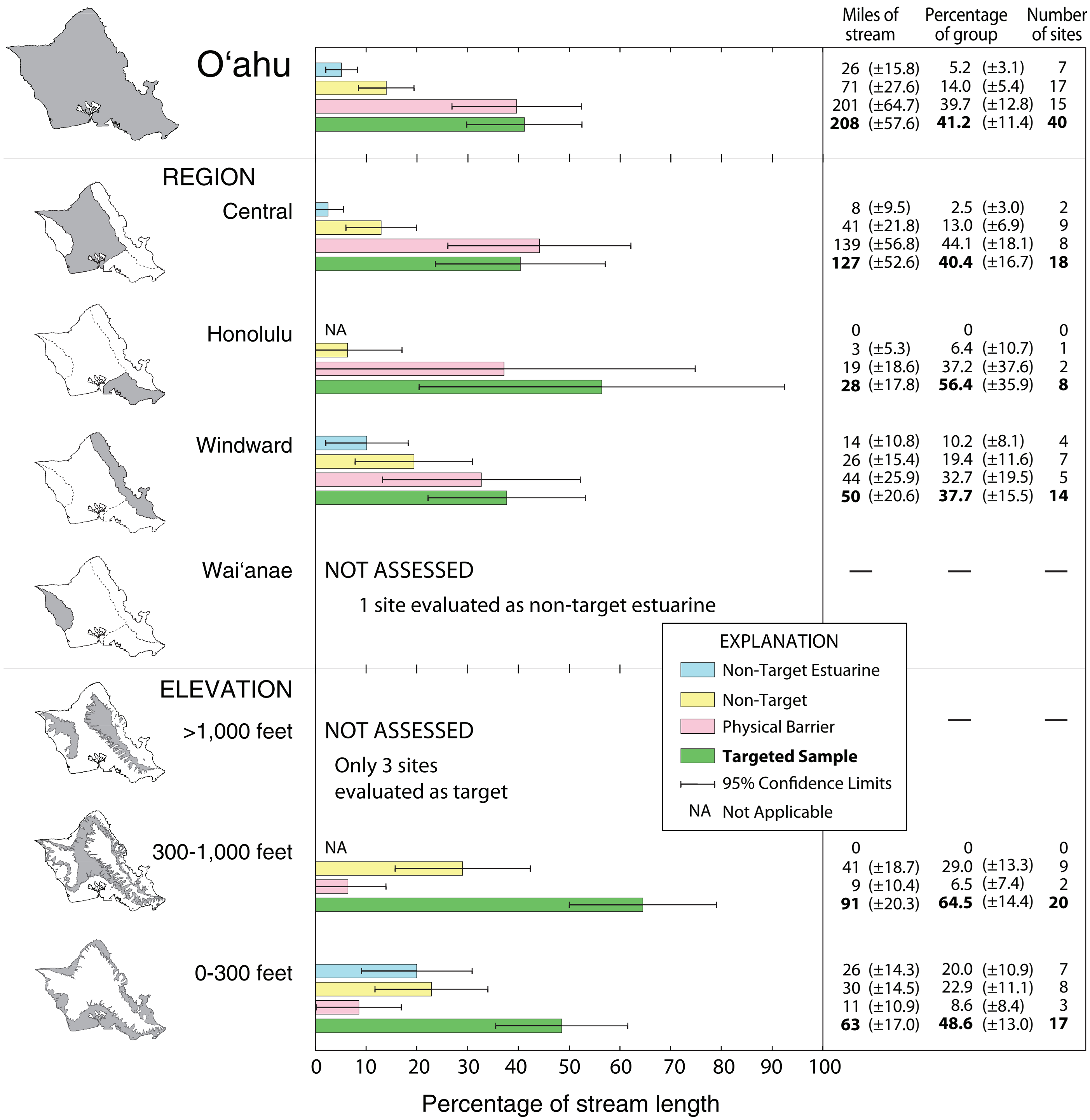

Figure 5. Stream length estimates (with 95-percent confidence limits), percent of category, and number of sites in each category for evaluated streams in the wadeable stream assessment on O'ahu, Hawai'i. Numbers in **bold** are for the targeted samples.

available at http://Hawaii.wr.usgs.gov/. The total stream length represented in the sampling frame (perennial streams on O‘ahu) was calculated to be 505.2 mi. A considerable amount of this stream length, 96.7 mi (19.2±6 percent), was evaluated to be non-target, ascertained as either nonperennial or estuarine (fig. 5). This represents the inaccuracy of the GIS coverage attributes for perennial streams that was used to create the sampling frame. Of the remaining 408.5 miles of target stream length, 200.5 mi (39.7±6.5 percent of the original sampling frame; 49.1 percent of the target stream length) was evaluated as being physically inaccessible because of physical barriers and (or) unsafe conditions such as steep cliffs or impenetrable thickets of the indigenous Hau tree, *Hibiscus tiliaceus*. Access was not denied to any of the WSA O‘ahu sampling sites. The remaining stream length of 208 miles (41.2±11.4 percent of the original sampling frame; 50.9 percent of the target stream length) was therefore the actual amount of stream that was assessed.

An estimated 138.8 miles, 69.2 percent of the estimated 200.5 miles of physically inaccessible stream length, were located in central O‘ahu. The main reason that these sites were unreachable was that they were located in rugged and steep remote areas on the leeward side of the Ko‘olau Range. The one and only site that was selected in the Wai‘anae region was evaluated as non-target estuarine, and therefore the stream lengths in the Wai‘anae region were not independently assessed. Most of the physically inaccessible stream length, 180.2 miles (89.9 percent), was located in the high elevation (>1,000 ft) range. These elevations are typically characterized by steep gradients. Of the 13 sites evaluated in the high elevation range, only 3 were sampleable.

Ecological Condition Indicators

The ecological conditions of wadeable, perennial streams on O‘ahu were quantified using components of the benthic macroinvertebrate assemblages as ecological indicators of stress in the environment. Benthic macroinvertebrates are the most commonly used group of organisms for this purpose because: (1) they are ubiquitous, and consequently can be affected by environmental perturbation in various aquatic systems and habitats, (2) the large number of species offers a wide spectrum of responses to environmental stressors, (3) their basic sedentary nature allows effective spatial analyses of pollutants or disturbance effects, (4) they have relatively long life cycles, which allows elucidation of temporal changes caused by perturbation, (5) they respond to natural and anthropogenic stressors in predictable and measureable ways, (6) they have been studied extensively and used as ecological indicators for many years, and (7) they can be sampled qualitatively and (or) semi-quantitatively with relative ease (Rosenberg and Resh, 1993; Gerth and Herlihy, 2006).

Benthic Macroinvertebrates

Parameters of the benthic macroinvertebrate assemblages were assessed using the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) developed by Wolff (2005). The multimetric P–HBIBI utilizes a set of core metrics with numerical criteria to score the metric parameters. There were seven core metrics that were incorporated into the P-HBIBI final score, including:

1. The total invertebrate abundance;
2. The abundance of alien mollusks;
3. The abundance of amphipods;
4. The relative abundance of insects;
5. The presence or absence of the native shrimp *Atyoida bisulcata*;
6. The presence or absence of the alien crayfish *Procambarus clarkii*;
7. The total number of taxa (richness).

Each of these metrics was scored and rated separately, and the sum of these scores determined the P–HBIBI final score which was then rated using statistically derived numerical criteria to determine the degree of impairment as mild, moderate or severe. For more information on how these metrics were calculated, scored, and rated see Wolff (2005). These assessments were performed independently of the reference condition as described earlier in this report. The P–HBIBI was developed using the NAWQA Richest Targeted Habitat (RTH) sampling method as the primary dataset. The results of the final P-HBIBI score and three of the core metrics are discussed in this report. CDF plots of all of the metrics, excluding the presence/absence metrics are in appendix B.

During the O‘ahu WSA sampling, RTH samples were not collected from seven stream sites that had only pool habitat and from two stream sites that were concrete-lined, flat-bottomed channels. Reachwide (RW) sample data were used in lieu of these RTH samples in calculating the P–HBIBI scores for the purposes of this pilot study. Although these habitat types were not sampled or included during the development of the P–HBIBI, this preliminary index is still the best available measure of stream quality in Hawai‘i, using benthic macroinvertebrates, at this time. Because these stream reaches were composed of a single, homogeneous habitat type, the RTH and RW sampling methods are likely to yield similar results. A study conducted by Rehn and others (2007) concluded that metrics responded similarly when comparing targeted riffle samples to reach-wide samples. The quantitative data for the RW, RTH, and the composite of both are presented using the cumulative distribution function (CDF) in appendix B. CDF plots of additional core metrics that were used in the P-HBIBI are shown in appendix B but are not discussed in the text. The extent of the resource assessed using the RTH sampling method was adjusted for the 9 unsampled sites (table 5).

The ratio of the observed number of macroinvertebrate taxa to the expected number of taxa (O/E) is a commonly used metric in many of the WSA studies in the continental United States (Hawkins, 2006; Yuan and others, 2008). The expected number of macroinvertebrate taxa is derived from the reference

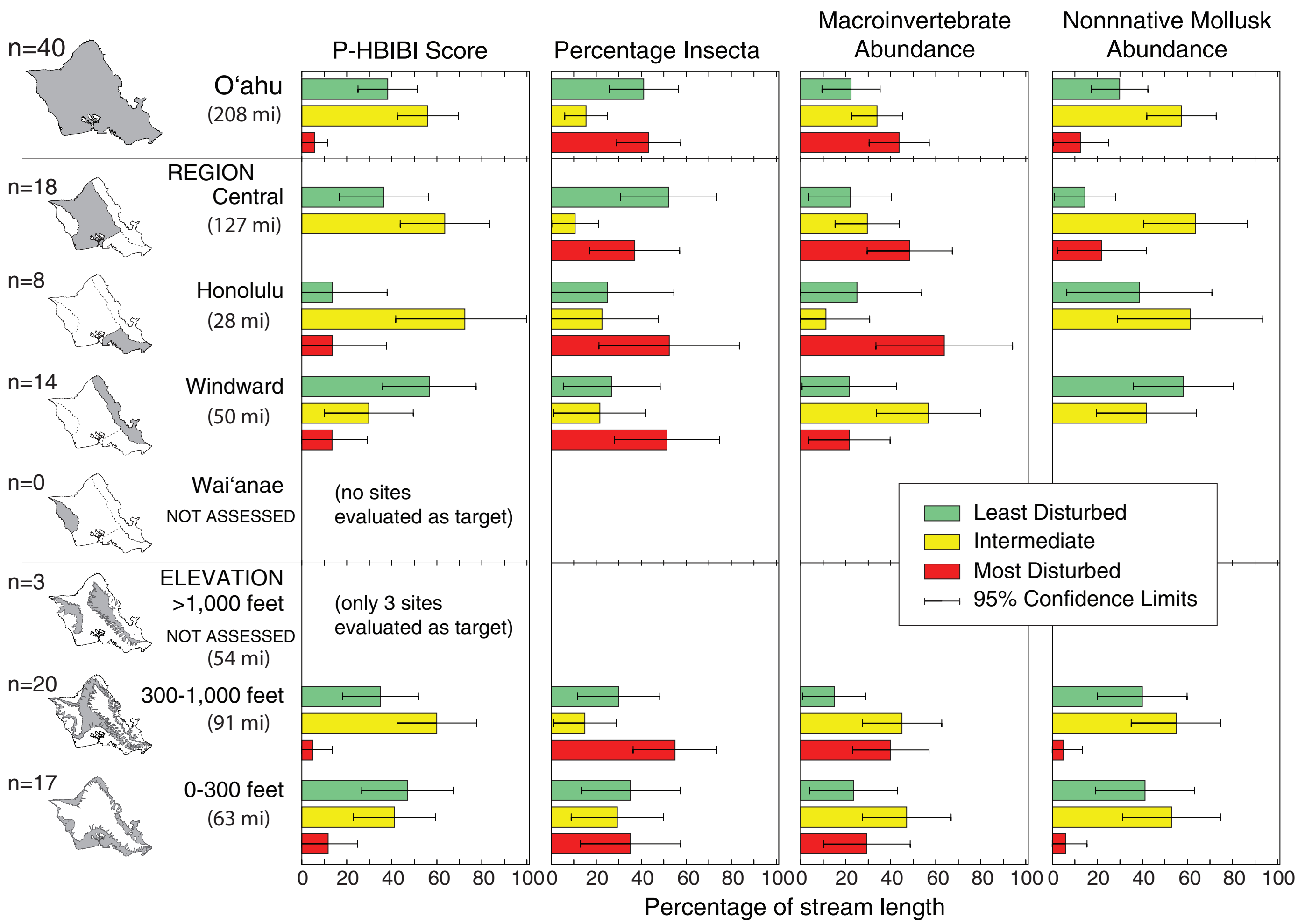

Figure 6. Biological condition of streams based on P-HBIBI scores and associated core metrics. (n, number of sites that were sampled)

least disturbed sites. This metric is a measure of the loss of biodiversity that commonly occurs in response to increases in disturbance of the environment (Hawkins and others, 2000). An O/E value of 1.0 indicates that the site is not different from the reference condition. Values of O/E that are less than 1.0 indicate a loss of biodiversity. However, for O‘ahu, the macroinvertebrate data did not support this metric. The biodiversity, or taxa richness, in benthic macroinvertebrate samples collected on O‘ahu and other Hawaiian Islands has a tendency to increase with increasing disturbance (Wolff, 2005). The majority of taxa collected in these samples, including at the least disturbed sites, are nonnative organisms that have become established and widespread throughout the islands. The once common native benthic macroinvertebrate taxa have been severely disturbed, with reduced populations largely relegated to the most remote areas. The trend for Hawai‘i, in the absence of the sensitive native species, is to see increased numbers of nonnative taxa, especially disturbance-tolerant midges, with increasing levels of disturbance in all but the most disturbed sites, where very few taxa can survive.

Macroinvertebrate P–HBIBI.—This IBI score was used to distinguish least disturbed sites as sites with scores of 14 or less and most disturbed sites as sites with scores greater than 22 as determined by Wolff (2005) (table 4). With respect to the P–HBIBI scores, 5.8 ± 5.8 percent of the stream length on O‘ahu (12.0 mi) was determined to be in the most disturbed condition. The majority of stream length, 56 ± 13.5 percent (116.6 mi), was determined to be in the intermediate condition, while 38 ± 13.2 percent (79.6 mi) was classified as least disturbed (fig. 6). The cumulative distribution plot showed that 95 percent of the stream length on O‘ahu had P-HBIBI scores of less than 22 (fig. B1). The relatively low percentage of islandwide most disturbed condition could be an artifact of the P–HBIBI itself. This macroinvertebrate IBI is in a preliminary stage of development and requires further study. Some of the O‘ahu WSA sites consisted of habitat types, such as concrete channels, nonflowing pools, and (or) low-flowing streams, that were not present at any of the sites used in the development of the P–HBIBI.

The largest proportion of the most disturbed P-HBIBI condition was in the Honolulu region (13.7 ± 24.1 percent; 3.9 mi), followed by windward O‘ahu (13.5 ± 15.7 percent; 6.8 mi). No sites scored in the most disturbed condition in central O‘ahu. The lower elevation range was determined to have the highest proportion (11.8 ± 13.1 percent; 7.5 mi) of the most disturbed condition, followed by the mid-elevation range (5 ± 8.7 percent; 4.5 mi). The median P-HBIBI score for the Honolulu region was 19, with 75 percent of the region's stream length scoring less than 21 (fig. B1). The median windward O‘ahu score was 12.6, with 75 percent of the stream length scoring less than 16. The central region median P-HBIBI score was 14.2, with 95 percent of the stream length scoring less than 21. Ninety percent of the stream length in the lower elevation range scored less than 22, while 95 percent in the mid-elevation range scored less than 22.

Insect Relative Abundance Metric.—One of the core metrics identified in the P–HBIBI was the relative abundance of insects in the quantitative sampling (Wolff, 2005). This metric was used to distinguish least disturbed sites as sites with samples containing greater than 90 percent insects and most disturbed sites as sites with samples containing less than or equal to 75 percent insects, as determined by Wolff (2005) (table 4). This metric does not discriminate between native and nonnative taxa. On O‘ahu, 43.4 ± 14.2 percent (90.3 mi) of the stream length was identified as having less than or equal to 75 percent insects and was classified in the most-disturbed condition (fig. 6). The cumulative distribution showed 50 percent of the wadeable stream length on O‘ahu had less than 83 percent insects (fig. B2). For comparative purposes, the reachwide (RW) sampling method resulted in 50 percent of the stream length having less than 62 percent insects, whereas the Richest Targeted Habitat (RTH) method resulted in 50 percent of the stream length having less than 84 percent insects (figs. B3, B4).

Regionally, using the relative abundance of insects metric, the largest proportion of most disturbed stream length was in the Honolulu region (52.4 ± 31.2 percent; 14.7 mi), followed closely by the windward region (51.4 ± 23.3 percent; 25.8 mi), with the central region at 37.1 ± 20.0 percent (47.2 mi). Fifty percent of the Honolulu stream lengths had less than an estimated 74 percent insects, while 50 percent of the central O‘ahu stream lengths had greater than 89 percent insects (fig B2). The mid-elevation range had the largest proportion of most disturbed stream length (55 ± 18.6 percent; 49.8 mi), with 50 percent of the stream length having estimated percentages of insects of less than 72 percent (fig. B2). The low-elevation range was next with 35 ± 22.2 percent (22.4 mi) of wadeable stream length in the most disturbed condition and half of the stream length estimated at less than 79 percent insects.

Total Macroinvertebrate Abundance Metric.—The P–HBIBI identified total macroinvertebrate abundance as another core metric. This metric did not discriminate between native and nonnative taxa. Sites with less than or equal to 65 individuals/ft^2 (700 individuals/m^2) were classified as most disturbed, and sites with greater than 279 individuals/ft^2 (3,000 individuals/m^2) were classified as least disturbed, as determined by Wolff (2005) (table 4). Roughly 43.7 ± 13.3 percent (91.0 mi) of the stream length on O‘ahu was determined to be in the most disturbed condition (fig. 6). Half of the stream lengths on O‘ahu had less than an estimated 69 individuals/ft^2 (744 individuals/m^2) (fig. B5). Again, for comparative purposes, the RW sampling method resulted in 50 percent of the stream length on O‘ahu having less than 36.2 individuals/ft^2 (390 individuals/m^2), whereas the RTH method resulted in 50 percent of the stream length having equal to or less than an estimated 94 individuals/ft^2 (1,007 individuals/m^2) (figs. B6, B7).

The Honolulu region again had the largest proportion of most disturbed stream length (63.7 ± 30.3 percent; 17.9 mi), with 50 percent of the stream length supporting less than 53 individuals/ft^2 (572 individuals/m^2) (fig. B5). Central O‘ahu results classified 48.4 ± 18.9 percent (61.5 mi) of wadeable stream length in the most disturbed condition, with 50 percent of the central O‘ahu stream length estimated at having less than 65 individuals/ft^2 (700 individuals/m^2). Half of the windward O‘ahu stream lengths had more than 102 individuals/ft^2 (1,099 individuals/m^2), with only 21.6 ± 18.1 percent (10.9 mi) classified as most disturbed. The mid-elevation range had 40 ± 16.9 percent (36.2 mi) of stream length in the most disturbed condition, including 75 percent of the wadeable stream length with less than 131 individuals/ft^2 (1,410 individuals/m^2), whereas the low-elevation range had 29.4 ± 19.2 percent (18.6 mi) of most disturbed stream length, with 75 percent of the wadeable stream length having equal to or less than 252 individuals/ft^2 (2,711 individuals/m^2).

Non-Native Mollusk Abundance Metric.—Another core metric identified in the P–HBIBI was the abundance of nonnative mollusks. Sites with greater than 8 nonnative mollusks/ft^2 (90 nonnative mollusks/m^2) were classified as most disturbed, while sites with no nonnative mollusks were classified as least disturbed, as determined by Wolff (2005) (table 4). Using this criterion, about 12.6 ± 12.3 percent (26.3 mi) of the O‘ahu stream length was determined to be in the most disturbed condition and 50 percent had less than 1 nonnative mollusks/ft^2 (3.5 nonnative mollusks/m^2) (fig. 6 and fig. B8). The Honolulu and windward regions each had no stream length in the most disturbed condition, with 50 percent of the stream length in each region having less than 1 nonnative mollusks/ft^2 (1.4 nonnative mollusks/m^2). The proportion of most disturbed stream length in central O‘ahu was 22 ± 29.7 percent (27.9 mi), and an estimated10 percent of the stream length had more than 9 nonnative mollusks/ft^2 (102 nonnative mollusks/m^2). The low-elevation range had a 5.9 ± 9.6 percent (3.7 mi) proportion of most disturbed stream length, with 50 percent having equal to or less than 1 nonnative mollusks/ft^2 (3.5 nonnative mollusks/m^2). This was followed closely by the mid-elevation range, with a 5 ± 8.5 percent (4.5 mi) proportion of most disturbed stream length and 50 percent having equal to or less than 1 nonnative mollusks/ft^2 (2.3 nonnative mollusks/m^2).

Ecological Stressor Indicators

The assemblages of aquatic biota, including vertebrates and invertebrates, can be affected by chemical, physical, and biological stressors in the environment. Ecological stressors have the potential, when exacerbated, to affect various components of biological communities, especially affecting those

Table 5. Extent of streams adjusted for the 9 sites that were not sampled for macroinvertebrates using the Richest Targeted Habitat sampling methods.

[Numbers in **bold** are the adjusted values; n, number of sites; –, no data; Not Sampled indicates there was no riffle habitat]

Region	Value	Evaluation Category					Total
		Estuarine	Not Sampled but Assessed	Non-Target	Physical Barrier	Sampled and Assessed	
O‘ahu	n	7	**9**	17	15	**31**	79
	extent in miles	26	**67**	71	200	**141**	505
	percent	5.2	**13.3**	14	39.7	**27.9**	100
Central	n	2	**6**	9	8	**12**	37
	extent in miles	8	**58**	41	139	**69**	314
	percent	2.5	**18.3**	13	44.1	**22.1**	100
Honolulu	n	–	**2**	1	2	**6**	11
	extent in miles	–	**7**	3	18	**21**	50
	percent	–	**14.1**	6.4	37.2	**42.3**	100
Windward	n	4	**1**	7	5	**13**	30
	extent in miles	14	**4**	26	43	**46**	133
	percent	10.2	**3.1**	19.4	32.7	**34.6**	100
0–300 ft	n	7	**1**	8	3	**16**	35
	extent in miles	26	**4**	30	11	**60**	130
	percent	20	**2.9**	22.9	8.6	**45.7**	100
300–1,000 ft	n	–	**6**	9	2	**14**	31
	extent in miles	–	**27**	41	9	**63**	140
	percent	–	**19.4**	29	6.5	**45.2**	100
>1,000 ft	n	–	**2**	–	10	**1**	13
	extent in miles	–	**36**	–	180	**18**	234
	percent	–	**15.4**	–	76.9	**7.7**	100

components that are more sensitive to the specific stressor. The impact of potential stressors is related to the magnitude of the stressor in the stream and the sensitivity of the species to the stress. Sensitive species may not be able to survive in certain conditions, while more tolerant species may thrive in the same conditions, or stressors may prevent any species from doing well. Diverse benthic macroinvertebrate assemblages with wide ranges of tolerances, as mentioned earlier, are therefore excellent indicators for the large number of potential stressors and the various levels and degrees of possible stress. We report here on potential water-chemistry and physical-habitat ecological stressors measured in O‘ahu streams.

Water Chemistry

Water quality can affect the biotic integrity of stream macroinvertebrate assemblages. The types and concentrations of chemical stressors related to anthropogenic activities vary within and among O‘ahu streams. The results for four water chemistry parameters are summarized in this section: total phosphorus, total nitrogen, total suspended solids, and sulfate. These parameters were selected because they have been identified in other WSA studies as possible anthropologically derived sources of impacts on water quality in the Nation’s streams. Sulfate is also of interest in Hawaii because it is a constituent of the volcanic fumes that emit into the atmosphere from the active vents on the island of Hawai‘i and are transported by the wind, as a haze known as ’vog,’ and deposited around the State (Heath and Huebert, 1999; Huebert and others, 1999). The threshold criteria for these water quality indicators were derived from the reference condition sites and are provided in table 4. The data for all the water chemistry parameters that were analyzed are presented in CDF format in appendix C.

Total Nitrogen (TN).—Common sources of excess nitrogen include fertilizers, wastewater, animal wastes, and atmospheric deposition. In regard to total nitrogen, approximately 41 ± 13.7 percent (85.6 mi) of the stream length on O‘ahu was classified as most disturbed (fig. 7). Another 38.6 ± 13.5 percent (80.4 mi) was classified as least disturbed. The estimated mean value for O‘ahu streams was 0.18 mg/L, with 75 percent of the stream length having estimated total nitrogen concentrations of less than 0.20 mg/L (fig. C1). The Honolulu region had the largest proportion of most disturbed stream length (61.3 ± 28.6 percent; 17.2 mi), with 10 percent of the stream length having estimated total nitrogen concentrations greater than 0.36 mg/L, followed by central O‘ahu (40.8 ± 20.1 percent; 51.9 mi), with 90 percent of the stream length having estimated total nitrogen concentrations less than 0.30 mg/L, and windward O‘ahu (29.8 ± 22.2 percent; 15.0 mi), with 90 percent of the stream length having estimated total nitrogen concentrations less than or equal to 0.17 mg/L. In terms of elevation, the low-elevation range had the largest proportion of most disturbed stream length (35.3 ± 19.2 percent; 22.4 mi), with 10 percent of the stream length having estimated total nitrogen concentrations greater than 0.40 mg/L, followed by the mid-elevation range (30.0 ± 17.0 percent; 27.2 mi), with 95 percent of the stream length having estimated total nitrogen concentrations less than 0.20 mg/L.

Total Phosphorus (TP).—Phosphorus is a common component of fertilizers and may be associated with agricultural practices, urban runoff, or effluents from sewage. Total phosphorous includes dissolved, particulate, and dissolved orthophosphate forms. In regard to total phosphorus, approximately 43.2 ± 14.0 percent (90.0 mi) of the stream length on O‘ahu was classified as most disturbed (fig. 7). Another 40.1 ± 14.7 percent (83.5 mi) was classified as least disturbed. The estimated mean value for O‘ahu streams was 0.02 mg/L, with 90 percent of the stream length having estimated total phosphorus concentrations of less than 0.04 mg/L (fig. C2). Windward O‘ahu had the largest proportion of most disturbed stream length (78.4 ± 19.5 percent; 39.3 mi), with 50 percent of the wadeable stream length having estimated phosphorous concentrations of less than 0.022 mg/L. The Honolulu region had 72.6 ± 27.4 percent (20.4 mi) of stream length classified as most disturbed, with 10 percent having estimated concentrations greater than 0.15 mg/L. The proportion of most disturbed stream length in central O‘ahu was only 18.9 ± 21.5 percent (24.0 mi), with 95 percent having estimated concentrations less than 0.016 mg/L. Regarding the elevation ranges, the low-elevation range had the largest proportion of most disturbed condition stream length (70.6 ± 13.2 percent; 44.7 mi), followed by the mid-elevation range (30.0 ± 16.6 percent; 27.2 m

Total Suspended Solids (TSS).—TSS includes fine organic and inorganic particulates suspended in the water column. TSS can impair primary productivity and affect fish and invertebrate communities. Islandwide, the proportion of most disturbed condition stream length was approximately 36.1 ± 13.6 percent (75.1 mi) and the least disturbed condition was an estimated 50.9 ± 13.0 percent (106 mi) (fig. 7). The estimated mean TSS concentration for O‘ahu streams was 1.64 mg/L, with a median estimated concentrations of 0.79 mg/L (fig. C3). Regionally, the Honolulu region had the largest proportion of most disturbed condition stream length (86.3 ± 13.7 percent; 24.2 mi), with a median estimated TSS concentration of 2.08 mg/L. An estimated 63.5 ± 18.6 percent (31.8 mi) of windward O‘ahu wadeable stream length was classified as most disturbed, with 50 percent having estimated TSS concentrations less than 0.74 mg/L. Central O‘ahu had the smallest proportion of most disturbed stream length (22.0 ± 21.8 percent; 27.9 mi), with a median value of 0.73 mg/L. In terms of elevation, the low-elevation range had the largest proportion of most disturbed stream length (47.1 ± 18.0 percent; 29.8 mi), with a median estimated TSS concentration of 0.78 mg/L. The proportion of most disturbed stream length in the mid-elevation range was 30.0 ± 13.4 percent (27.2 mi), with a median estimated TSS concentration of 0.73 mg/L.

Sulfate (SO_4^{2-}).—The islandwide proportion of most disturbed stream length was approximately 37.5 ± 10.1 percent (78.1 mi), while the least disturbed condition was 47.0 ± 10.8 percent (97.8 mi) (fig. 7). The estimated mean value for O‘ahu streams was 2.95 mg/L, with 50 percent of the stream length having estimated sulfate concentrations equal to or less than 2.24 mg/L (fig. C4). The Honolulu region again had the largest proportion of most disturbed stream length (86.3 ± 13.7 percent; 24.2 mi), with 50 percent of the stream length having estimated sulfate concentrations less than 5.11 mg/L. Windward O‘ahu had 56.7 ± 21.7 percent (28.5mi) of its stream length classified as most disturbed, with half having estimated concentrations less than 2.88 mg/L. Central O‘ahu had the smallest proportion of most disturbed stream length (15.1 ± 9.1 percent; 19.2 mi), with half having estimated concentrations less than 1.82 mg/L. The proportion of most disturbed stream length in the low-elevation range was 58.8 ± 14.6 percent (37.3 mi), with 50 percent having estimated concentrations less than or equal to 3.18 mg/L. An estimated 45 ± 15.7 percent (40.8 mi) of the mid-elevation range stream length was classified as most disturbed, with 50 percent having estimated concentrations less than 2.61 mg/L.

Physical Habitat

The results for four physical habitat indices are summarized in this section: embeddedness, relative bed stability, riparian vegetative cover, and riparian disturbance. These indices were selected because they have been identified in other WSA studies as good indicators of ecological stress and of human impacts on stream quality. The threshold criteria for these habitat indicators were derived from the reference condition sites and are provided in table 4. The data for these and all the other physical habitat metrics and indices that were calculated are presented in CDF format in appendix D. For more information on how these indices were calculated, please refer to the USEPA reports Quantifying Physical Habitat in Wadeable Streams (Kaufmann and others, 1999) and Environmental Monitoring and Assessment Program (EMAP): Western Streams and Rivers Statistical Summary (Stoddard and others, 2005a).

Embeddedness (xembed).—This metric calculates the areal percentage of the streambed that is embedded by sand and finer particles (Stoddard and others, 2005a).

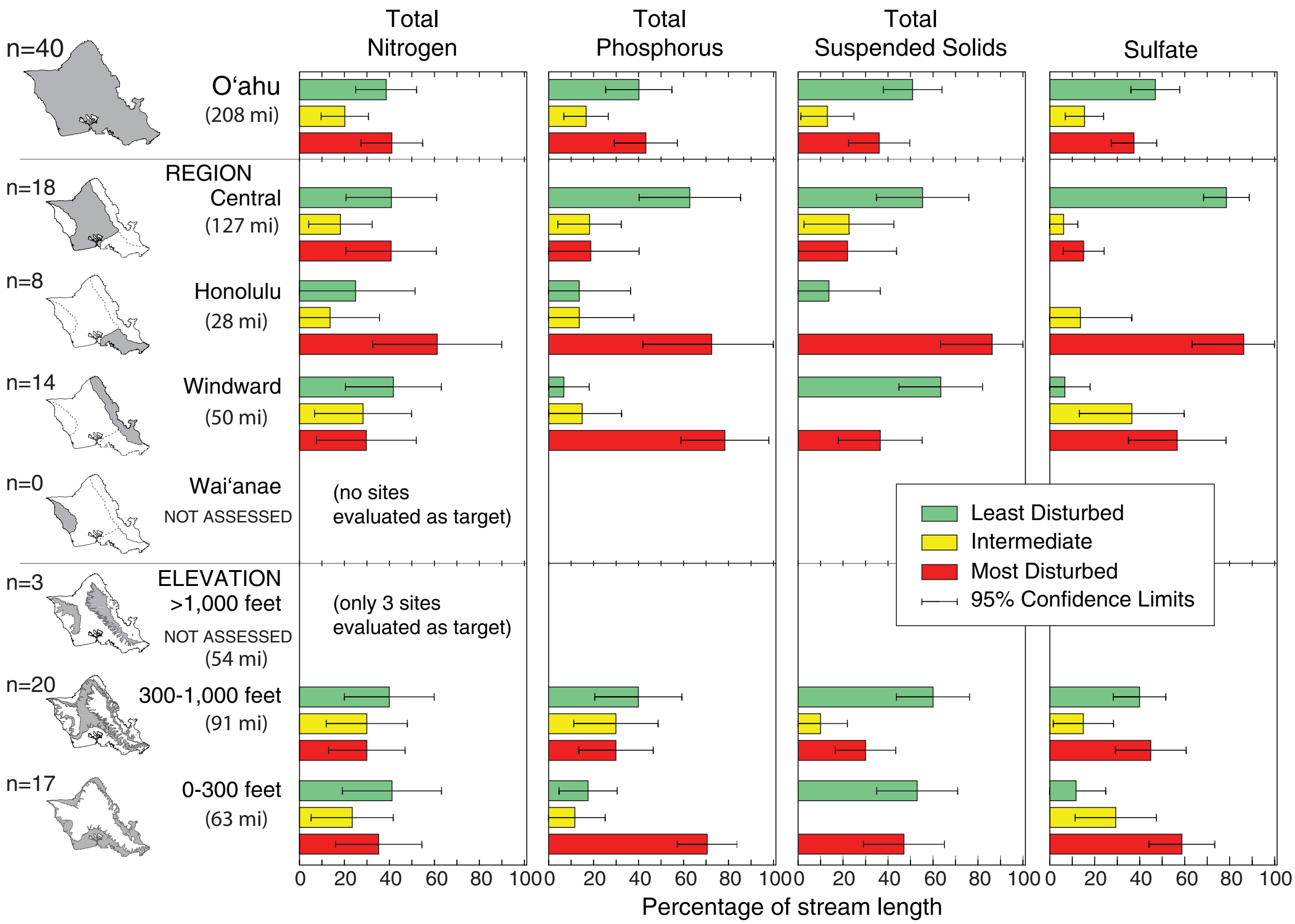

Figure 7. Summary of water quality aquatic indicators of ecological stress. (n, number of sites that were sampled)

Embeddedness refers to the extent to which cobble/boulder substrate is covered by or sunk into sediments on the stream bottom. This sedimentation can be caused by natural erosional processes such as landslides, but is often the result of human or feral pig activities in watersheds. Optimal embeddedness is characterized by limited amounts of sediment in which cobble and boulder substrate are exposed. High embeddedness resulting from excessive sediment erosion can affect habitat availability for aquatic organisms (Lenat and others, 1981; Kaller and Hartman, 2004; Rabeni and others, 2005; Maloney and Feminella, 2006). Threshold values were calculated from the reference condition. The threshold for the most disturbed condition was calculated as >40.2 percent embeddedness and the least disturbed condition threshold was calculated as <35.3 percent embeddedness.

Islandwide, the proportion of most disturbed condition stream length was approximately 30.3 ± 14.7 percent (63.1 mi) and the least disturbed condition was about 50.5 ± 14.3 percent (105.1 mi) (fig. 8). The estimated mean value for O'ahu streams was 34.4 percent, with 50 percent of the stream length having estimated embeddedness equal to or less than 34.4 percent (fig. D1). Regionally, windward O'ahu had the largest proportion of most disturbed stream length (43.3 ± 17.1 percent; 21.7 mi), with 10 percent having estimated embeddedness values greater than or equal to 60.7 percent, followed by central O'ahu (25.8 ± 22.9 percent most disturbed; 32.7 mi), with 50 percent having estimated embeddedness values of less than or equal to 35.5 percent, and the Honolulu region (25.0 ± 28.6 percent most disturbed; 7.0 mi), with half having estimated embeddedness values less than or equal to 25.3 percent. In terms of elevation, the low-elevation range had the largest proportion of most disturbed stream length (35.3 ± 21.6 percent; 22.3 mi), with 10 percent having estimated embeddedness values greater than or equal to 50.2 percent, followed by the mid-elevation range with 25.0 ± 15.3 percent (22.7 mi) most disturbed and 50 percent having estimated embeddedness values of less than or equal to 33.5 percent.

Relative Bed Stability (RBS).—This index evaluates instream habitat stability in relation to sediment load and substrate mobility based on particle size and the size and slope of the stream channel (Stoddard and others, 2005a). It is calculated here as the reachwide geometric mean substrate diameter divided by the bankfull critical (mobile) diameter (see Stoddard and others, 2005a, for more detail) and is expressed using a log transformation, $\log_{10}$(RBS). It basically compares the observed instream particle sizes with the calculated sizes of particles that can be mobilized by the stream (USEPA, 2006b). Larger values indicate greater bed substrate stability and lower sedimentation. Smaller values are indicative of bed substrate instability and more fine sediments than expected. Very large positive values are indicative of bedrock or concrete channels, while large negative values indicate streams with frequently mobile substrates, even during small spates (USEPA, 2006b). Threshold values were calculated from the reference condition sites. The relative bed stability most disturbed condition threshold was calculated as values <-0.92 and the least disturbed condition threshold was calculated as values >-0.57 (table 4).

An estimated 38.2 ± 14.3 percent (79.6 mi) of O‘ahu's stream length was determined as most disturbed, with approximately 52.0 ± 14.3 percent (108.3 mi) classified as least disturbed (fig. 8). Slightly less than 50 percent of the stream length on O‘ahu had estimated relative bed stability values less than the median value of –0.56 (fig. D2). Windward O‘ahu had the largest proportion of the most disturbed condition at 79.8 ± 17.4 percent (40.0 mi), with a median relative bed stability index estimated at –1.00. Central O‘ahu had the largest proportion of least disturbed stream length at 70.4 ± 12.6 percent (89.5 mi), with a median relative bed stability index estimated at –0.37. The Honolulu region had an estimated 50.0 ± 34.6 percent (14.0 mi) of stream length in least disturbed condition and 38.7 ± 33.3 percent (10.9 mi) in most disturbed condition, with a median relative bed stability index of –0.42. Regarding the elevation ranges, the low-elevation range had the largest estimated proportion of most disturbed wadeable stream length at 47.1 ± 18.4 percent (29.8 mi), with a median value of –0.84. The mid-elevation range had an estimated 35 ± 15.7 percent (31.7 mi) of most disturbed stream length and an estimated 55.0 ± 17.3 percent (49.8 mi) of least disturbed stream length, with a median value of –0.48.

Riparian Vegetative Cover (xcmg).—The riparian vegetative cover index is a combined measure of all vegetation types summed over three layers, canopy, mid-layer, and groundcover, giving an indication of the abundance of vegetation cover and its structural complexity (Stoddard and others, 2005a). The maximum value is 3.0, where each of the vegetation layers has 100-percent cover. The most disturbed condition was calculated from the reference condition as riparian vegetation cover values <0.67. The least disturbed condition was calculated as riparian vegetation cover values >0.81. The separate measures of large- and small-diameter trees, woody mid-layer vegetation, and woody ground cover were all visual estimates of areal cover, giving an indication of the longevity and sustainability of perennial vegetation in the riparian corridor (Kaufmann and others, 1999).

An estimated 7.9 ± 6.7 percent (16.5 mi) of the island's stream length was classified as most disturbed. A majority of the stream length was classified as least disturbed condition (83.3 ± 9.6 percent; 173.5 mi) (fig. 8). The estimated mean areal cover for O‘ahu streams was 1.09, with 50 percent of the stream length having estimated riparian vegetative areal cover of less than or equal to 1.05 (fig. D3). In all the regions, the majority of stream length was in the least disturbed condition. Honolulu had the largest proportion of most disturbed stream length at 25.0 ± 28.7 percent (7.0 mi), with 50 percent of wadeable stream length having estimated areal cover less than or equal to 0.96. This is followed by windward O‘ahu at 8.2 ± 13.0 percent (4.1 mi), with 50 percent of wadeable stream length having estimated areal cover less than or equal to 1.18, and central O‘ahu at 3.1 ± 5.1 percent (4.0 mi) with 50 percent of wadeable stream length having estimated areal cover less than or equal to 1.05. The least disturbed condition was the largest proportion, greater than 70 percent, of stream length in each elevation range. The mid- and low-elevation ranges had small proportions of most disturbed stream length of 10.0 ± 11.5 percent (9.1 mi) and 11.8 ± 13.6 percent (7.5 mi), respectively, with 50 percent of wadeable stream length having estimated areal cover less than or equal to 1.09 and 1.15, respectively.

Riparian Disturbance (w1.hall).—This is an index of the proximity-weighted tally of inchannel, riparian, and near-stream human activities (Stoddard and others, 2005a). It is the sum of the proximity-weighted tally of riparian and near-stream anthropogenic influences, including walls, buildings, pavement, roads, pipes, trash, maintained lawns, row crops, pastures, logging, and mining.

Approximately 42.9 ± 13.0 percent (89.3 mi) of stream length on O‘ahu was classified as most disturbed (fig. 8). The estimated mean riparian disturbance index for O‘ahu streams was 1.25, with 50 percent of the stream length having an estimated riparian disturbance index of less than or equal to 0.31 (fig. D4). The largest proportion of wadeable stream length classified as most disturbed condition was in the Honolulu region at 86.3 ± 13.7 percent (24.2 mi), with 50 percent of wadeable stream length having an estimated disturbance index greater than or equal to 4.65. This is followed by windward O‘ahu at 70.2 ± 20.4 percent most disturbed (35.2 mi), with 90 percent of wadeable stream length having an estimated disturbance index less than or equal to 2.67, and by a smaller proportion in central O‘ahu at 18.3 ± 14.4 percent (23.2 mi) most disturbed, with 90 percent of wadeable stream length having an estimated disturbance index less than or equal to 1.08. The low-elevation range had the largest proportion of most disturbed stream length at 76.5 ± 13.5 percent (48.5 mi), with 25 percent of wadeable stream length having an estimated disturbance index greater than or equal to 4.26, followed by the mid-elevation range at 45.0 ± 18.9 percent (40.8 mi) most disturbed, with 10 percent of wadeable stream length having an estimated disturbance index greater than or equal to 3.30.

Relative Extent of Stressors

An islandwide comparison of the relative extent of the most disturbed condition for each ecological stressor shows that the water chemistry constituent total phosphorus was the most widespread stressor with 43.2 ± 14.0 percent (90.0 mi) of stream

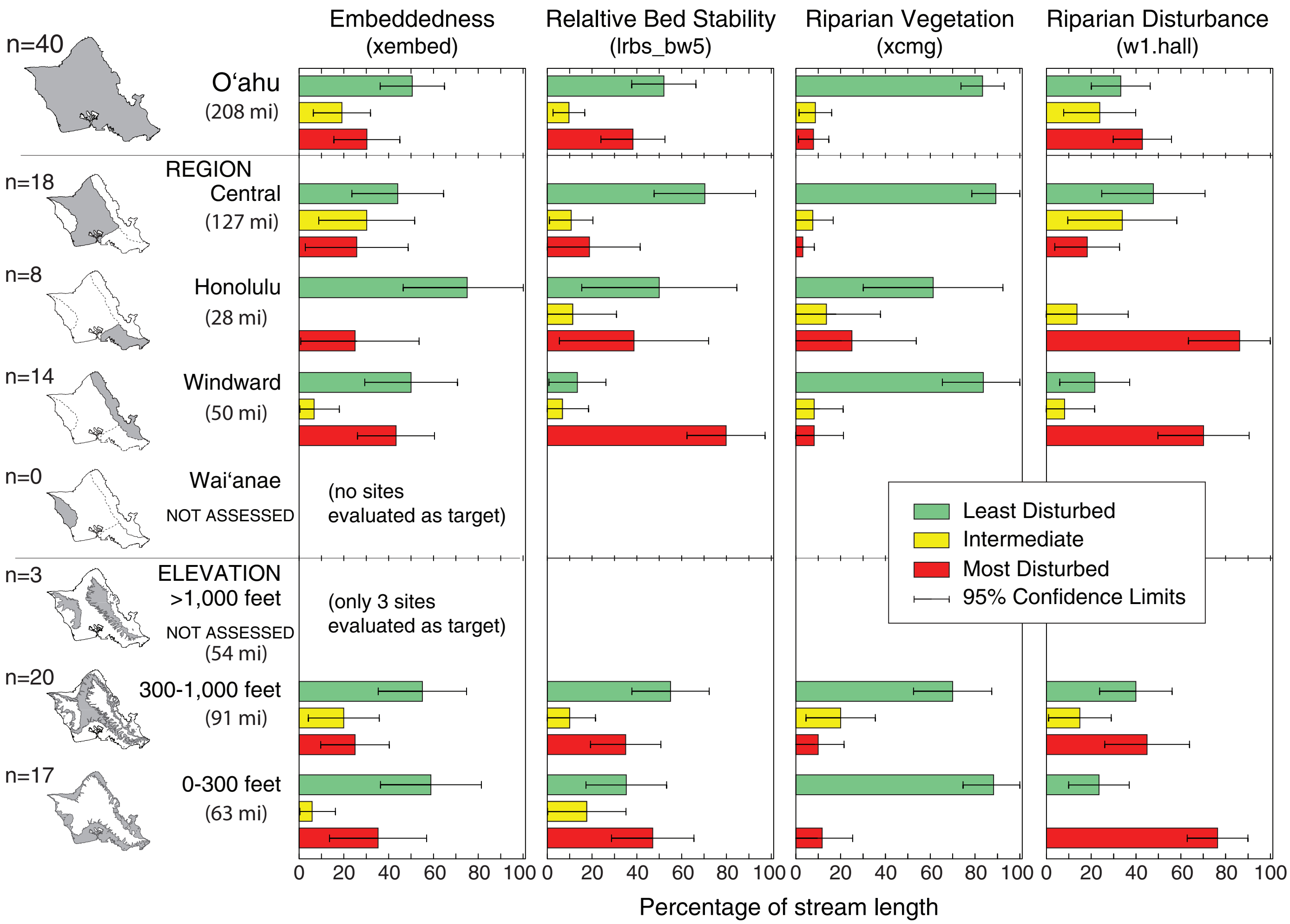

Figure 8. Summary of physical habitat aquatic indicators of ecological stress. (n, number of sites that were sampled)

length in the most disturbed condition (fig. 9). The riparian disturbance index was next with 42.9 ± 13.0 percent (89.3 mi) of stream length, followed by water chemistry constituent total nitrogen with 41 ± 13.7 percent (85.6 mi) of stream length on O‘ahu in the most disturbed condition. These stressors were followed in descending order by the relative bed stability index (38.2 ± 14.3 percent; 79.6 mi), sulfate (37.5 ± 10.1 percent; 78.1 mi) , total suspended solids (36.1 ± 13.6 percent; 75.1 mi), and embeddedness (30.3 ± 14.7 percent; 63.1 mi). The riparian vegetative cover index had the smallest percentage of most disturbed stream length, 7.9 ± 6.7 percent (16.5 mi), on O‘ahu. The 95-percent confidence intervals for the extents of the stressors, except for the riparian vegetative cover index, overlapped considerably, and therefore the extents of these stressor indicators may not be statistically different.

Needs for Additional Information

The study described in this report was the first attempt in the Hawaiian Islands at developing and testing a statistically unbiased, probability-based, subsampling of a larger population of streams so that inferences regarding the ecological conditions can be extrapolated to that larger population. The study was limited to perennial, wadeable streams on the island O‘ahu. The results of this study cannot be extrapolated to streams on the other islands in the State. Additional studies on the other Hawaiian Islands would provide information on the ecological condition of perennial streams on a statewide level. This would be an advantageous tool for determining the current overall condition of streams in Hawai‘i and for gauging the success or failure of actions taken to improve stream conditions in the future.

The number of sites sampled for this pilot study was relatively small, especially in comparison to the number of sites sampled in many of the WSA studies in continental settings. Increasing the number of sampling sites would be required in order to decrease the uncertainty within the 95-percent confidence limits for the estimated extents. More samples (30-50 per region) would also lead to better extrapolation within designated physiographic or elevation regions within each island. In this study, there were no randomly chosen sampling

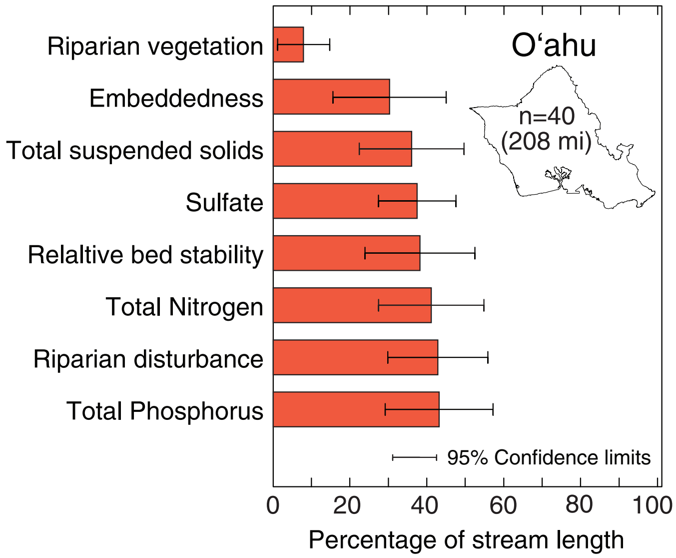

Figure 9. Extent of the ecological stressors' most-disturbed condition on O‘ahu. Based on 40 sites and an estimated 208 miles of perennial, wadeable stream length. (n, number of sites that were sampled)

sites in the Wai‘anae region and only three sites in the upper elevation region. Wai‘anae has fewer perennial stream miles than the other physiographic regions, and consequently there was a lower probability of sites being selected within the region. The upper elevation region, >1,000 ft, had 10 of 13 of sites evaluated as inaccessible, mainly because of the rough and steep terrain. Changes to the sampling design would be necessary to ensure better representation of these regions. One alternative would incorporate an unequal-probability spatially balanced survey design in which the target population is stratified by the subpopulations of interest and site selection is allocated within each stratum (Olsen and Peck, 2008). With the *advance* knowledge that a greater percentage of higher elevation stream reaches are inaccessible, the design would increase the probability of selecting sites in the upper reaches so that the final number of accessible sites would be adequate. This method would provide a sufficient number of sites within the subpopulations of special interest, but might also increase the amount of time that the field crew would spend going to sites that would prove to be inaccessible.

Increasing the number of sampling sites would also facilitate the determination of accurate reference conditions. An increase in the number of randomly selected sampling sites and the use of targeted sites would increase the probability of selecting sites in truly least disturbed areas. A review of previous stream studies conducted in Hawaiian streams, such as the NAWQA program, may also provide data that could be used to establish reference criteria. The limited number of sites within each physiographic and elevation region delineated in this pilot study made it impractical to calculate discrete reference thresholds for each region, resulting in a single set of thresholds for the entire island that may or may not be accurate benchmarks for the different regions. The design phase of any future WSA studies in Hawai‘i needs to address the required number of sites for regional areas and developing reference criteria.

A critical component of the WSA includes analyses of benthic macroinvertebrate data to ascertain the ecological condition of the perennial streams. The ecological condition is derived from elements of the benthic macroinvertebrate assemblages that serve as ecological indicators of stress in the environment. These elements of the assemblages are assessed using metrics or indices such as an Index of Biotic Integrity (IBI). For this study in Hawai‘i, benthic macroinvertebrate assemblages were assessed using the Preliminary Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) and its associated core metrics (Wolff, 2005). This preliminary IBI was developed as part of a previous study investigating the feasibility of using benthic invertebrate metrics as indicators of water quality in Hawai‘i. That study concluded that using benthic invertebrate metrics as indicators of water quality was feasible, but that more research and sampling were required to produce a comprehensive IBI, especially for the islands other than O‘ahu. Currently, the P–HBIBI represents the best available criteria for assessing benthic macroinvertebrate assemblages on O‘ahu and was therefore used in this report to estimate the ecological conditions of streams. More sampling and analyses are required for finalizing the HBIBI for it to be of use for future WSA studies in Hawai‘i. The USGS, in cooperation with the HDOH, is currently conducting a study on Maui to address this issue.

The aquatic vertebrate communities, including fish and amphibians, were not surveyed during this study. Future WSA studies in Hawai‘i would be more comprehensive if they included a sampling plan for these important components of the stream biota. Information on fish assemblages can be extremely important in assessing water and habitat quality. The presence or absence and abundances of the native and nonnative stream fish have been used to rank the quality of the aquatic resources in Hawaiian streams (Hawaii Cooperative Park Service Unit, 1990; Parham and others, 2008). The HDOH Environmental Planning Office (EPO) has used the Hawaii Stream Bioassessment Protocol (Kido, 2002), a multimetric Index of Biotic Integrity (IBI) based on components of the stream-fish communities, in some of their stream assessments (HIDOH, 1998; Burr, 2001, 2003; Henderson, 2003; Paul and others, 2004) and as a tool to help evaluate the attainment of designated and existing native and other aquatic life uses protected by the Clean Water Act and the Water Quality Standards for the 303(d) List of Impaired Waters (Koch and others, 2004; HIDOH, 2006). Additionally, vertebrates such as fish can affect the macroinvertebrate communities by predation. Macroinvertebrates are a main part of the diets of many of the numerous nonnative species of fish and amphibians (Yamamoto and Tagawa, 2000). Various combinations of nonnative vertebrates, with diverse dietary preferences, inhabit many Hawaiian streams, thus having the potential to inflict a wide range of impacts on the invertebrate communities (Heacock and others, 1994; Kido and others, 1999; Englund and others, 2000; Brasher and others, 2006; Parham and others, 2008). The ability for nonnative species to compete with and exclude native species could be seen as a threat to the biological integrity the CWA is intended to protect. Knowledge of the vertebrate communities may provide more insight into the structuring of the invertebrate communities.

The current version of the P-HBIBI calls for macroinvertebrate sampling to be conducted using the RTH (Richest Targeted Habitat) methodology used during the O‘ahu NAWQA program. In this study however, RTH samples could not be collected from seven streams that had only pool habitat and from two streams that were entirely concrete-lined channels. Samples collected using the WSA RW (Reachwide) methods were consequently used in lieu of the RTH samples in the analyses. An HBIBI adaptable to data collected using sampling methods other than the RTH methods, like the RW or similar methods, that can be consistently applied in every wadeable stream reach, would make future WSA studies in Hawai‘i more complete.

One of the findings of this study was that approximately 19 percent of the stream lengths designated as perennial streams on the NHD stream coverage were incorrectly designated. Approximately 5.2 ± 3.1 percent (7 random sites), or roughly 26 miles of stream were determined to be estuaries and 14 ± 5.5 percent (17 random sites), or roughly 71 miles of stream, were either dry during the site visit or no longer existed as streams. Olsen and Peck (2008) found coding errors while conducting probabilistic studies on the continental United States consisting of nonperennial streams miscoded as perennial and vice versa. It would be advantageous to users of the vector digital NHD stream coverage if an effort was made to revise and update this dataset. For future probabilistic stream studies in Hawai‘i, it may be more practical to use stream coverages developed at the local or State level. State agencies, including the HDOH and the Hawai‘i Department of Land and Natural Resources (DNLR), have developed their own digital stream coverages incorporating local knowledge and experience to increase the attribute coding accuracy. Incorrect designations can affect regulatory agencies, such as the HDOH, who manage perennial streams differently from nonperennial streams, for example, in regards to permitting.

Summary and Conclusions

In cooperation with the HDOH and the USEPA, the USGS conducted a pilot study to assess the effectiveness of the USEPA’s national WSA program for perennial streams in Hawai‘i. The goals of this study were to assess the WSA methodologies and to assess the ecological condition of wadeable perennial streams on O‘ahu using components of the benthic macroinvertebrate assemblages and potential ecological stressors associated with water chemistry and physical habitat. The information provided by this pilot study will allow the HDOH and the USEPA, as well as other local, State, and Federal agencies to assess the utility and effectiveness of the WSA as a tool to help evaluate their efforts in trying to meet the mandates of the CWA.

A probabilistic sampling design was used to randomly select 40 sampling sites on perennial, wadeable streams on the island of O‘ahu, Hawai‘i. The USEPA NHEERL was provided with an NHD vector digital dataset of perennial streams on O‘ahu and produced a list of 150 random stream sites (latitude and longitude coordinates) and a list of 150 random oversample sites. A total of 79 possible sites were investigated to obtain the final 40 targeted sites. Sites were eliminated from consideration for reasons of the stream reaches being nonperennial, nonexistent, estuarine, or physically inaccessible and replaced by sites from the oversample list of sites. The fieldwork was conducted over a 2-year period, 2006–07, with 20 sites sampled in each year. Sampling in 2006 began in late April and ran through July. Sampling in 2007 began in mid-May and ran through mid-August. WSA protocols were closely adhered to in the collection of physical habitat characteristics, benthic macroinvertebrates, and water-quality samples at each targeted site.

An analysis of the original sampling frame of streams from the NHD vector digital stream GIS coverage determined that there were approximately 505.2 miles of perennial stream length on the island of O‘ahu. Because of miscoded attributes in the GIS coverage and changes in streamflow over time, an estimated 96.7 miles of the original sample frame were determined to be nonperennial. Another 200.5 miles were not physically accessible because of dangerously steep terrain or impenetrable thickets of intertwined branches of the indigenous Hau tree (*Hibiscus tiliaceus*). The final extent of the stream length on O‘ahu that was assessed was approximately 208 miles, 41 percent of the original sample frame. Areas that were not physically accessible expose gaps in the data for these locations and habitats, especially at higher elevations (>1,000 ft), where 10 of the 13 higher elevation sites considered for sampling were designated as inaccessible. Additionally, no sample sites were selected in the perennial streams in Wai‘anae. This was an artifact of the random sampling process. Future WSA studies in Hawai‘i would be more comprehensive by increasing the likelihood of selecting *accessible* and *sampleable* sites in the higher elevations, the Wai‘anae region, and other underrepresented areas of interest.

The relative extents (percentages of stream length) affected by the potential chemical and physical habitat stressors were derived from comparisons to threshold (benchmark) values established from reference *least disturbed* sites. The 10 sites selected as reference sites were screened using both a consensus-based best professional judgment method and a criteria-based evaluation of water chemistry and physical habitat parameters. Thresholds for the benthic macroinvertebrate analysis were taken from the Preliminary Hawaiian Benthic Index of Biotic Integrity (P–HBIBI) and its associated core metrics (Wolff, 2005). This preliminary IBI was developed as part of a study investigating whether it was possible to use benthic invertebrate metrics as indicators of water quality in Hawai‘i. Although it is still in development, the P–HBIBI represents the best available criteria for assessing benthic macroinvertebrate assemblages on O‘ahu.

Based on the P–HBIBI scores, the ecological condition of most of O‘ahu’s streams were classified as least disturbed

(38.2 ± 13.2 percent; 79.6 mi) or intermediate (56 ± 13.5 percent; 116.6 mi), with only 5.8 ± 5.8 percent (12 mi) of the island’s stream length classified as most disturbed. A different trend was observed using the core metric Insect Relative Abundance, with an estimated 43.4 ± 14.2 percent (90.3 mi) of the stream lengths on O‘ahu classified as most disturbed. A similar trend was observed using the core metric Total Macroinvertebrate Abundance scores, with an estimated 43.7 ± 13.3 percent (91 mi) of O‘ahu stream lengths classified as most disturbed and only 22.4 ± 12.9 percent (46.6 mi) classified as least disturbed. The Non-native Mollusk Abundance metric scores estimated that about 12.6 ± 12.3 percent (26.3 mi) of O‘ahu stream length was most disturbed. The highly urbanized Honolulu region was the most impaired region, with P–HBIBI scores classifying 13.7 ± 24.1 percent (3.9 mi) as most disturbed, Insect Relative Abundance metric scores classifying 52.4 ± 31.2 percent (14.7 mi) as most disturbed, and Total Macroinvertebrate Abundance metric scores classifying 63.7 ± 30.3 percent (17.9 mi) as most disturbed. None of the stream length in the Honolulu region was classified as most disturbed using the Non-native Mollusk Abundance metric. The ecological conditions of windward O‘ahu streams were similar to those of Honolulu streams, with P–HBIBI scores classifying 13.5 ± 15.7 percent (6.7 mi) as most disturbed, Insect Relative Abundance metric scores classifying 51.4± 23.3 percent (25.8 mi) as most disturbed, and Total Macroinvertebrate Abundance metric scores classifying 21.6 ± 18.1 percent (10.8 mi) as most disturbed. None of the stream length in the Wai‘anae region was classified as most disturbed using the Non-native Mollusk Abundance metric. The overall ecological condition of streams in the central O‘ahu region was quite different, with no stream length classified as most disturbed using the P–HBIBI scores. However, 37.1 ± 20 percent (47.1 mi) were classified as most disturbed with the Insect Relative Abundance metric and 48.4 ± 18.9 percent (61.5 mi) using the Total Macroinvertebrate Abundance metric. All of the Non-native Mollusk Abundance metric most disturbed stream length, 22 ± 19.7 percent (28 mi), was in the central O‘ahu region. It was not possible to estimate the ecological condition of the higher elevation range (> 1,000 ft) because of a lack of sites. The P–HBIBI scores classified 5 ± 8.7 percent (4.5 mi) of the mid-elevation range (300–1,000 ft) and 11.8 ± 13.1 percent (7.5 mi) of the low-elevation range (0–300 ft) as most disturbed.

Aquatic indicators of stress that have been recognized as widespread throughout the Nation include elevated levels of nitrogen and phosphorus, riparian disturbance, and excess streambed sediments. Islandwide, 41.1 ± 13.7 percent (85.6 mi) of the stream length was classified as most disturbed for concentrations of total nitrogen and 43.2 ± 14 percent (90 mi) for concentrations of total phosphorus as compared to the *least disturbed* reference condition. An estimated 42.9 ± 13 percent (89.3 mi) of O‘ahu stream length was classified as most disturbed for riparian disturbance (human alterations in and around the riparian zone), 30.3 ± 14.7 percent (63.1 mi) was classified as most disturbed for embeddedness, and 38.2 ± 14.3 (79.6 mi) was classified as most disturbed for relative bed stability.

The information in this report is the first attempt in Hawai‘i to assess the islandwide ecological condition of wadeable, perennial streams on O‘ahu using the USEPA WSA probabilistic design. This study has demonstrated that such an assessment is practical and that it can provide the information necessary to assess the current baseline ecological condition. It can then be used, with future WSA studies, to measure the positive or negative changes in the those conditions and the effectiveness of management efforts to protect, restore, and maintain Hawai‘i’s aquatic environment.

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Glossary

anthropogenic A condition that is the result of, or is influenced by, human activity.

base-sample sites The list of spatially balanced, randomly selected sites, from the sample frame, that need to be evaluated with the criteria defined by the target population.

benthic Refers to plants or animals that live on the bottom of lakes, streams, or oceans.

ecological indicator A characteristic of an ecosystem that is related to, or derived from, a measure of biotic or abiotic attributes that can provide quantitative information on ecological condition, structure and function.

Generalized Random Tessellation Stratified Design (GRTS) A statistical method for creating a spatially balanced random sample of sites from a geographic area.

intermittent stream A stream that flows only when it receives water from rainfall runoff or springs, or from some surface source such as melting snow.

multi-density categories Subpopulations (categories) within the target population with unequal weights (unequal probability of selection), i.e., physiographic regions of O‘ahu.

non-target sites Sites that appear appropriate during the selection process that, after evaluation, do not meet the criteria for inclusion in the target population, i.e. nonperennial streams that were misidentified as perennial streams in the sample frame.

oversample sites A substitute list of spatially balanced, randomly selected sites available for use whenever a base-sample site cannot be sampled.

perennial streams Waters draining land surfaces in discrete channels and flowing year-round.

physical barrier The evaluation category for sites that met the criteria defined by the target population but were not sampled because of being physically inaccessible (that is, located on a dangerously steep slope).

probability sample A sample where every element of the target population has a known, nonzero probability of being selected.

proximity-weighted Weights assigned according to the nearness of the observation to the stream: 1.5 for observations within the channel or on the stream bank, 1.0 for observations within the riparian sample plots, and 0.667 for those behind or adjacent to the plots.

reach A continuous part of a stream between two specified points along its length.

relative abundance The number of organisms of a particular kind present in a sample relative to the total number of organisms in the sample.

riparian Areas adjacent to rivers and streams with a high density, diversity, and productivity of plant and animal species relative to nearby uplands.

sample frame A geographical information system (GIS) representation of the target population that provides the basis for the selection of distinct sampling sites.

sampled population The portion of the target population represented in the final set of sites that were actually sampled, that is, the 40 sites that were actually sampled on O‘ahu.

subpopulation A subset of the target population that has been identified for a specific purpose; usually requires the ability to estimate an attribute of the subpopulation (for example, elevation categories of O‘ahu).

target not sampled Sites that met the criteria defined by the target population but were not sampled for some reason.

target population The explicitly and precisely defined component of the aquatic resource to be assessed, that is, all the wadeable perennial stream lengths on O‘ahu.

targeted sampling The sampling of sites that are purposely selected, as opposed to randomly selected, to achieve the specific objectives of a study (for example, targeting sites believed to be contaminated).

thalweg The line formed by connecting the points of the deepest parts of the stream channel.

unequal probability When subpopulations of a target population are selected to have a greater sampling effort, that is, more sampling sites, than other subpopulations of the target population.

wadeable Sections of a stream where a person can safely walk into the water from one end of the sampling reach to the other and conduct the WSA protocols.

Appendix A. List of Targeted Sampling Sites

Table A1. List of Targeted Sample sites.

[Dates in parentheses ( ) are when invertebrate and water quality samples were collected; DAR Code, Hawai'i State Division of Aquatic Resources code for segments and tributaries of perennial streams; mi, miles; ft, feet; latitude in decimal degrees N; longitude in decimal degrees W; North American Datum of 1983 (NAD 83)]

Site ID	Latitude	Longitude	DAR Code	Region	Multi-Density Categories (ft)	Sample	Initial Weight (mi)	Adjusted Weight (mi)	Sample Date(s)
HIO05518-002	21.3224	-157.8475	33009008	Honolulu	0–300	Base sample	2.271	3.728	4/17/06 (6/1/06)
HIO05518-003	21.40578	-157.8608	34002006	Central	300–1,000	Base sample	2.51	4.53	6/14/06
HIO05518-005[1]	21.52694	-157.9968	36006137	Central	> 1,000	Base sample	7.2	18.02	7/18/06
HIO05518-010[2]	21.4966	-157.9574	36006106	Central	300–1,000	Base sample	2.51	4.53	7/16/07
HIO05518-011	21.48146	-157.847	32004001	Windward	0–300	Base sample	2.271	3.728	5/30/06
HIO05518-013[2]	21.6304	-158.0398	36010020	Central	0–300	Base sample	2.271	3.728	6/26/06
HIO05518-018	21.34521	-157.8659	33011003	Honolulu	0–300	Base sample	2.271	3.728	5/9/06 (6/5/06)
HIO05518-023[2]	21.5214	-157.9086	31018029	Windward	300–1,000	Base sample	2.51	4.53	7/24/06
HIO05518-0251	21.53909	-158.0056	36007024	Central	300–1,000	Base sample	2.51	4.53	7/17/06
HIO05518-026[2]	21.47376	-157.9341	34010071	Central	300–1,000	Base sample	2.51	4.53	6/20/07
HIO05518-027	21.49428	-157.8525	32002003	Windward	0–300	Base sample	2.271	3.728	5/16/06
HIO05518-029[2]	21.62643	-158.0208	36010021	Central	300–1,000	Base sample	2.51	4.53	6/28/06
HIO05518-034[1]	21.33389	-157.8347	33009008	Honolulu	300–1,000	Base sample	2.51	4.53	4/26/06 (5/23/06)
HIO05518-035	21.41813	-157.8248	32008004	Windward	0–300	Base sample	2.271	3.728	5/21/07
HIO05518-037	21.59142	-158.0831	36008004	Central	0–300	Base sample	2.271	3.728	5/15/07
HIO05518-038[2]	21.48895	-157.9773	36006104	Central	300–1,000	Base sample	2.51	4.53	7/2/07
HIO05518-039	21.50412	-157.8771	32002011	Windward	300–1,000	Base sample	2.51	4.53	8/8/07
HIO05518-151[2]	21.52727	-157.8965	31018028	Windward	0–300	Oversample	2.271	3.728	7/11/06
HIO05518-153[1,2]	21.56276	-158.0142	36007035	Central	300–1,000	Oversample	2.51	4.53	7/26/06
HIO05518-155[1]	21.2898	-157.8043	33007003	Honolulu	0–300	Oversample	2.271	3.728	4/24/06 (5/24/06)
HIO05518-158[1]	21.3958	-157.8854	34002006	Central	300–1,000	Oversample	2.51	4.53	6/13/06
HIO05518-159[1]	21.34209	-157.7709	32013038	Windward	300–1,000	Oversample	2.51	4.53	7/9/07
HIO05518-160	21.53484	-157.8887	31018024	Windward	0–300	Oversample	2.271	3.728	7/10/06
HIO05518-162	21.36652	-157.8384	33011005	Honolulu	300–1,000	Oversample	2.51	4.53	5/9/06 (6/5/06)
HIO05518-163	21.43688	-157.8376	32007015	Windward	0–300	Oversample	2.271	3.728	5/22/06
HIO05518-164	21.38387	-157.7963	32010033	Windward	0–300	Oversample	2.271	3.728	5/15/06
HIO05518-166[2]	21.46874	-157.9526	34010065	Central	300–1,000	Oversample	2.51	4.53	5/29/07
HIO05518-168[1]	21.57002	-157.9869	36008011	Central	> 1,000	Oversample	7.2	18.02	6/11/07
HIO05518-171	21.32695	-157.8007	33007008	Honolulu	0–300	Oversample	2.271	3.728	5/1/06 (5/24/06)
HIO05518-174[1]	21.43601	-157.9013	34006022	Central	300–1,000	Oversample	2.51	4.53	7/10/07
HIO05518-175	21.36953	-157.7733	32013018	Windward	0–300	Oversample	2.271	3.728	7/25/07
HIO05518-177	21.49056	-157.9988	36006096	Central	300–1,000	Oversample	2.51	4.53	6/25/07
HIO05518-181	21.58733	-158.0574	36008006	Central	0–300	Oversample	2.271	3.728	8/6/07
HIO05518-182	21.51305	-157.9786	36006076	Central	300–1,000	Oversample	2.51	4.53	6/13/07
HIO05518-183	21.48043	-157.8566	32004001	Windward	0–300	Oversample	2.271	3.728	7/24/07
HIO05518-186[2]	21.51602	-157.9451	36006088	Central	> 1,000	Oversample	7.2	18.02	7/30/07
HIO05518-187	21.35082	-157.8083	33009014	Honolulu	300–1,000	Oversample	2.51	4.53	6/26/07
HIO05518-191	21.34022	-157.7507	32015013	Windward	300–1,000	Oversample	2.51	4.53	8/13/07
HIO05518-194	21.33034	-157.8303	33009002	Honolulu	300–1,000	Oversample	2.51	4.53	7/31/07
HIO05518-203	21.50826	-157.857	32001001	Windward	0–300	Oversample	2.271	3.728	8/14/07

[1]No Richest Targeted Habitat macroinvertebrate samples were collected

[2]Sites used to develop thresholds for chemistry and physical habitat variables

Appendix B.
Cumulative Distribution Functions for Macroinvertebrate Data

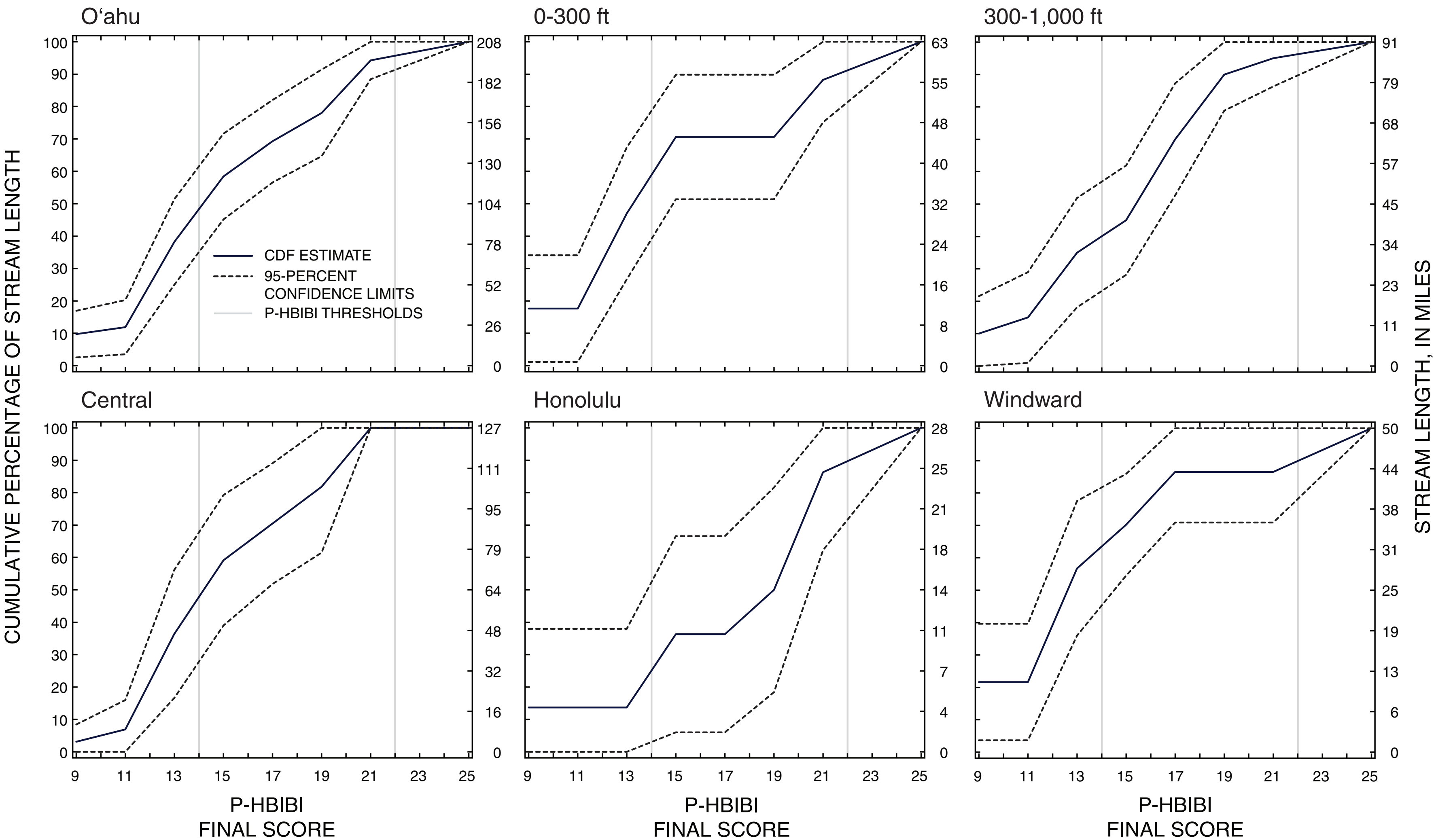

Figure B1. Cumulative distribution function plots of final Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) score. Reachwide samples were used where no targeted riffle habitat samples were collected. P-HBIBI thresholds taken from Wolff (2005).

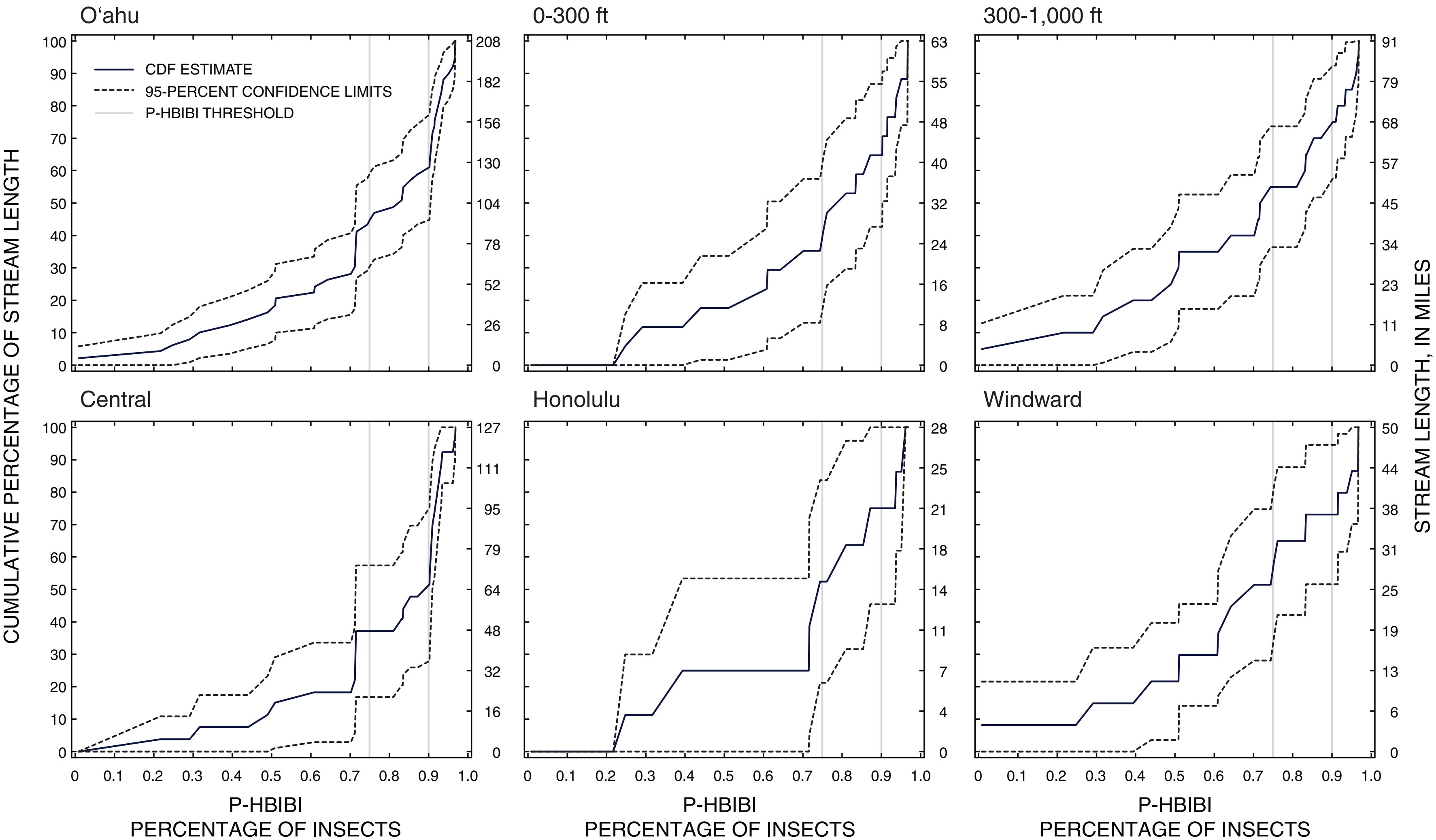

Figure B2. Cumulative distribution function plots of the relative abundance of insects metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI). Reachwide samples were used where no targeted riffle habitat samples were collected. P-HBIBI thresholds taken from Wolff (2005).

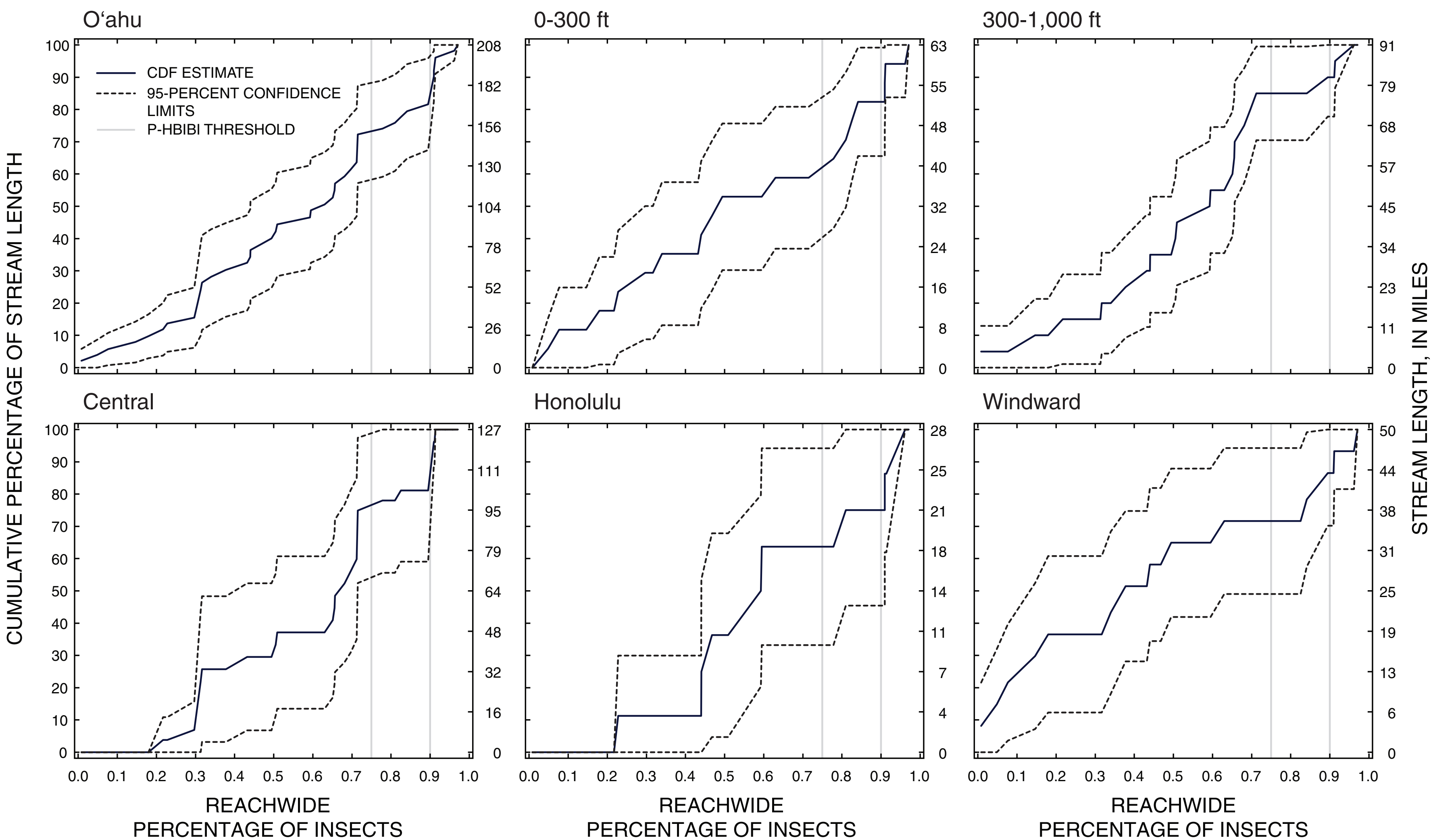

Figure B3. Cumulative distribution function plots of the relative abundance of insects metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) for reachwide samples. P-HBIBI thresholds taken from Wolff (2005).

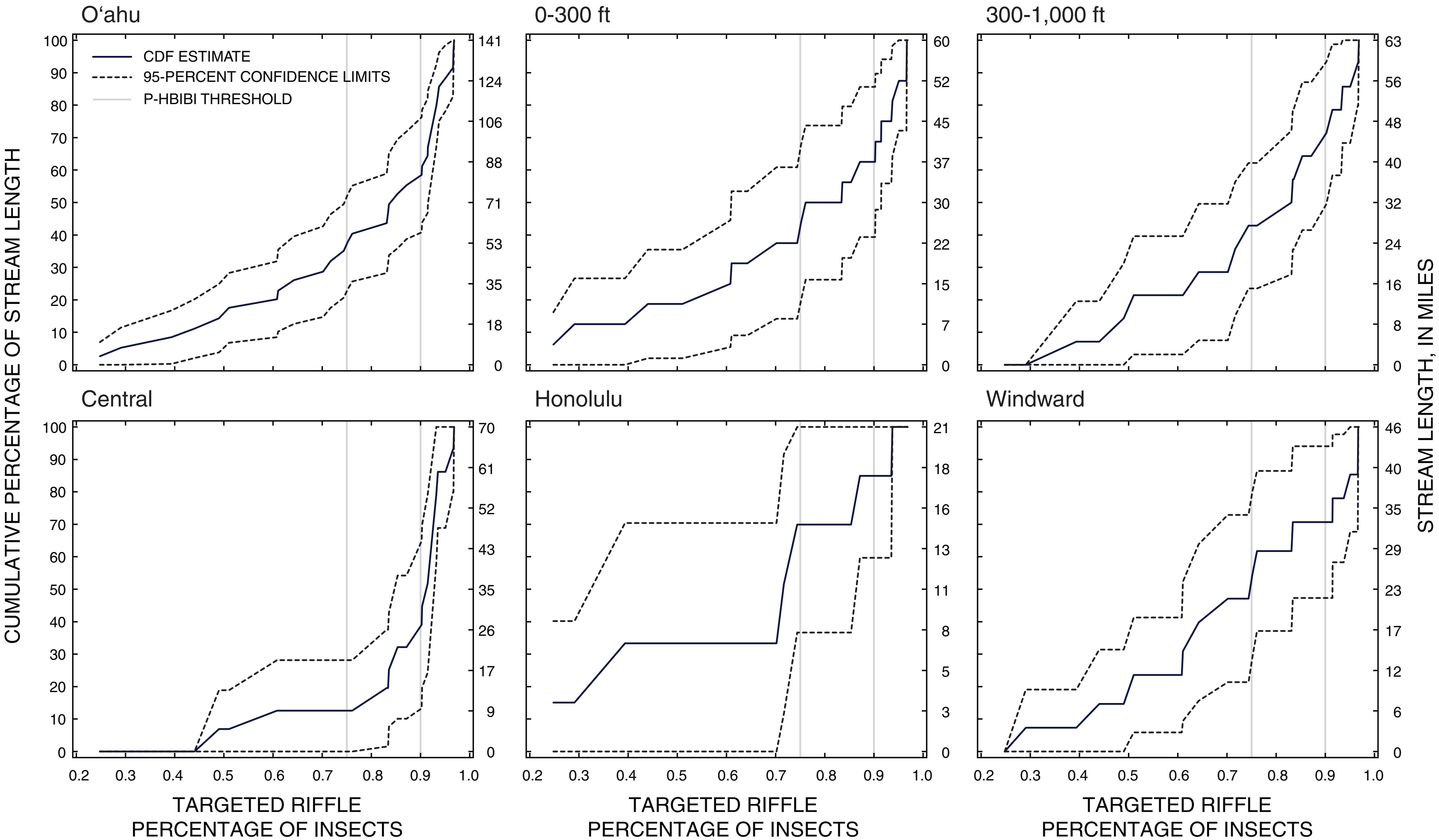

Figure B4. Cumulative distribution function plots of the relative abundance of insects metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) for targeted riffle habitat samples. P-HBIBI thresholds taken from Wolff (2005).

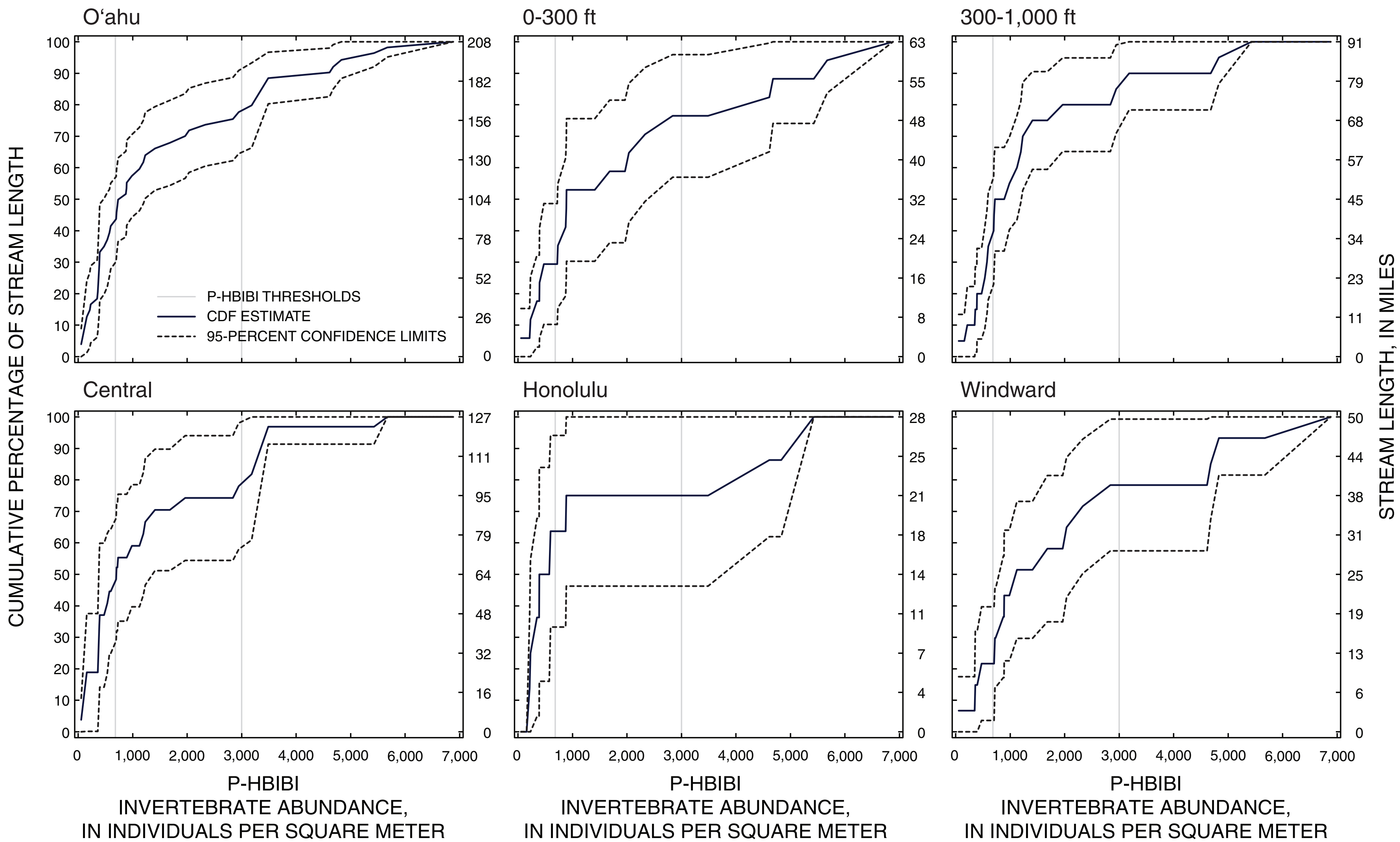

Figure B5. Cumulative distribution function plots of invertebrate abundance metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI). Reachwide samples were used where no targeted riffle habitat samples were collected. P-HBIBI thresholds taken from Wolff (2005).

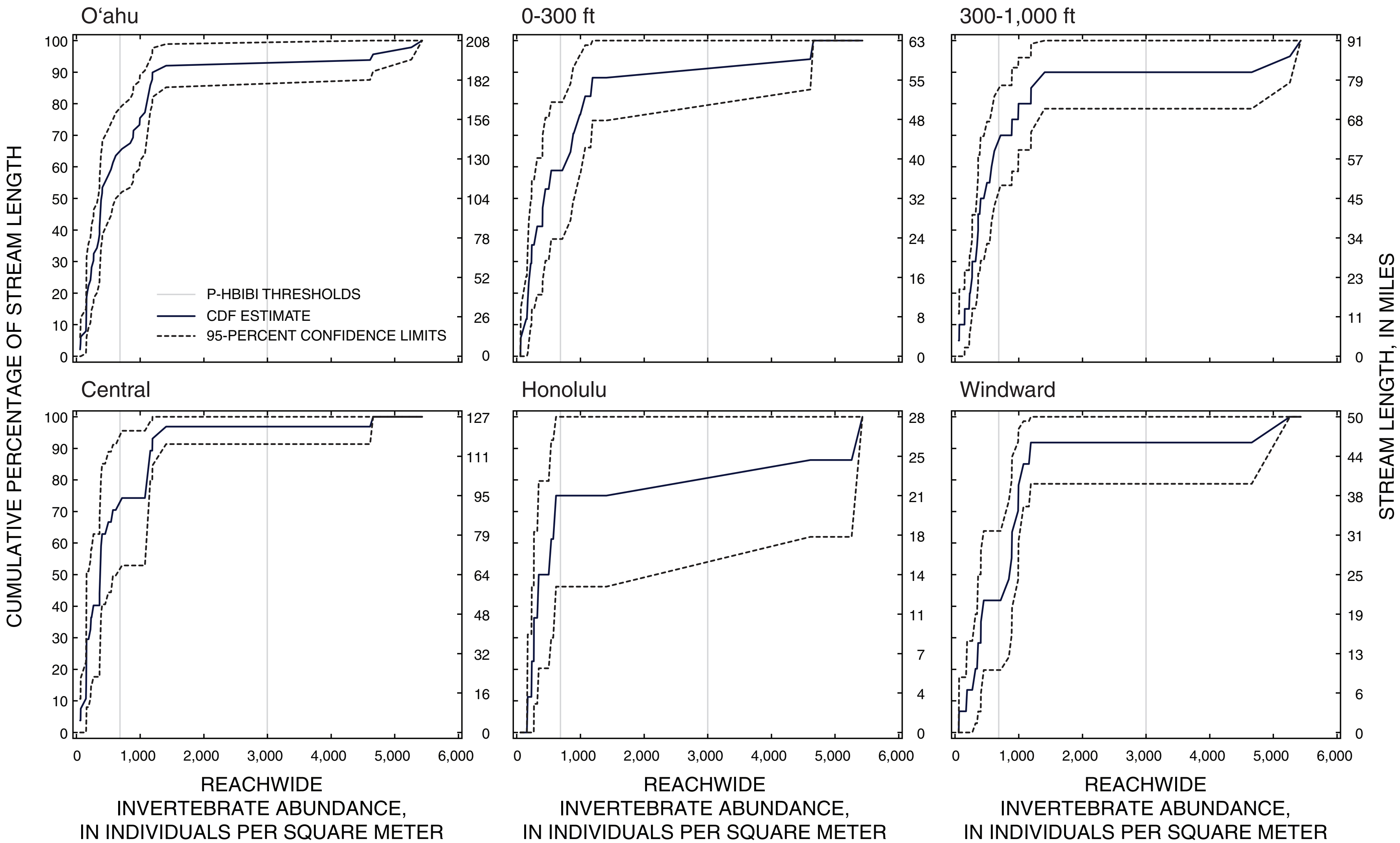

Figure B6. Cumulative distribution function plots of invertebrate abundance metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) for reachwide samples. P-HBIBI thresholds taken from Wolff (2005).

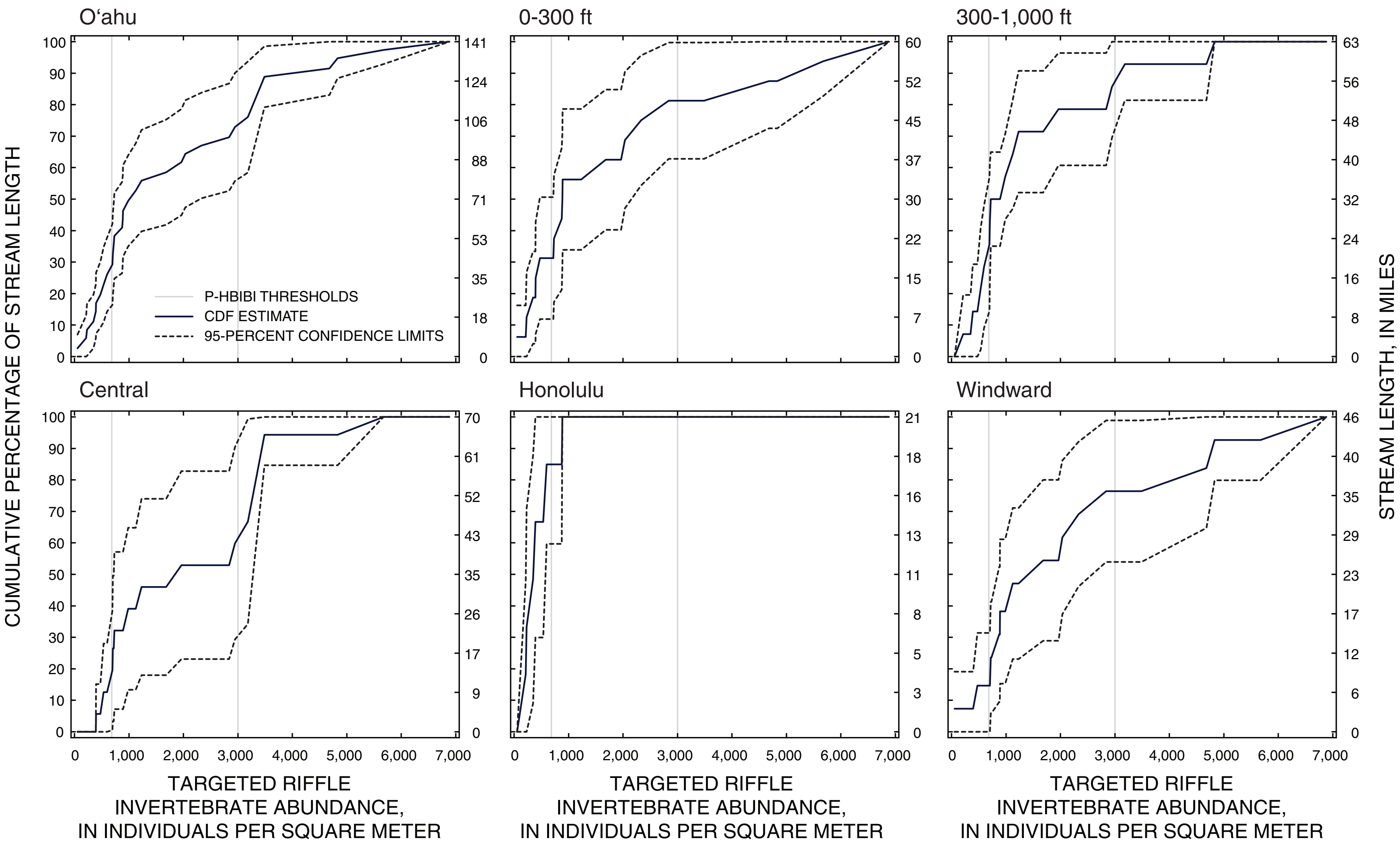

Figure B7. Cumulative distribution function plots of invertebrate abundance metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI) for targeted riffle habitat samples. P-HBIBI thresholds taken from Wolff (2005).

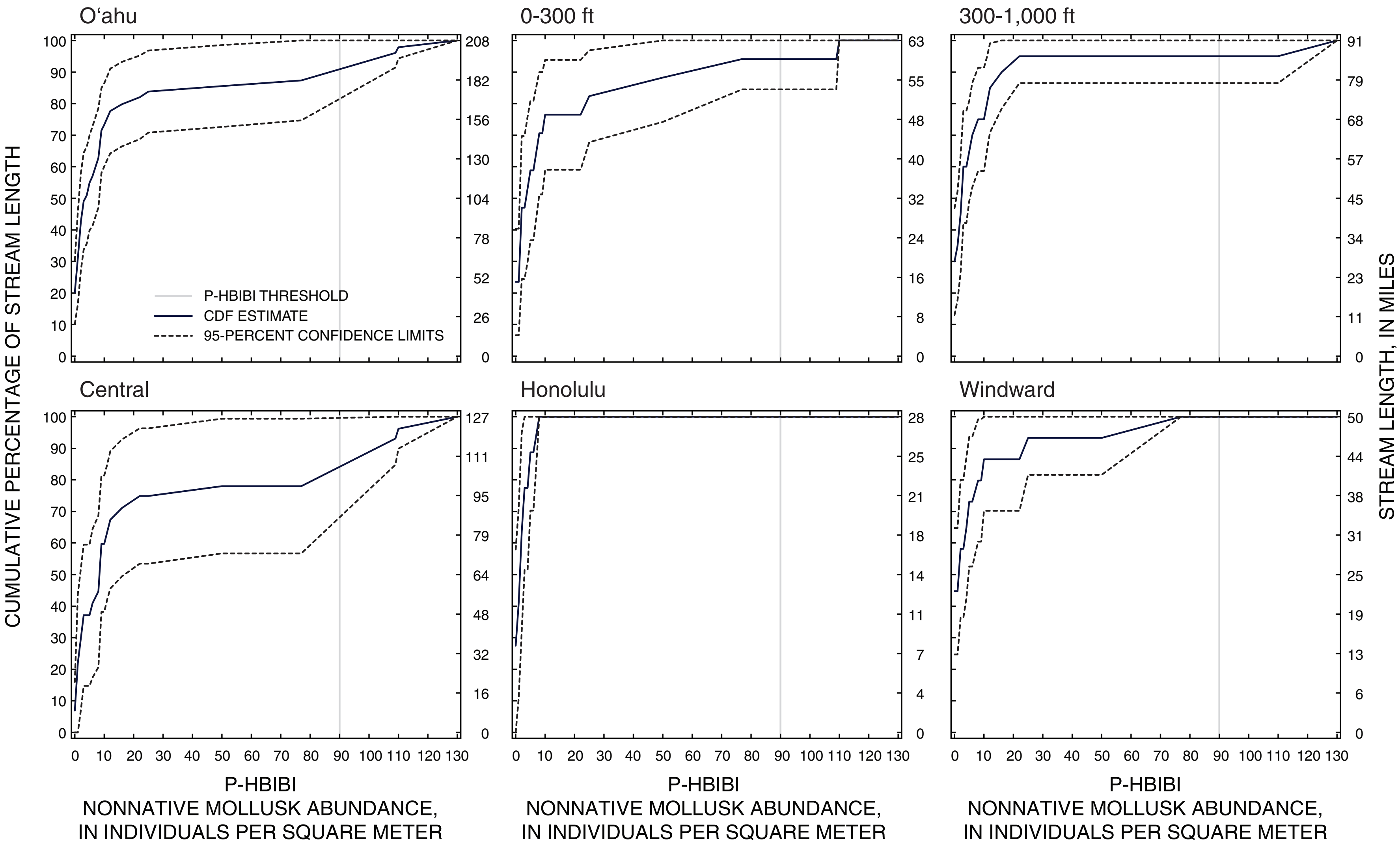

Figure B8. Cumulative distribution function plots of nonnative mollusk abundance metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI). Reachwide samples were used where no targeted riffle habitat samples were collected. P-HBIBI thresholds taken from Wolff (2005).

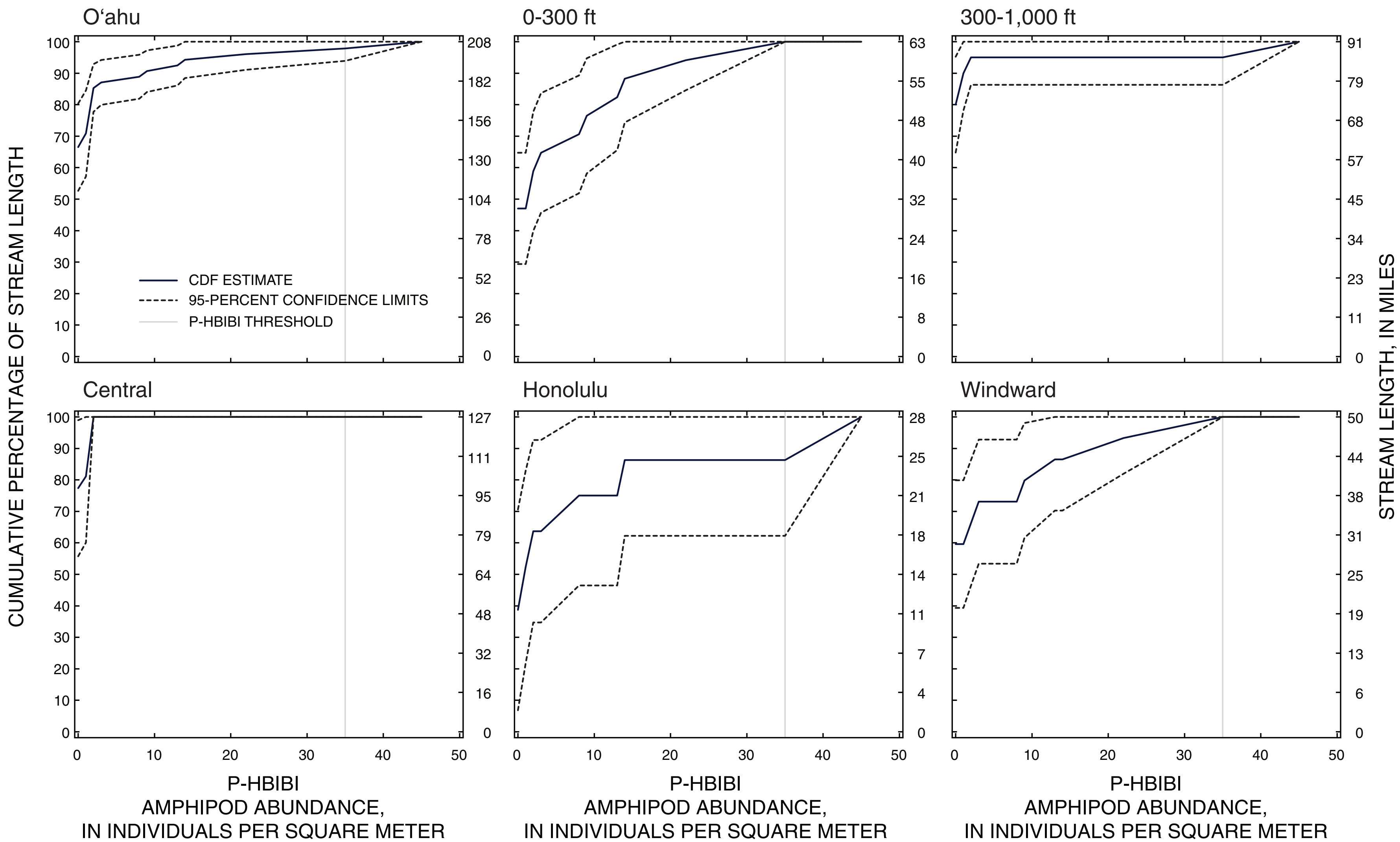

Figure B9. Cumulative distribution function plots of amphipod abundance metric used in the Preliminary-Hawaiian Benthic Index of Biotic Integrity (P-HBIBI). Reachwide samples were used where no targeted riffle habitat samples were collected. P-HBIBI thresholds taken from Wolff (2005).

Appendix C.
Cumulative Distribution Functions for Water Chemistry Data

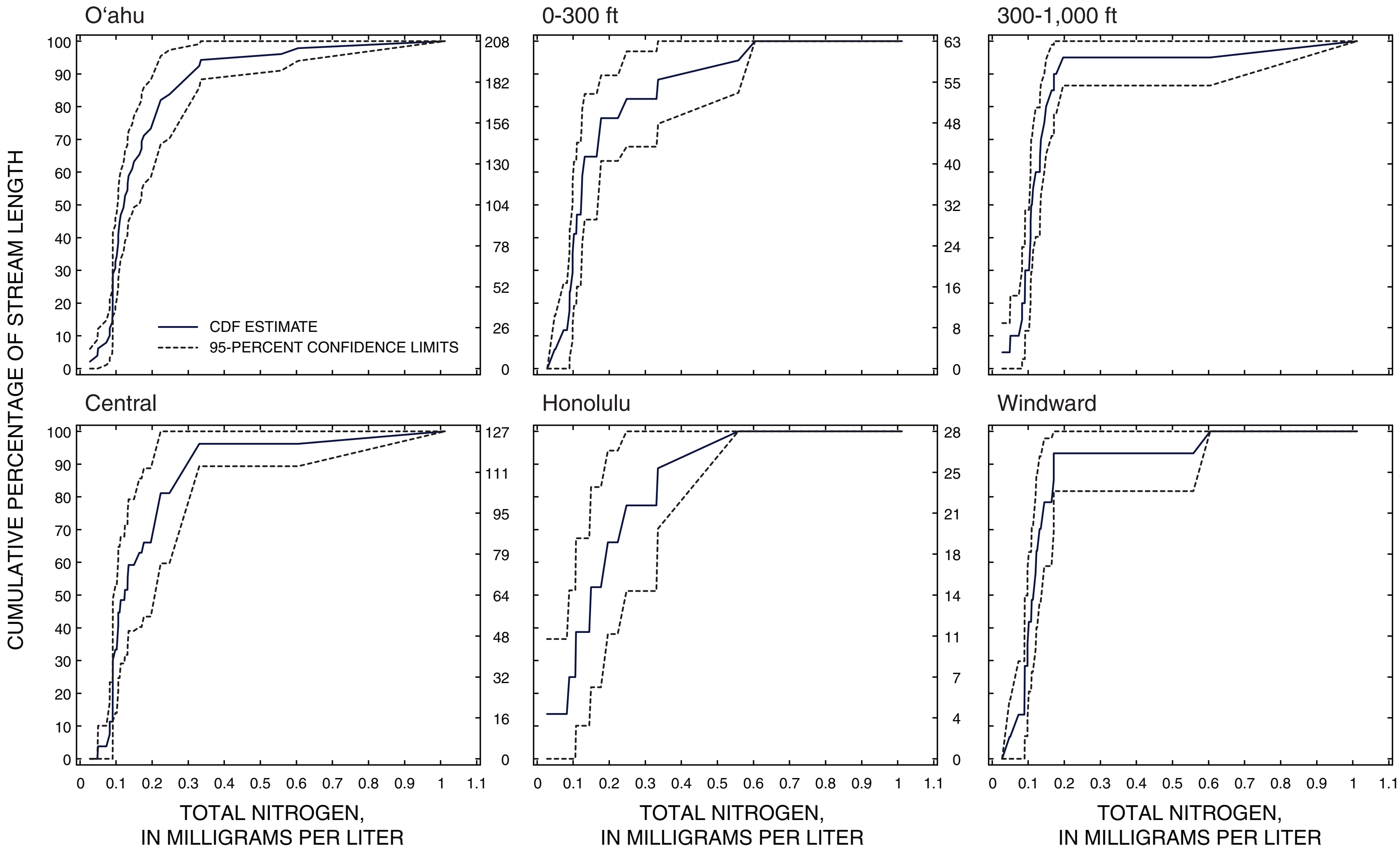

Figure C1. Cumulative distribution function plots of total nitrogen.

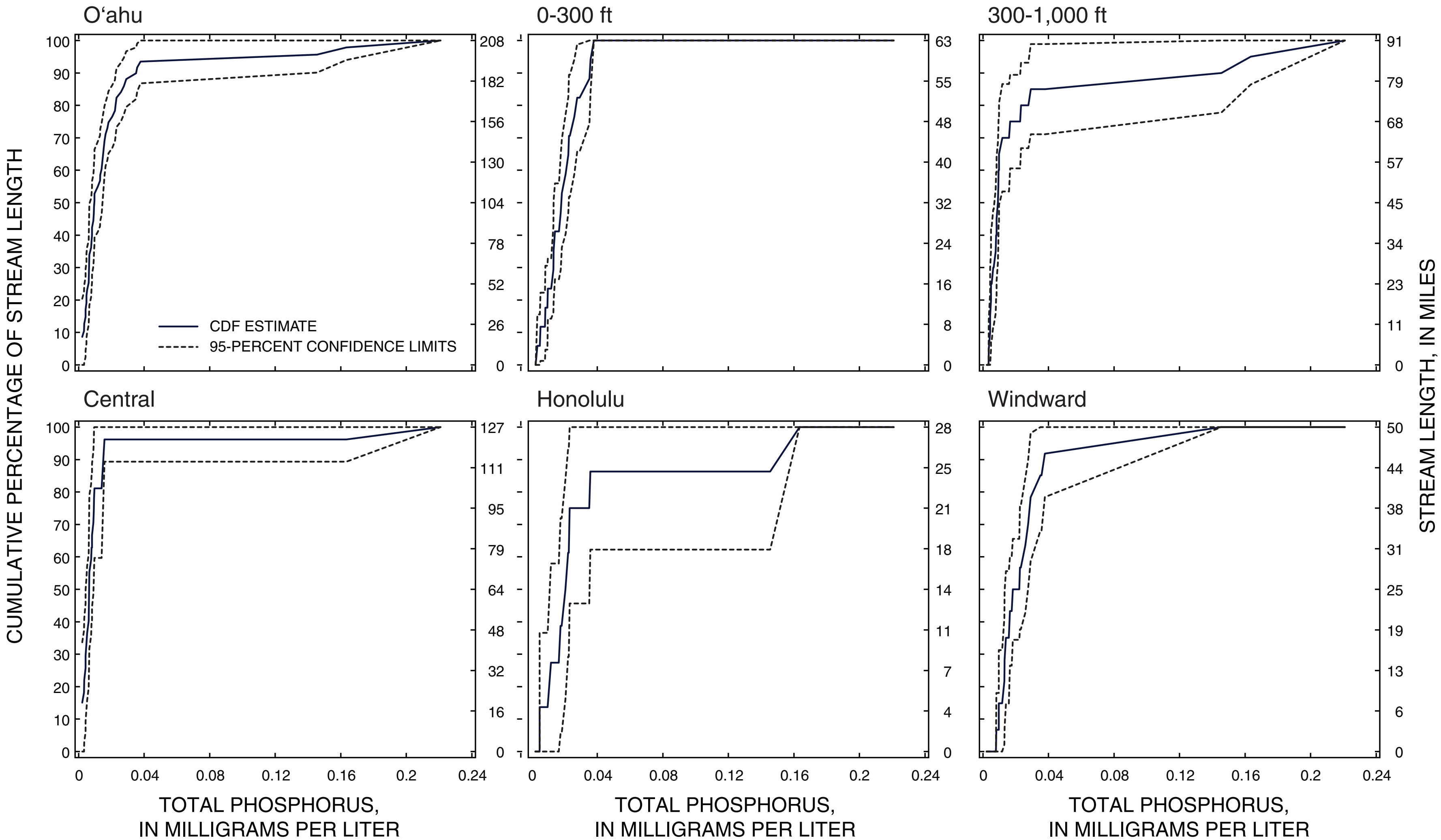

Figure C2. Cumulative distribution function plots of total phosphorus.

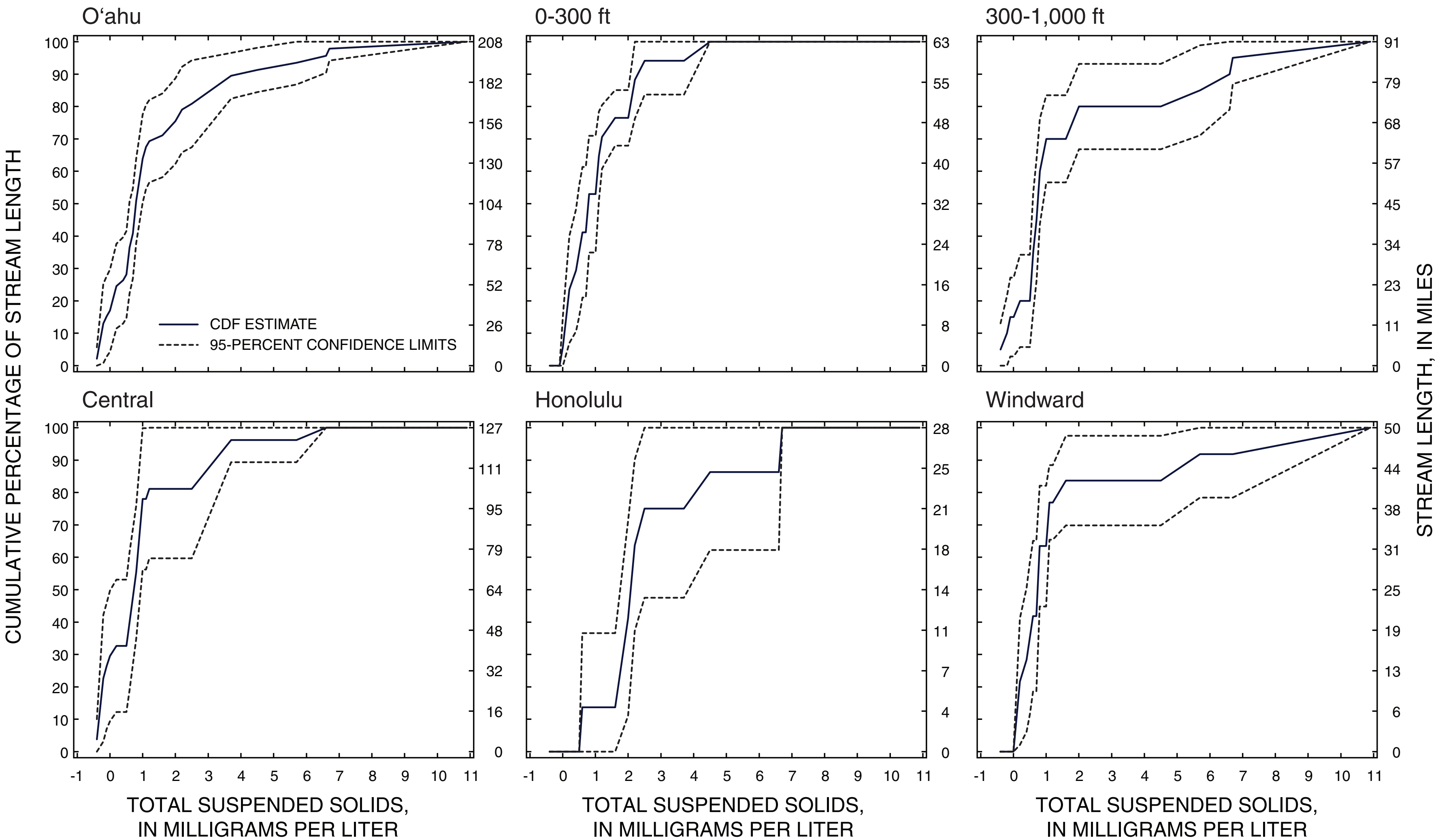

Figure C3. Cumulative distribution function plots of total suspended solids.

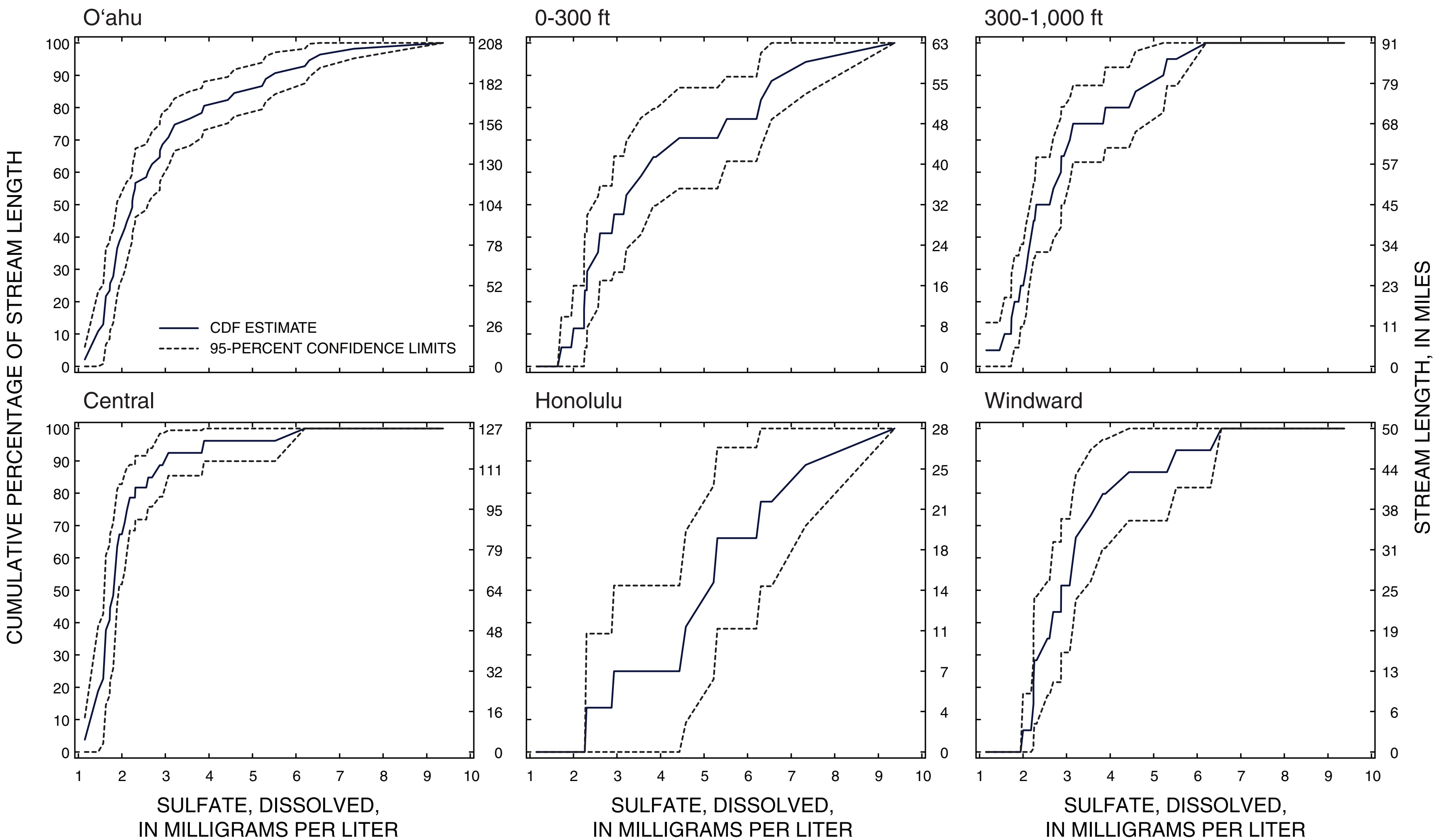

Figure C4. Cumulative distribution function plots of sulfate.

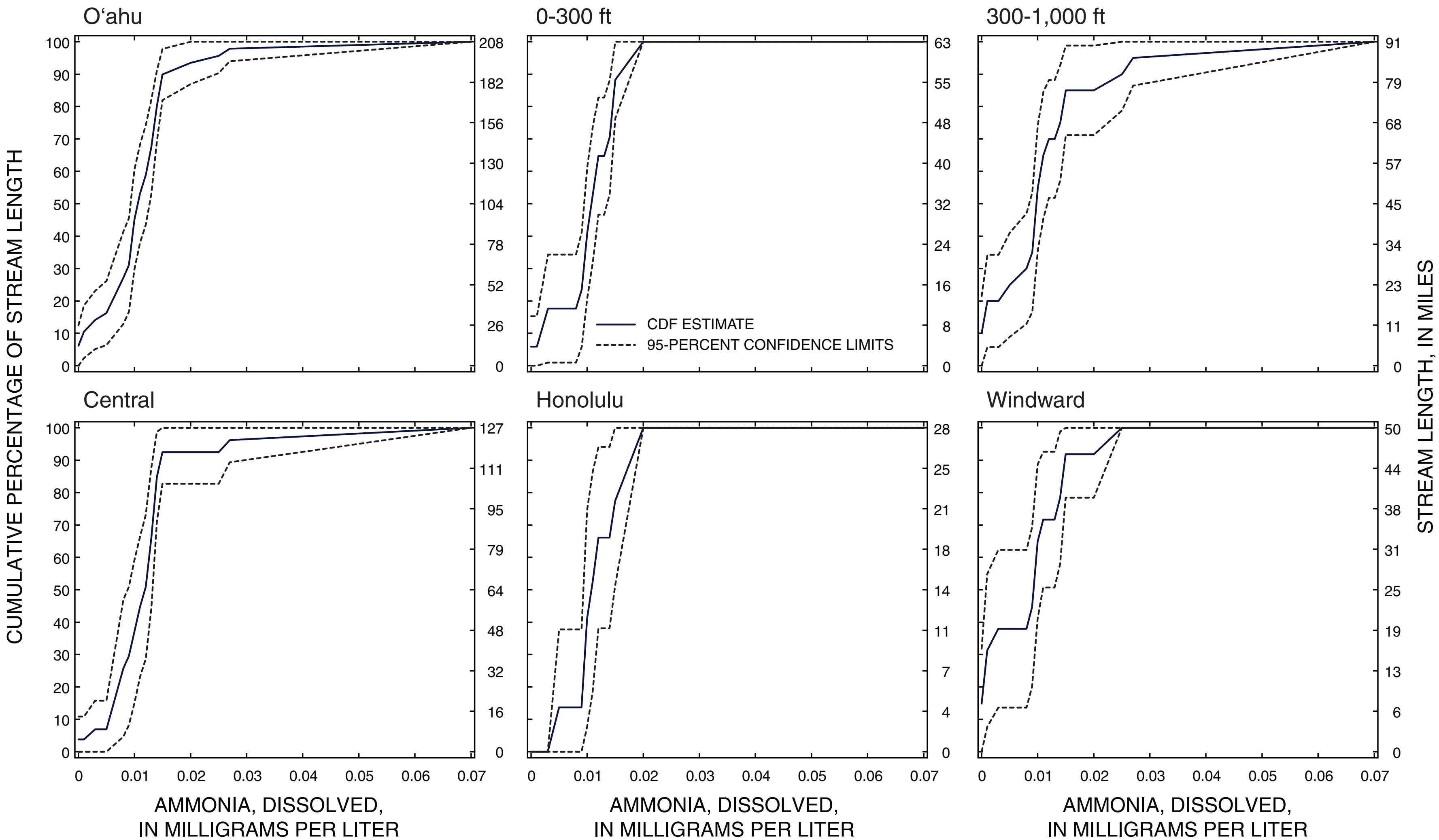

Figure C5. Cumulative distribution function plots of ammonia.

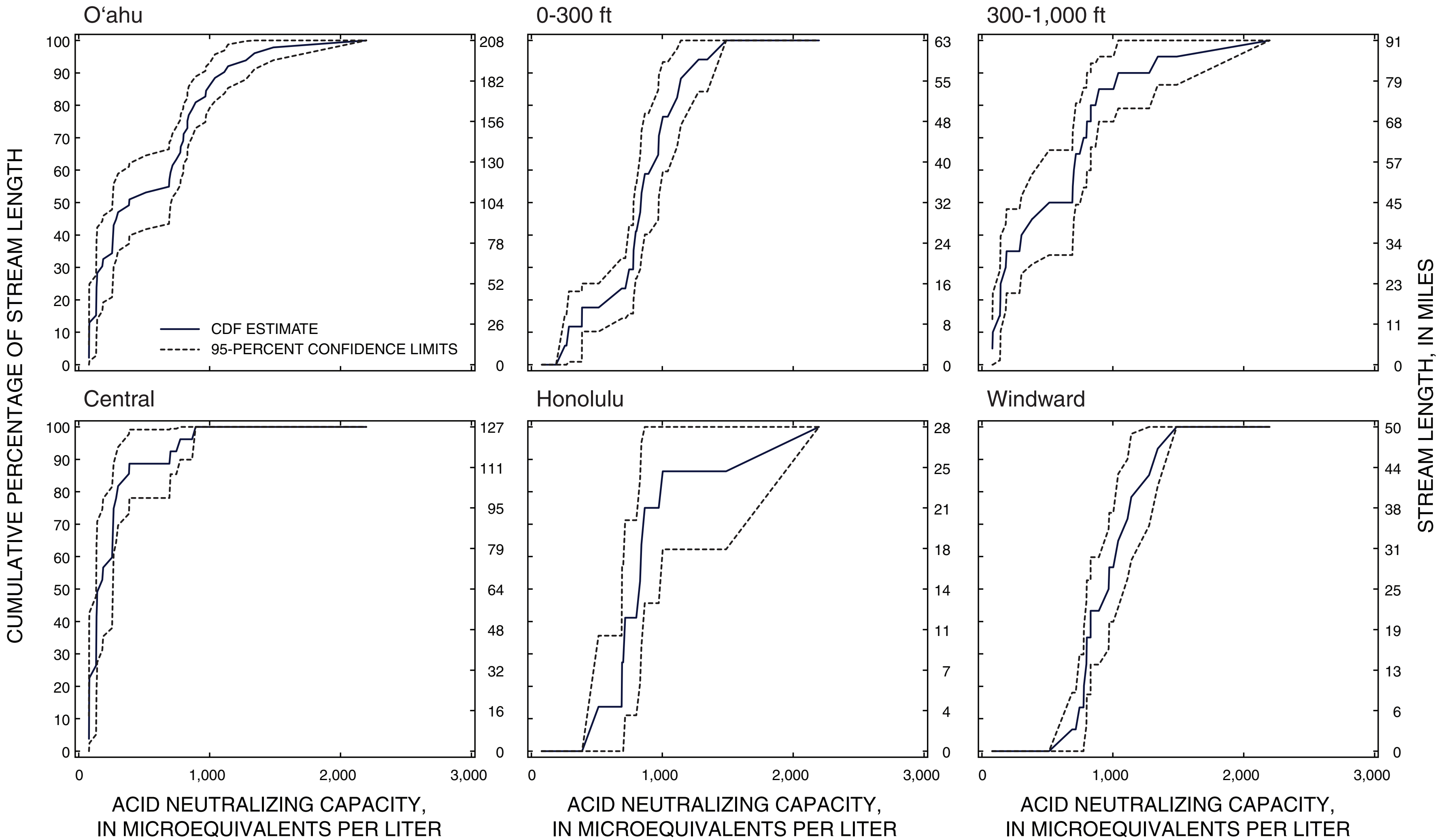

Figure C6. Cumulative distribution function plots of acid neutralizing capacity.

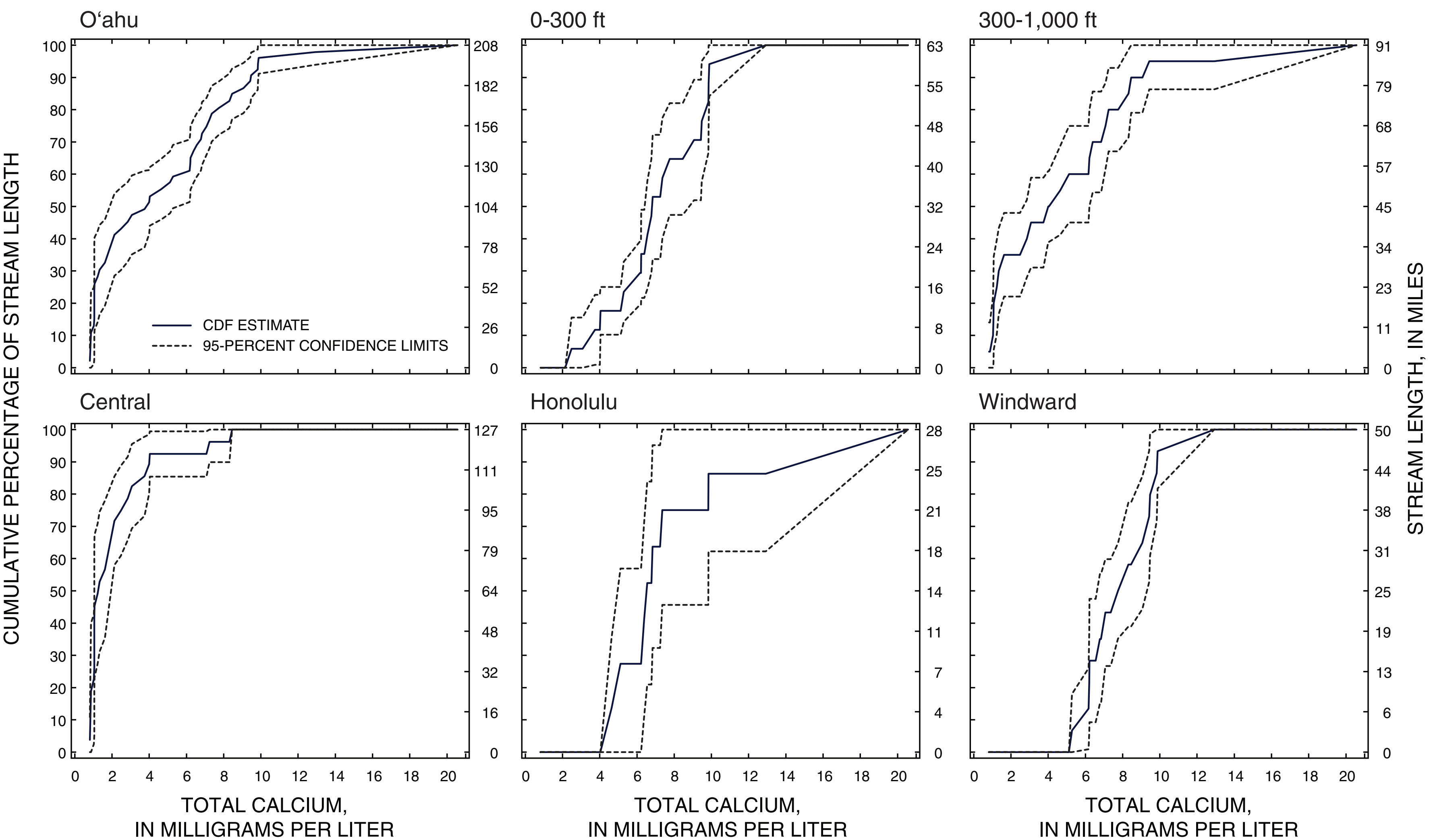

Figure C7. Cumulative distribution function plots of total calcium.

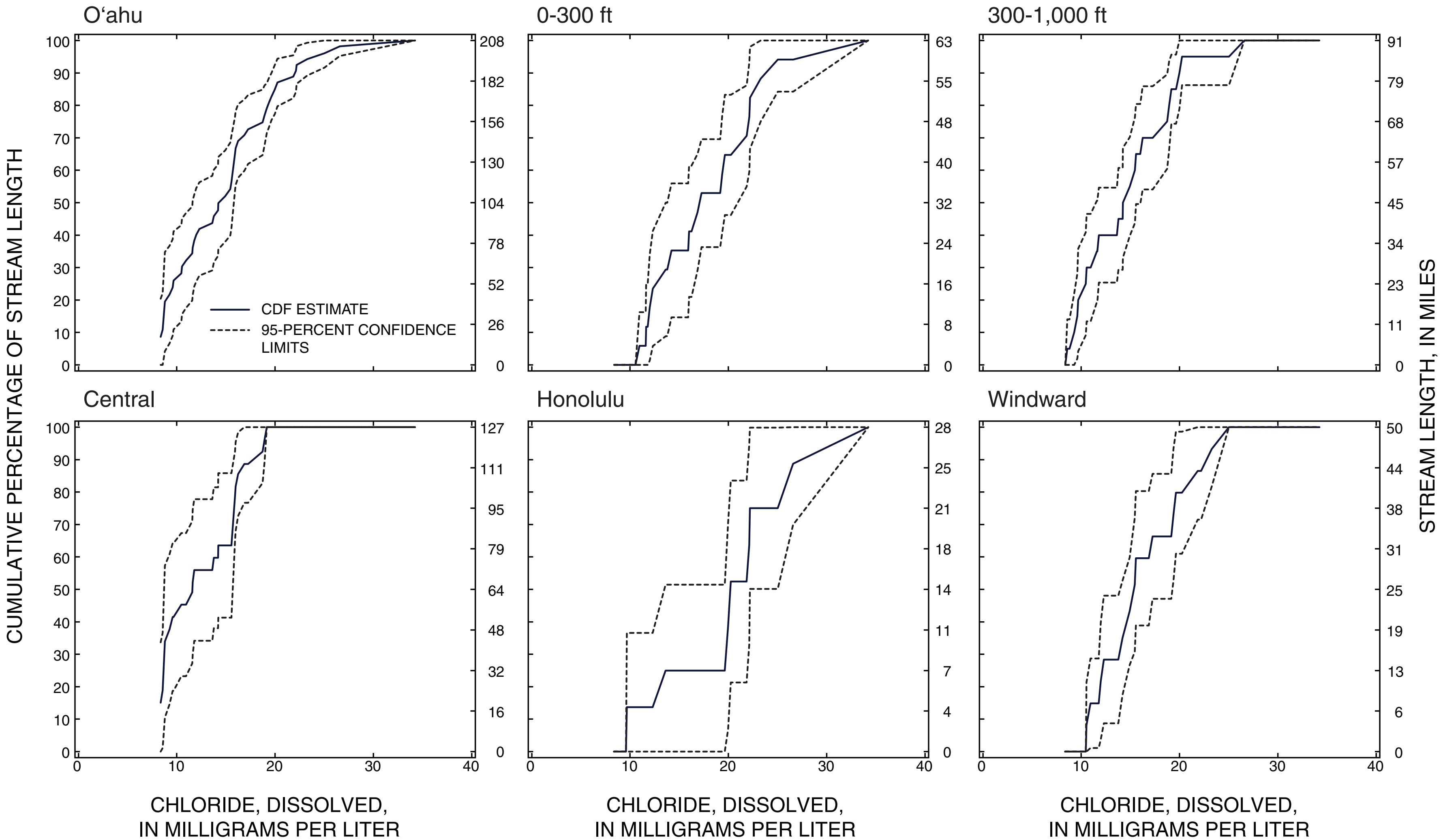

Figure C8. Cumulative distribution function plots of chloride.

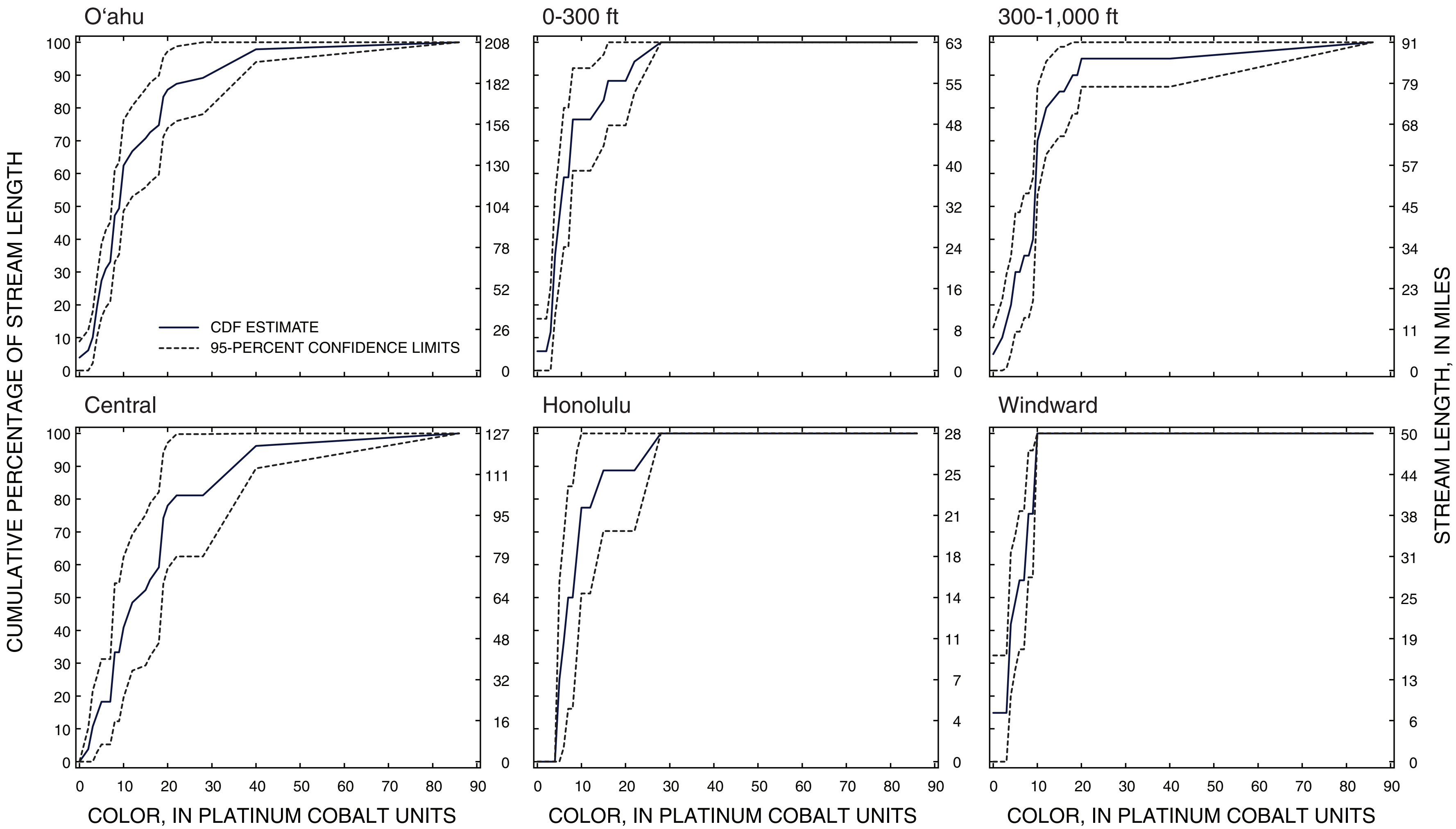

Figure C9. Cumulative distribution function plots of color.

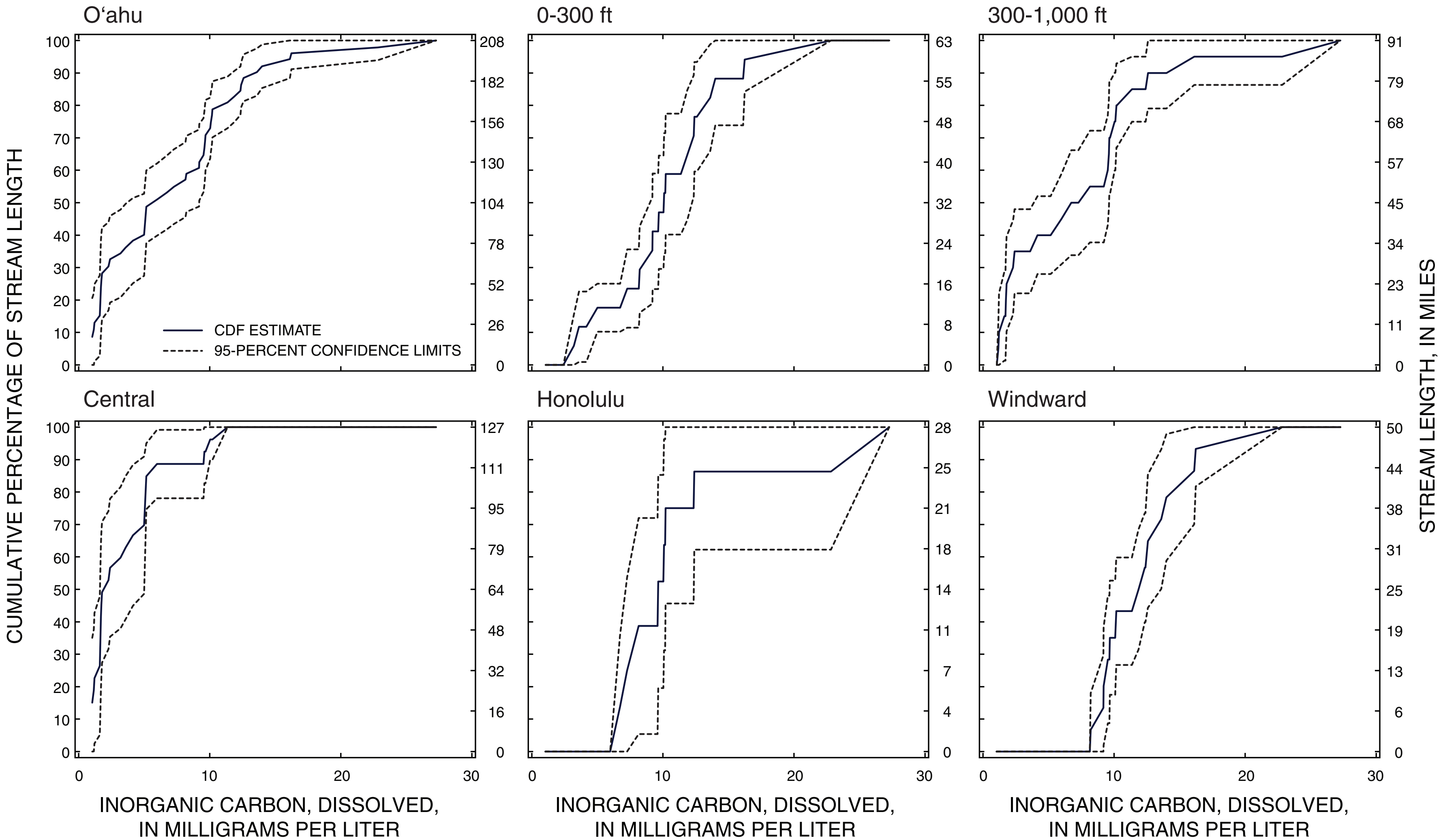

Figure C10. Cumulative distribution function plots of dissolved inorganic carbon.

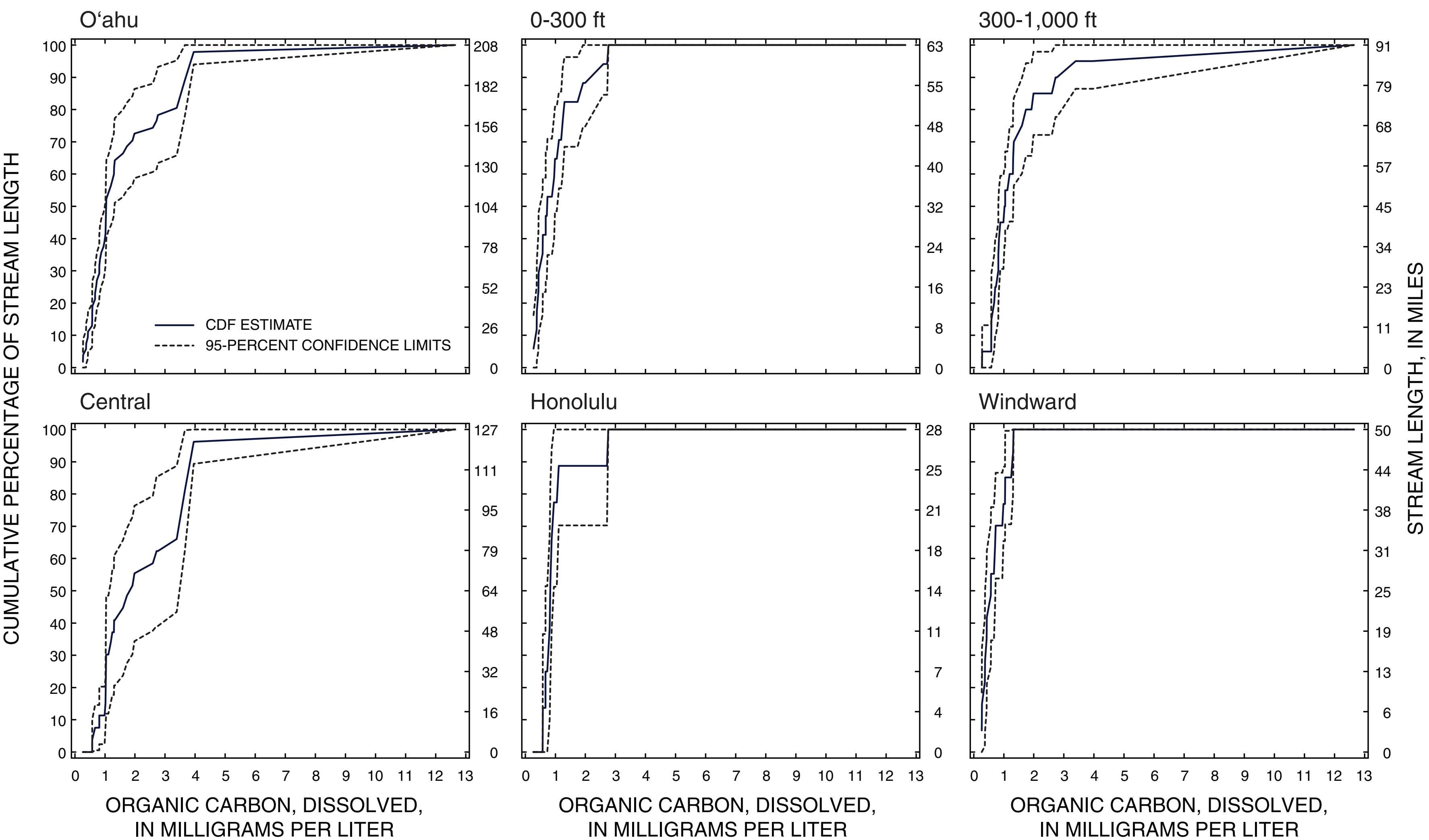

Figure C11. Cumulative distribution function plots of dissolved organic carbon.

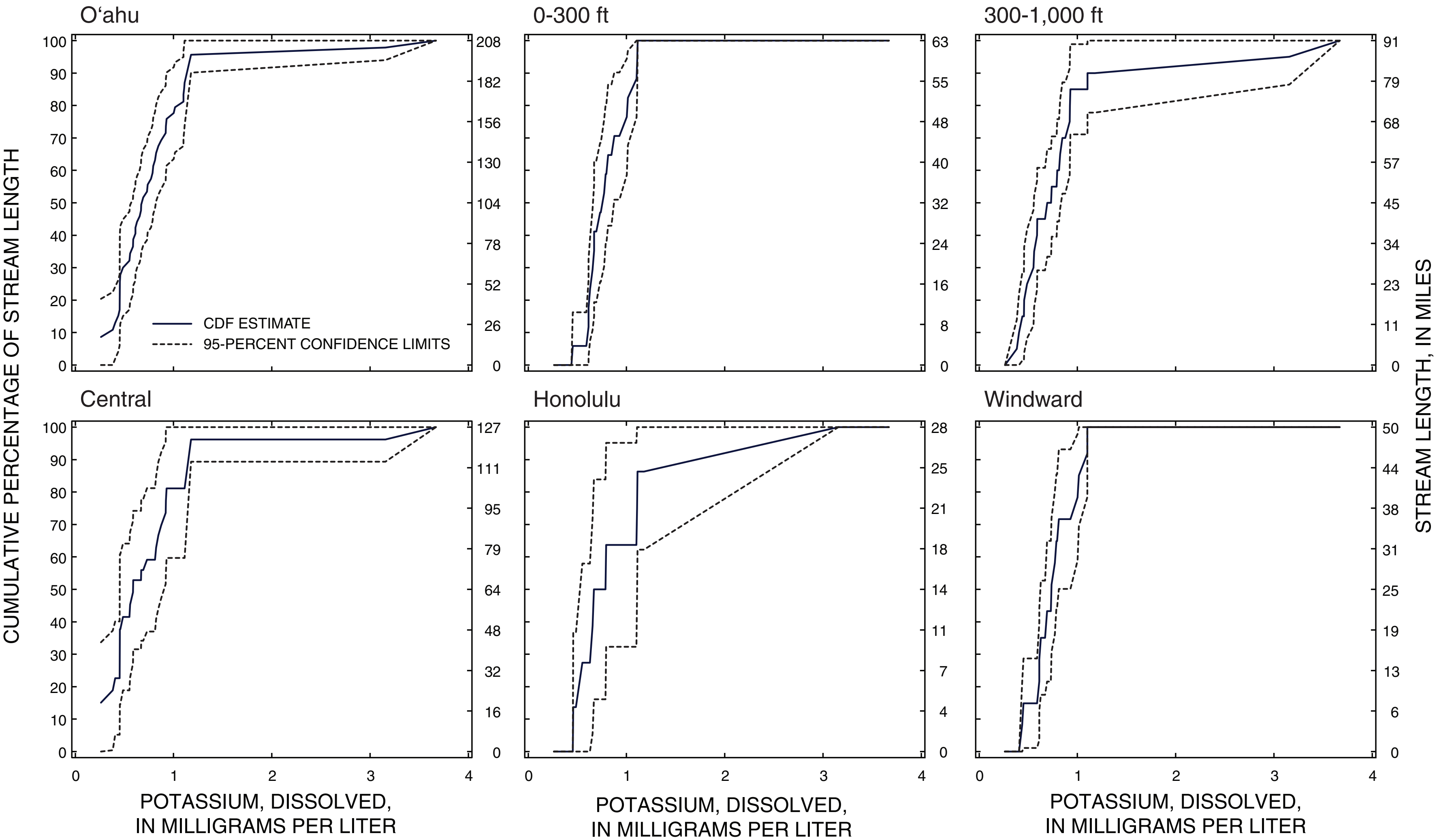

Figure C12. Cumulative distribution function plots of dissolved potassium.

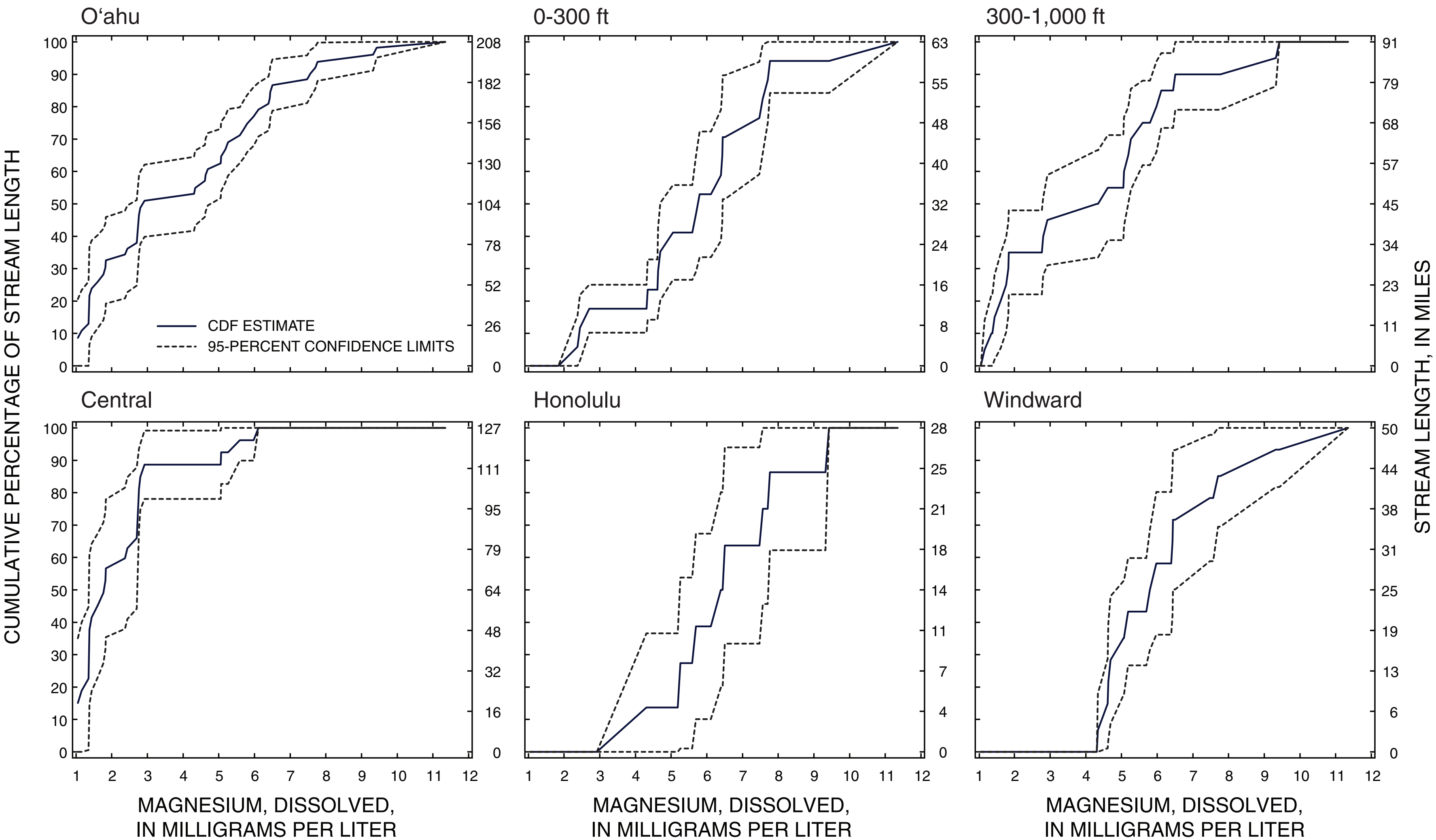

Figure C13. Cumulative distribution function plots of dissolved magnesium.

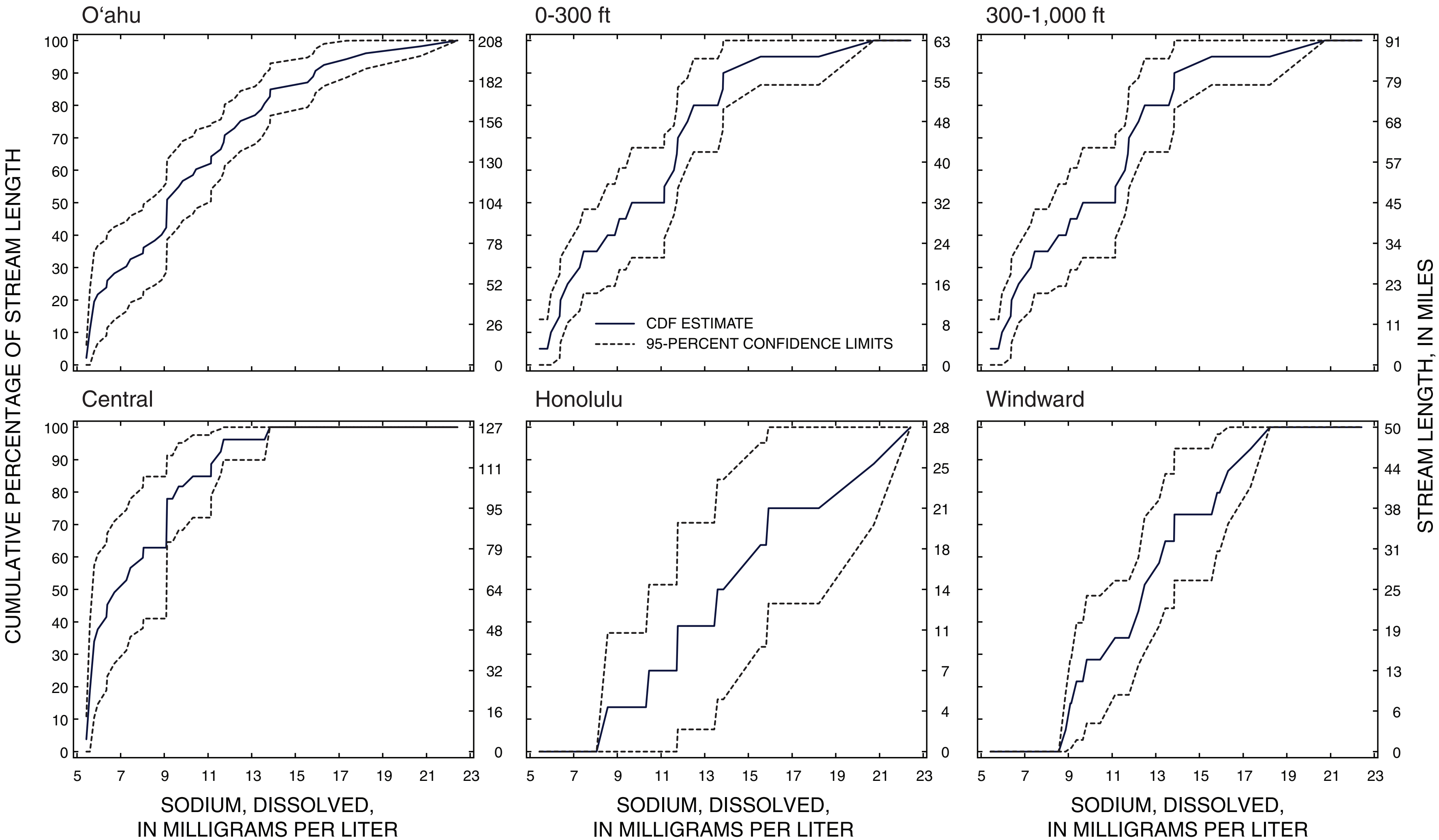

Figure C14. Cumulative distribution function plots of dissolved sodium.

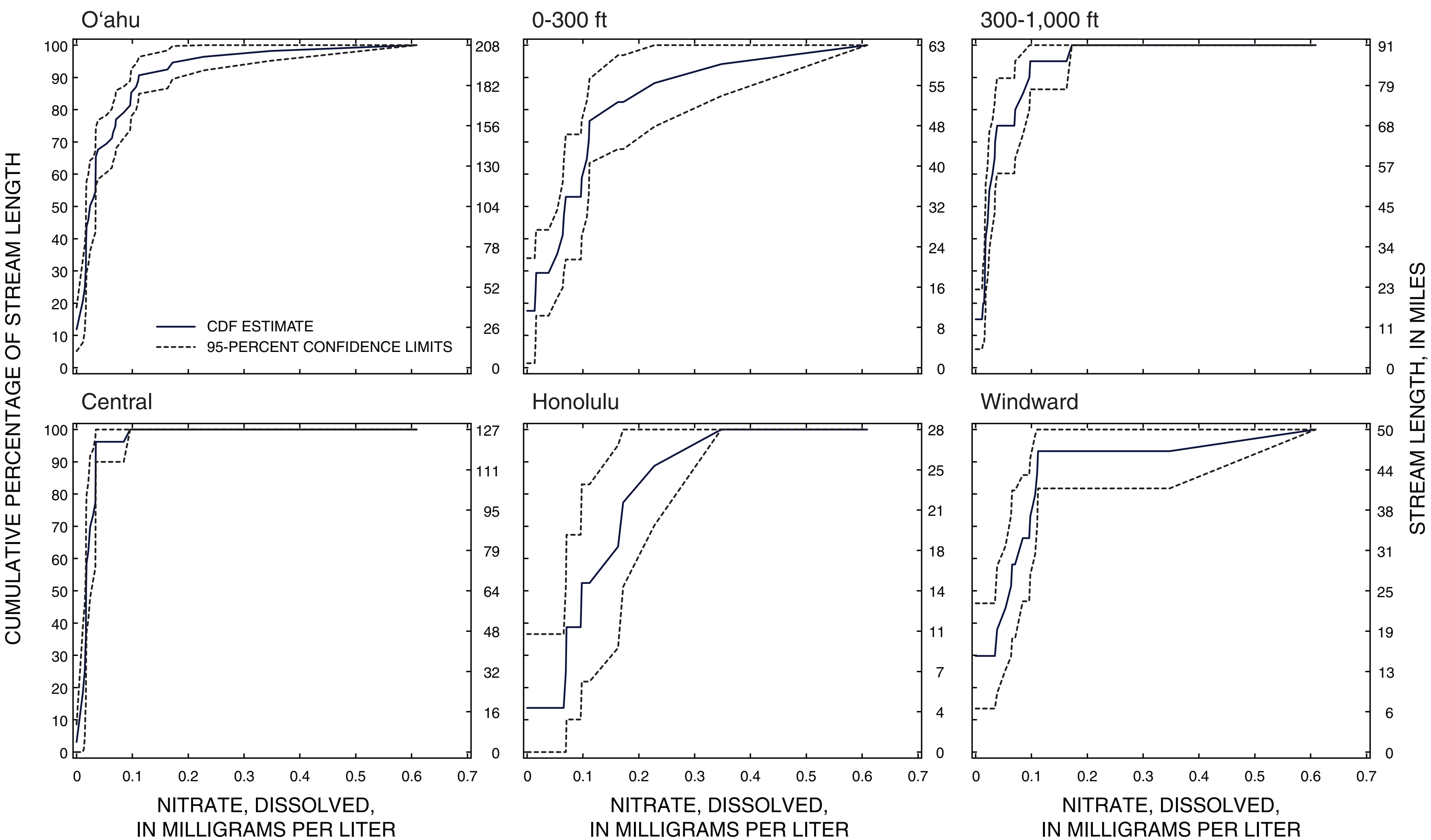

Figure C15. Cumulative distribution function plots of nitrate.

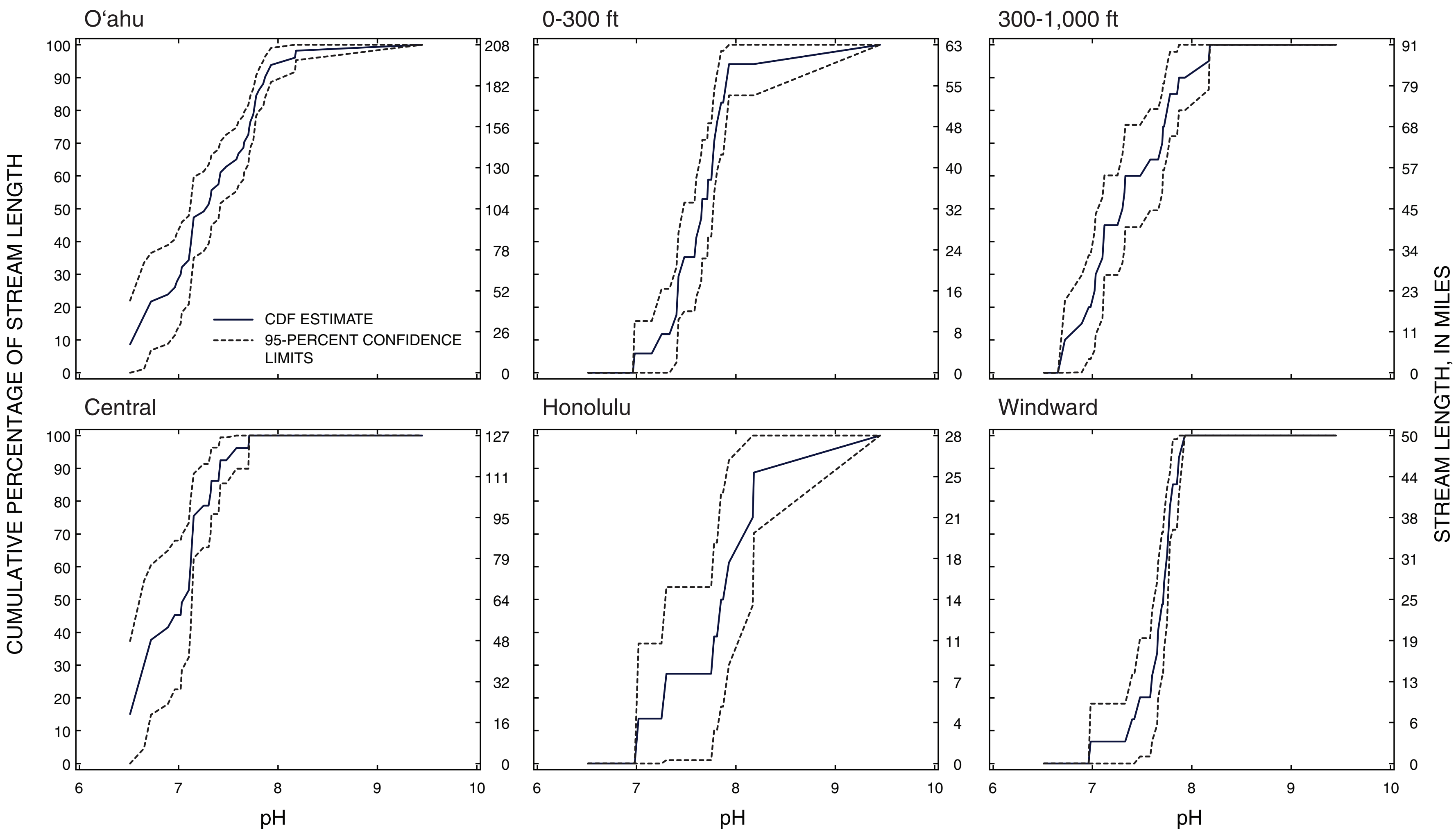

Figure C16. Cumulative distribution function plots of pH.

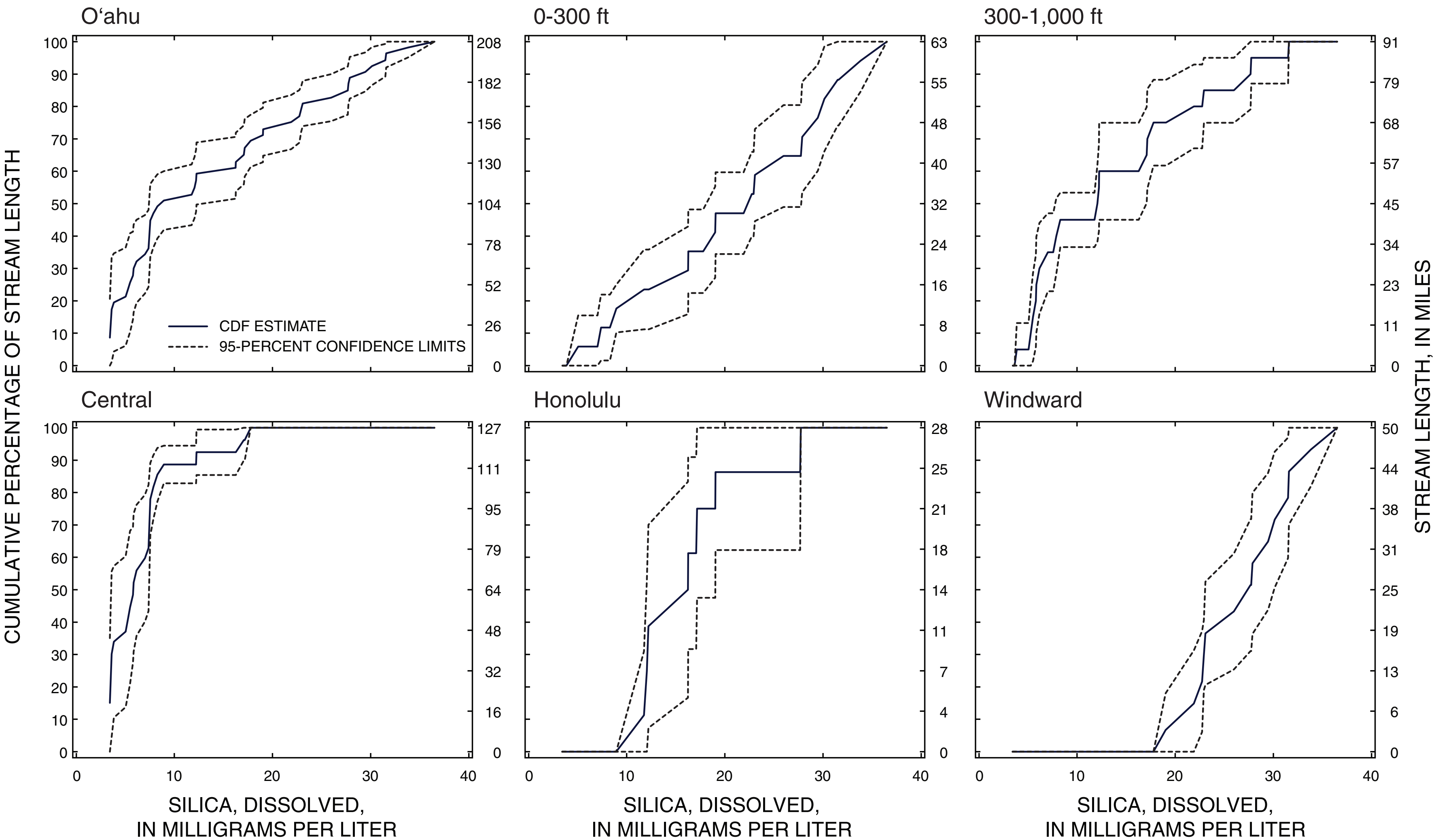

Figure C17. Cumulative distribution function plots of silica.

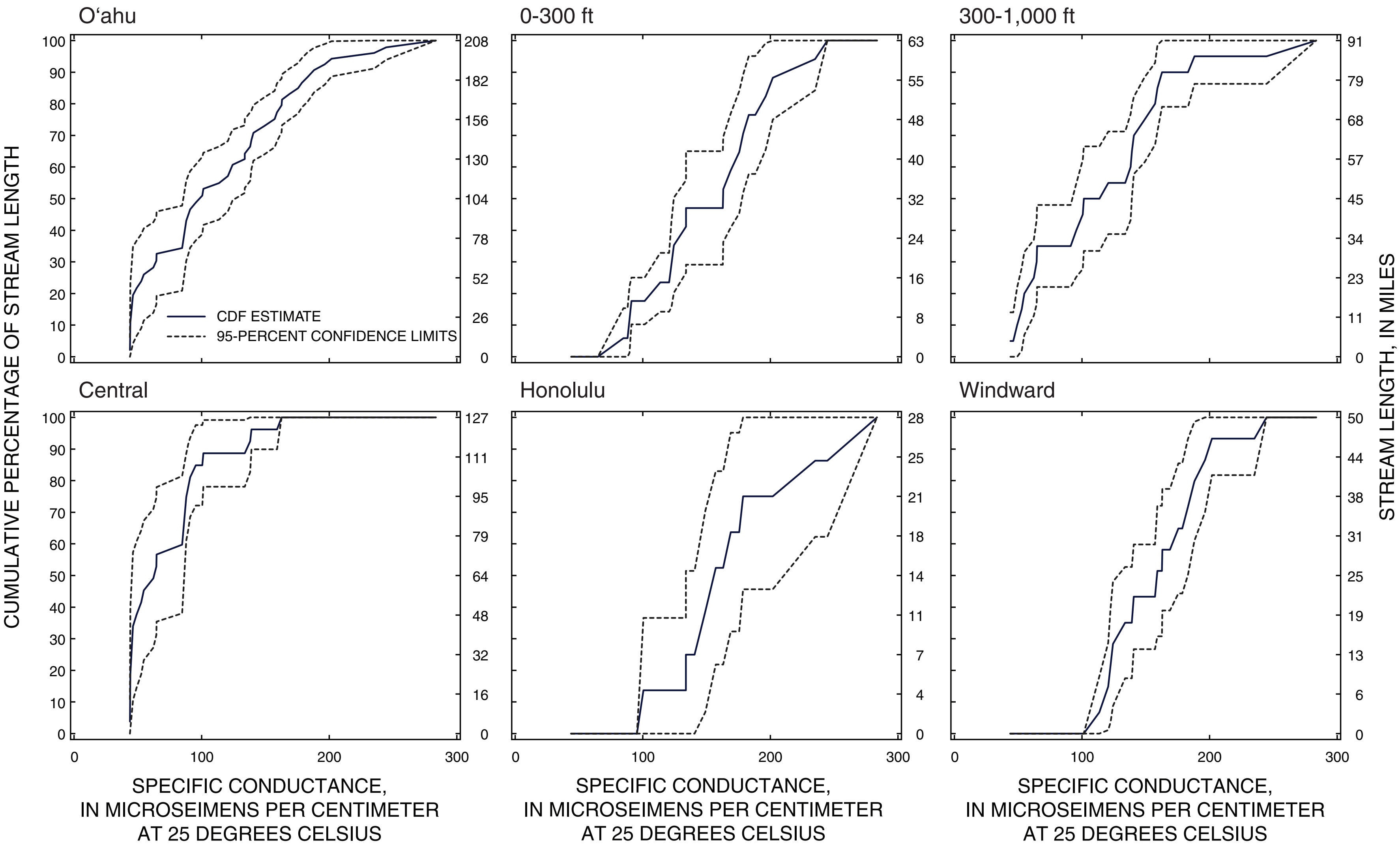

Figure C18. Cumulative distribution function plots of specific conductance.

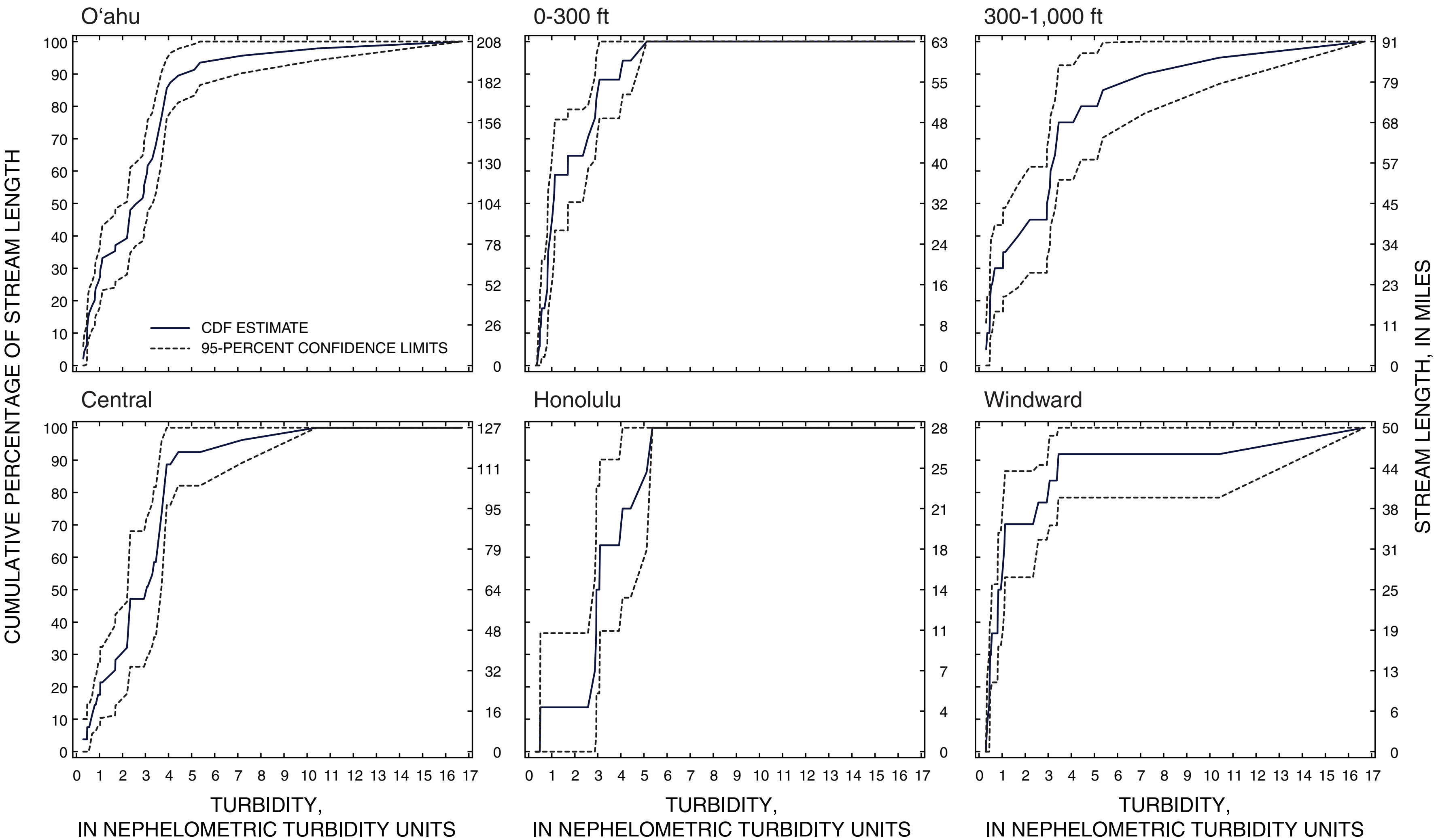

Figure C19. Cumulative distribution function plots of turbidity.

Appendix D.
Cumulative Distribution Functions for Physical Habitat Data

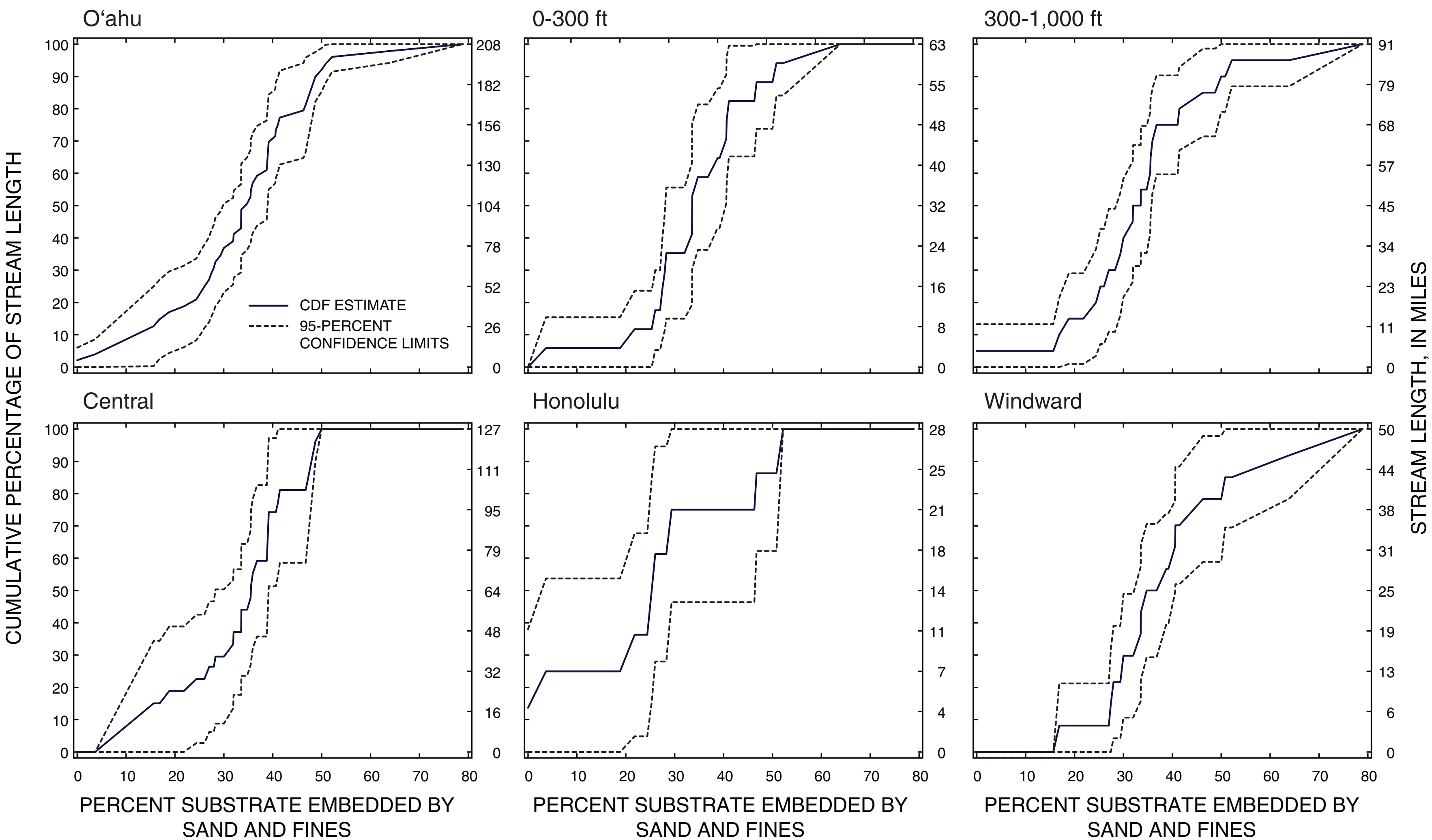

Figure D1. CDF plots of percent substrate embedded by sand and fines (XEMBED).

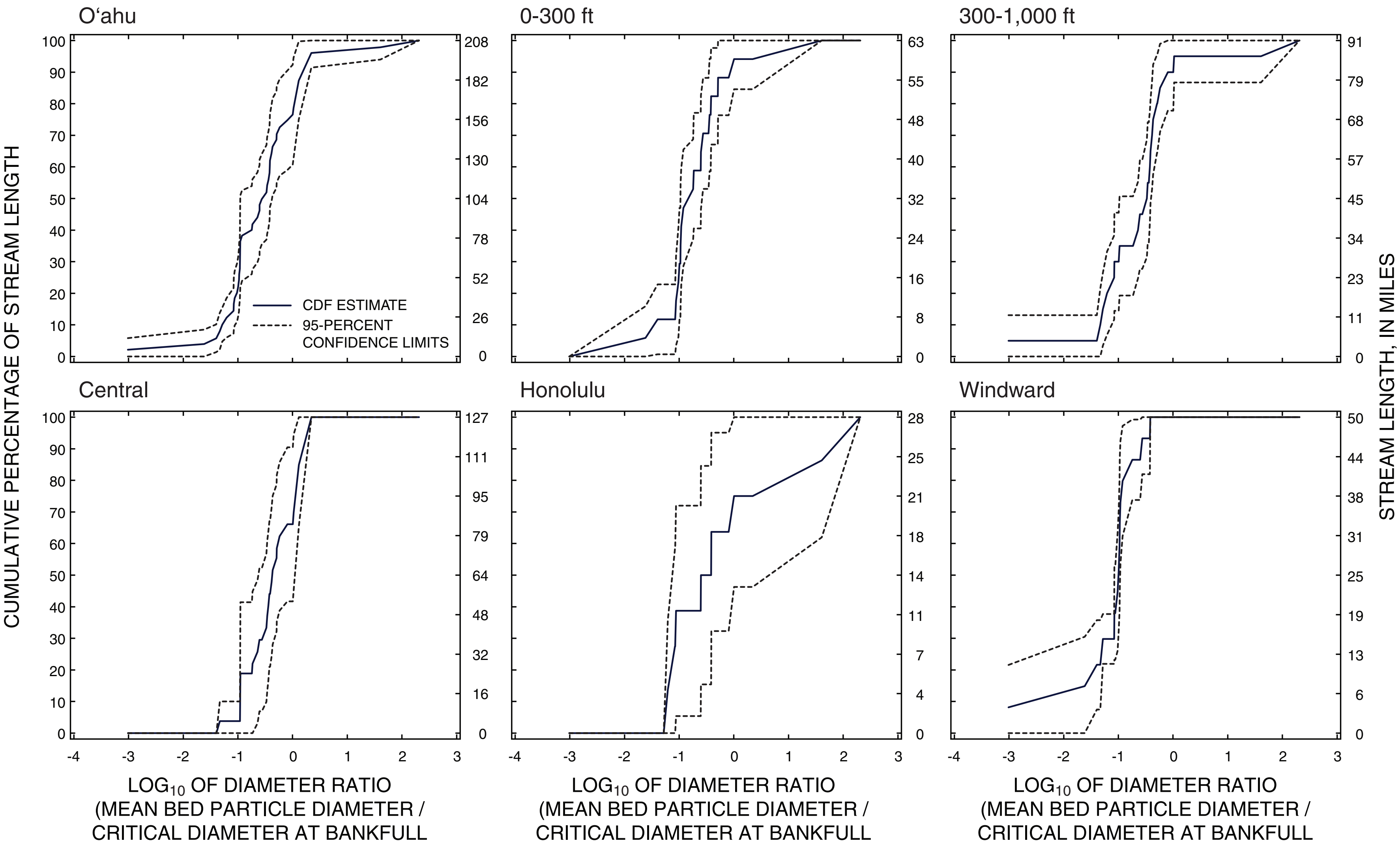

Figure D2. CDF plots of log10 of diameter ratio: mean bed particle diameter / critical (mobile) diameter at bankfull (LRBS_bw5).

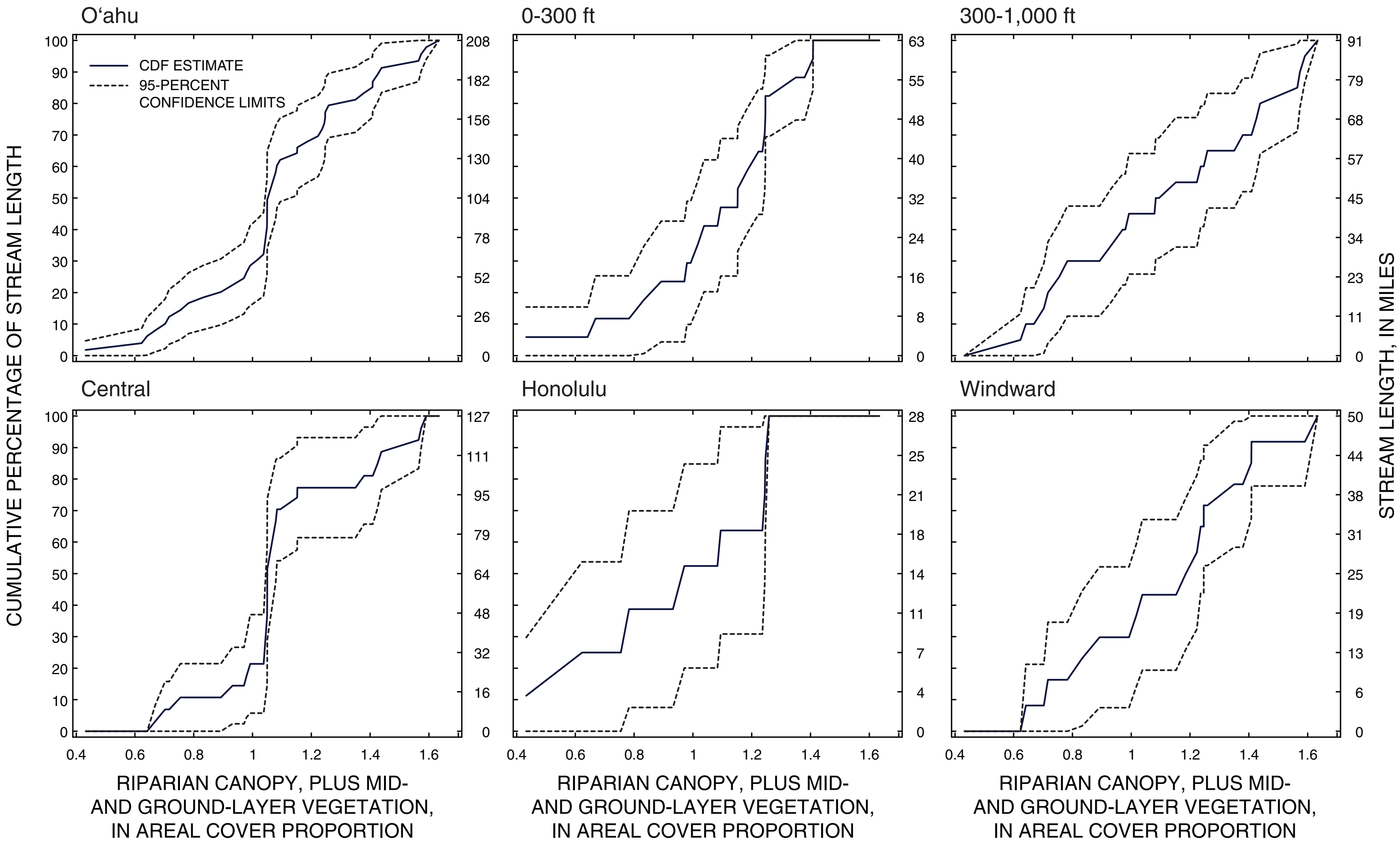

Figure D3. CDF plots of areal cover proportion of riparian canopy, plus mid- and ground-layer vegetation (XCMG).

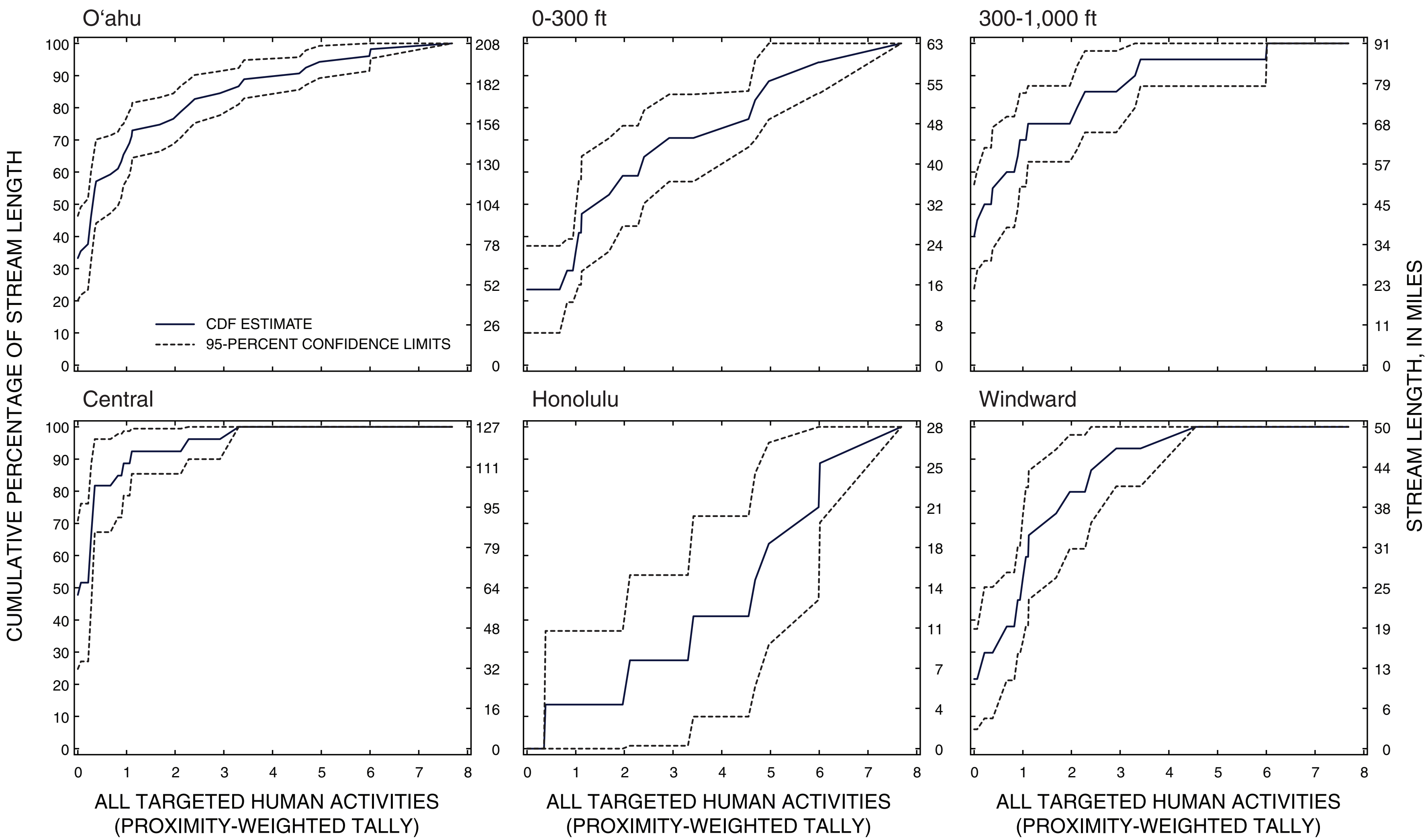

Figure D4. CDF plots of human disturbances of all types (W1_HALL).

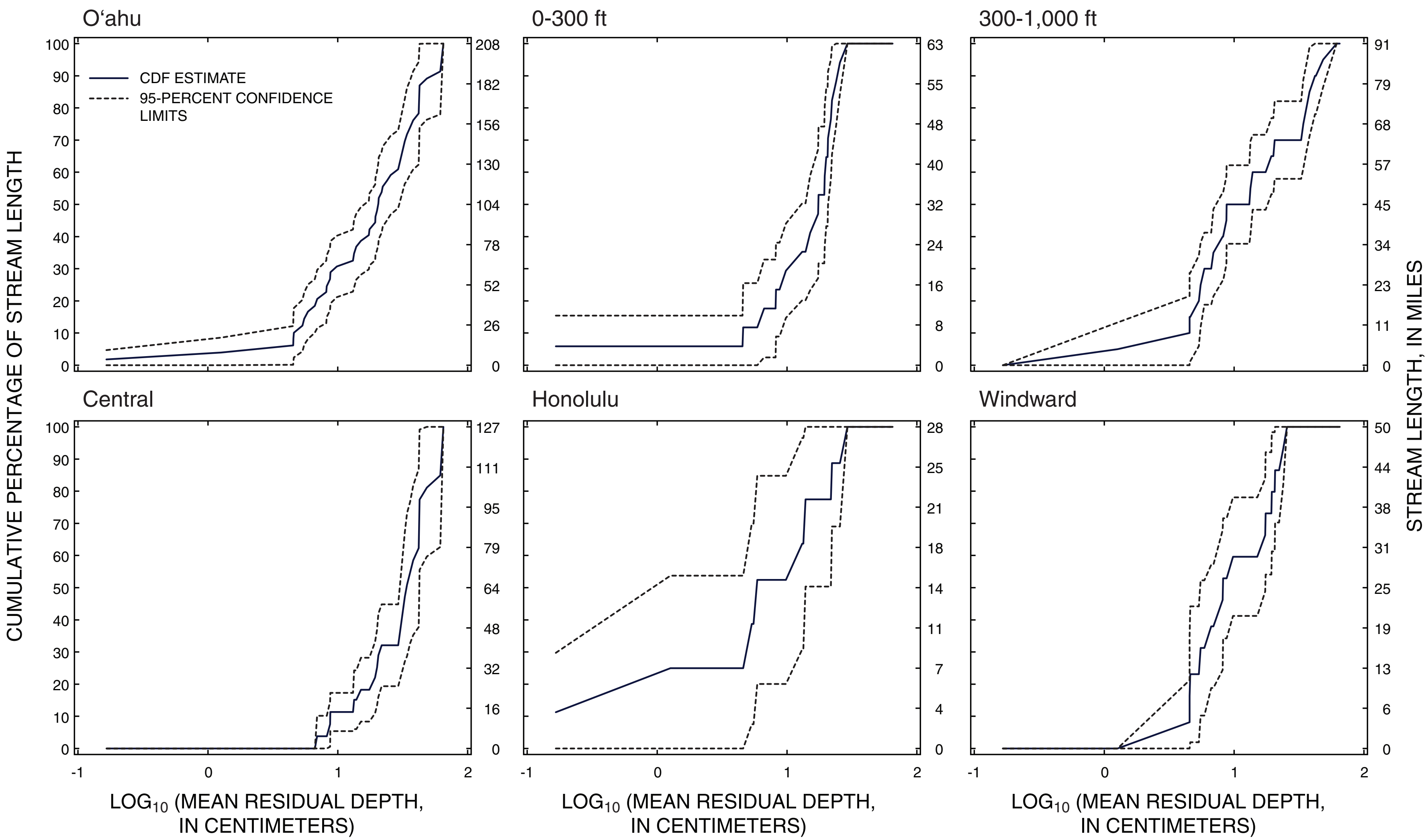

Figure D5. CDF plots of log10 of mean residual depth (LRP100).

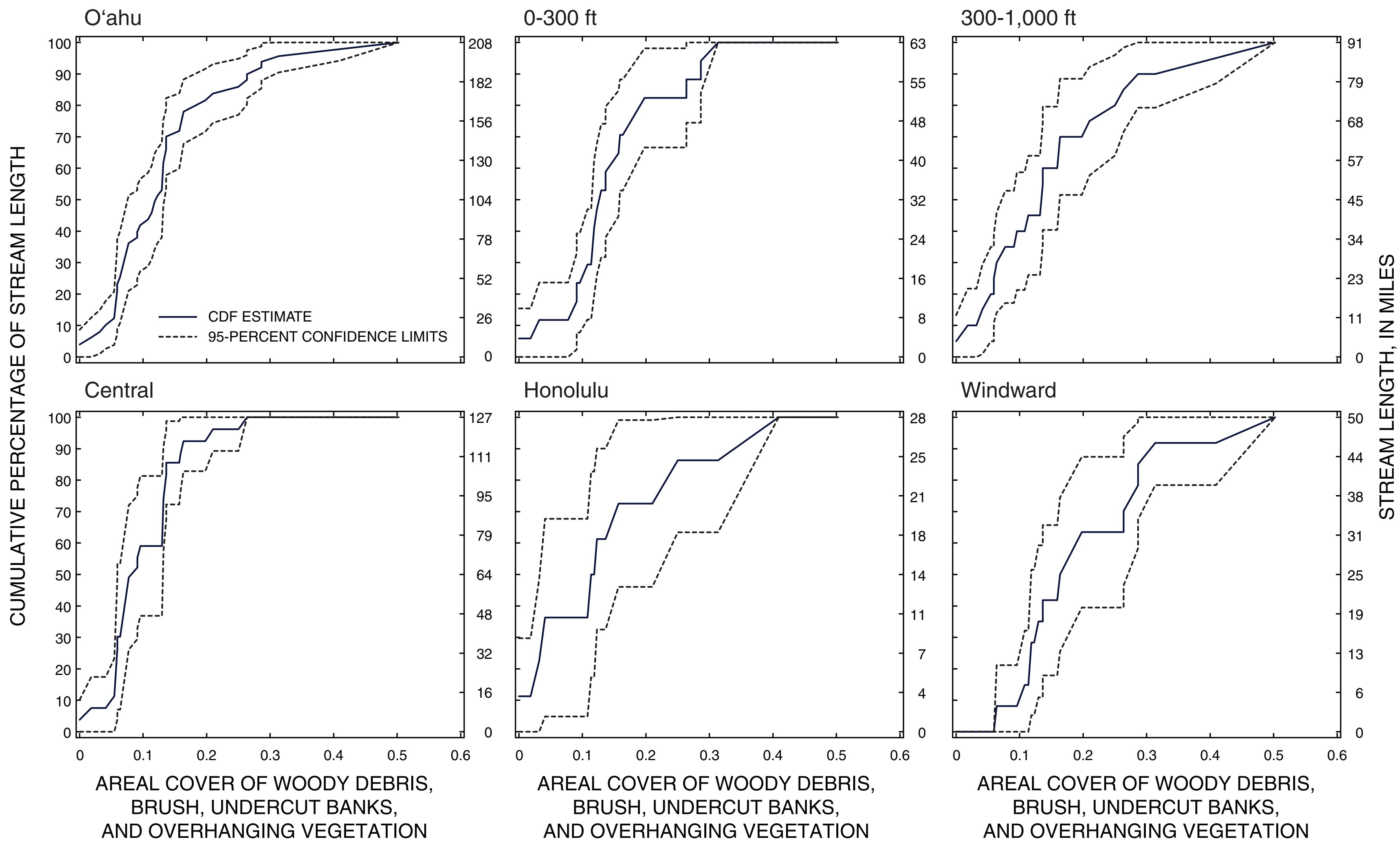

Figure D6. CDF plots of areal cover of woody debris, brush, undercut banks, and overhanging vegetation (XFC_NORK).

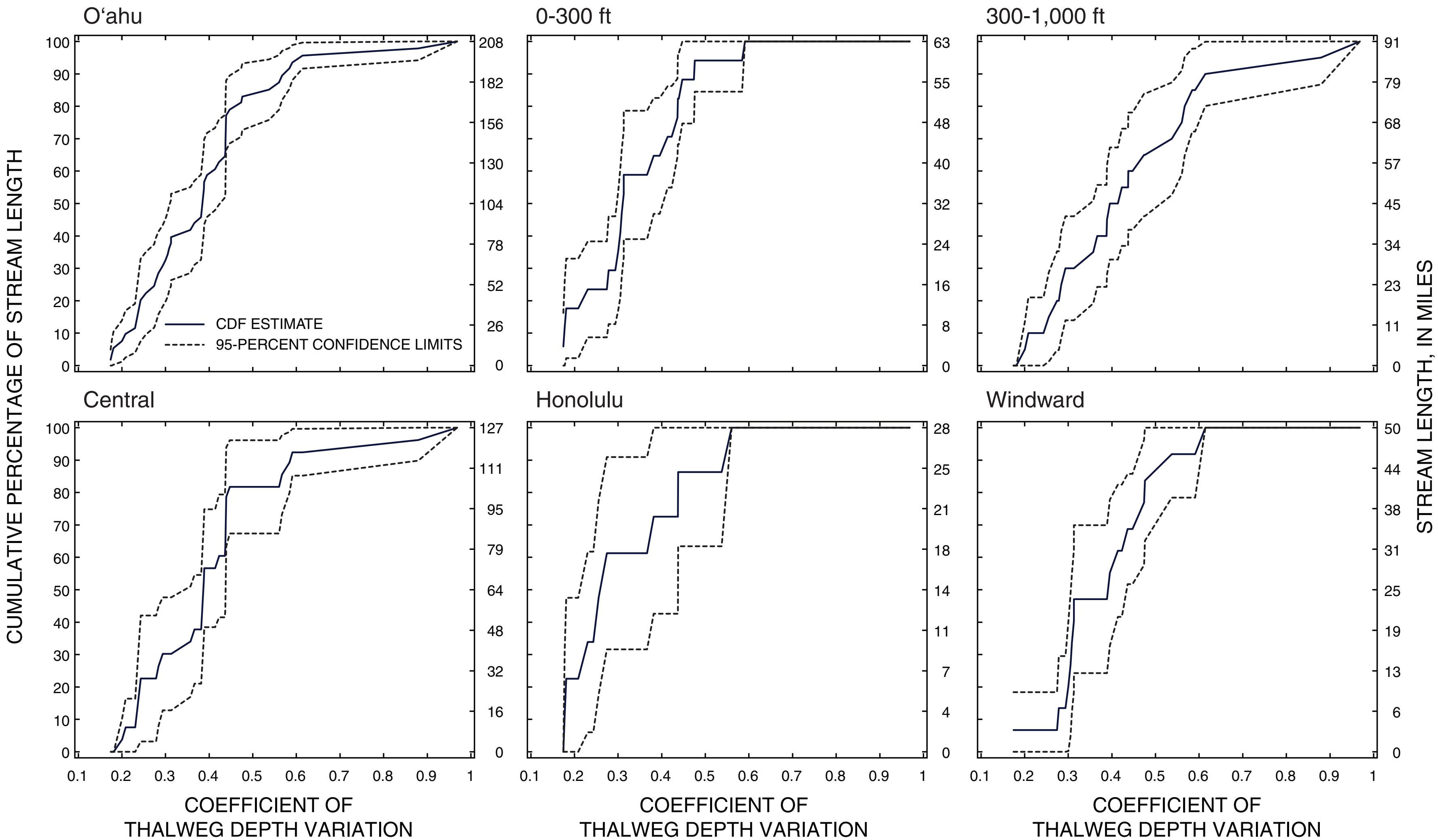

Figure D7. CDF plots of coefficient of thalweg depth variation (CVDpth).

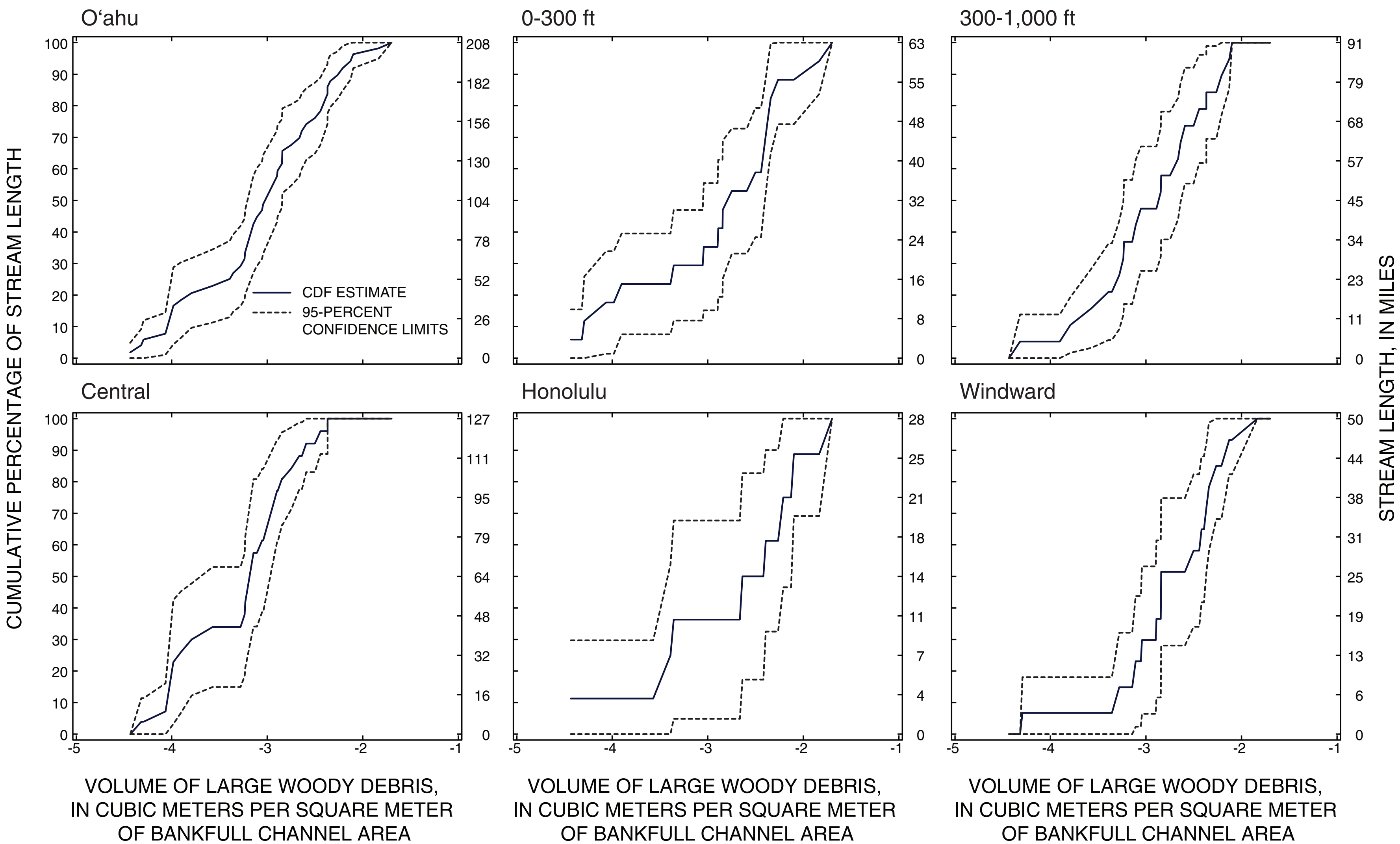

Figure D8. CDF plots of volume of large woody debris per square meter of bankfull channel area (LV1W_msq).

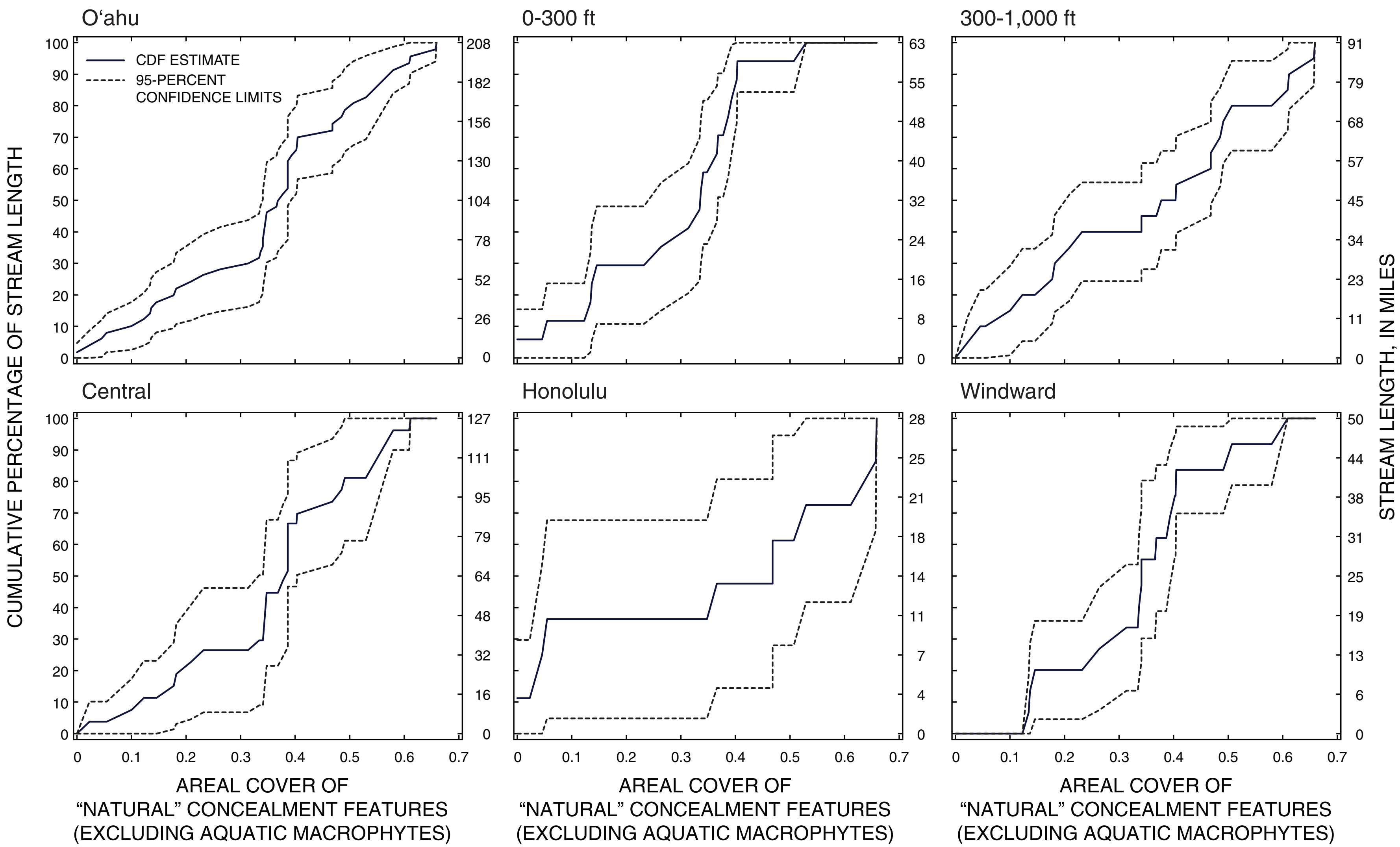

Figure D9. CDF plots of areal cover of “natural” concealment features (excluding aquatic macrophytes) (XFC_NAT).

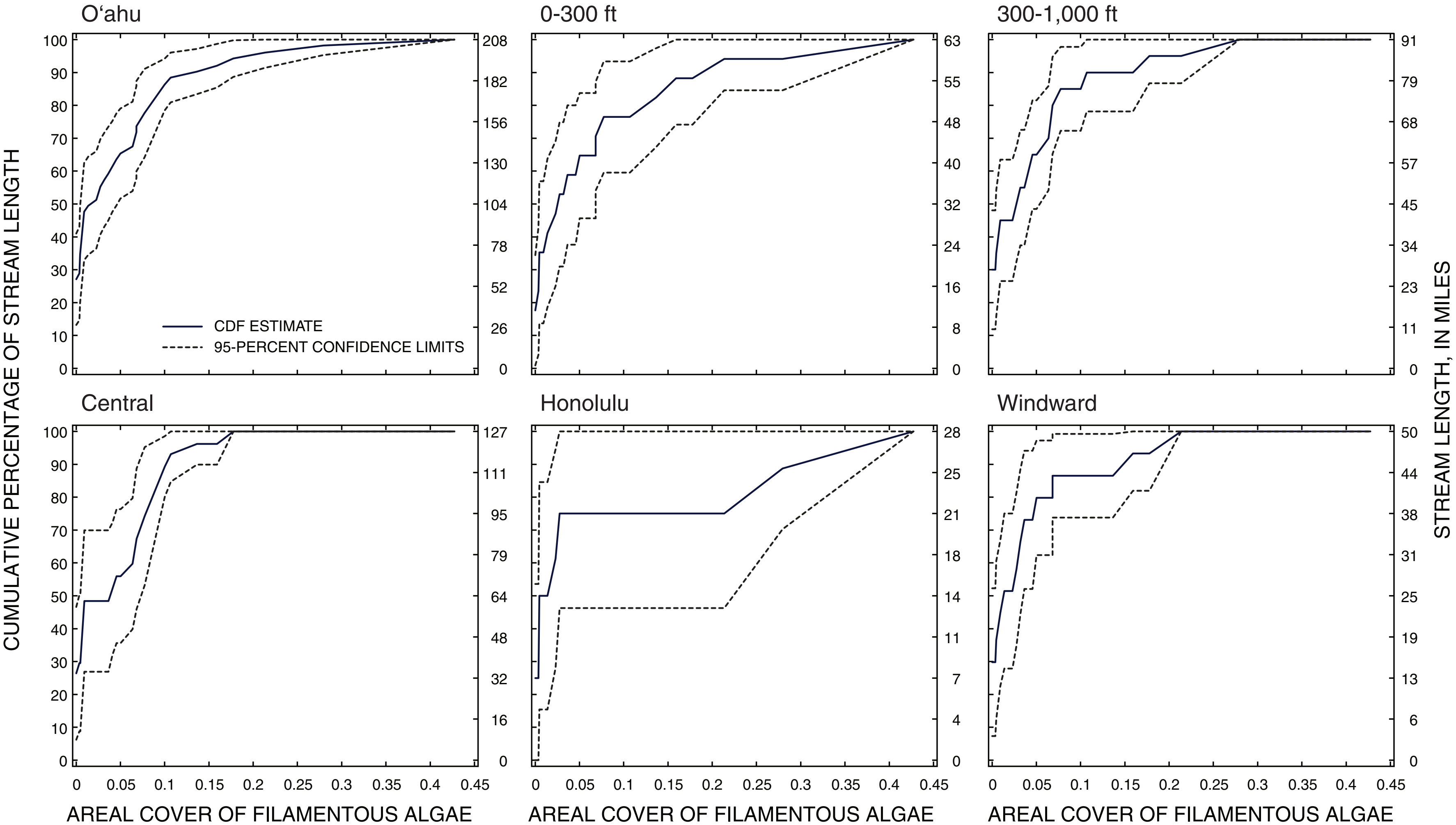

Figure D10. CDF plots of areal cover of filamentous algae detectable by the unaided eye (XFC_ALG).

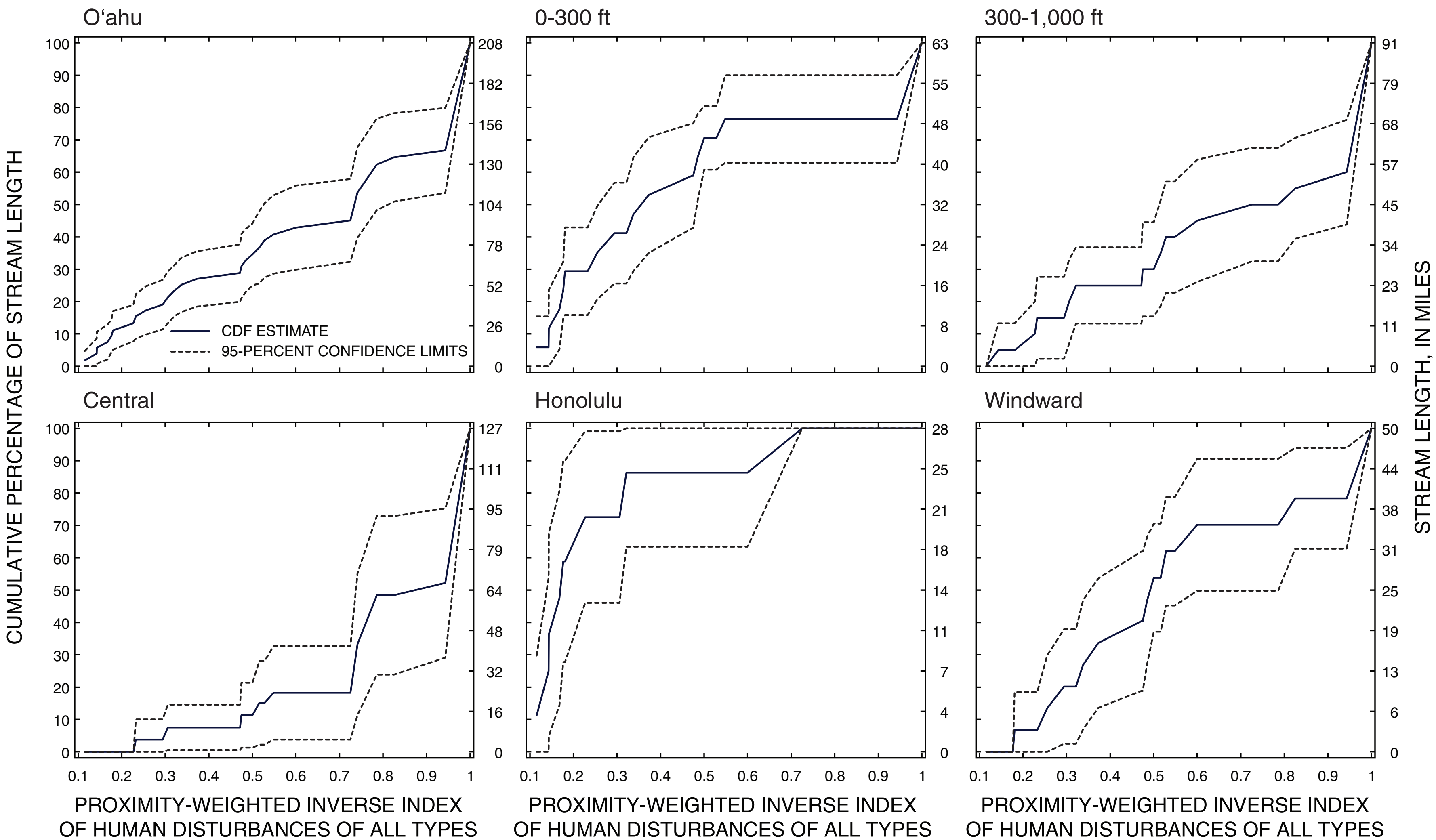

Figure D11. CDF plots of proximity-weighted inverse index of human disturbances of all types (QRDIST1).

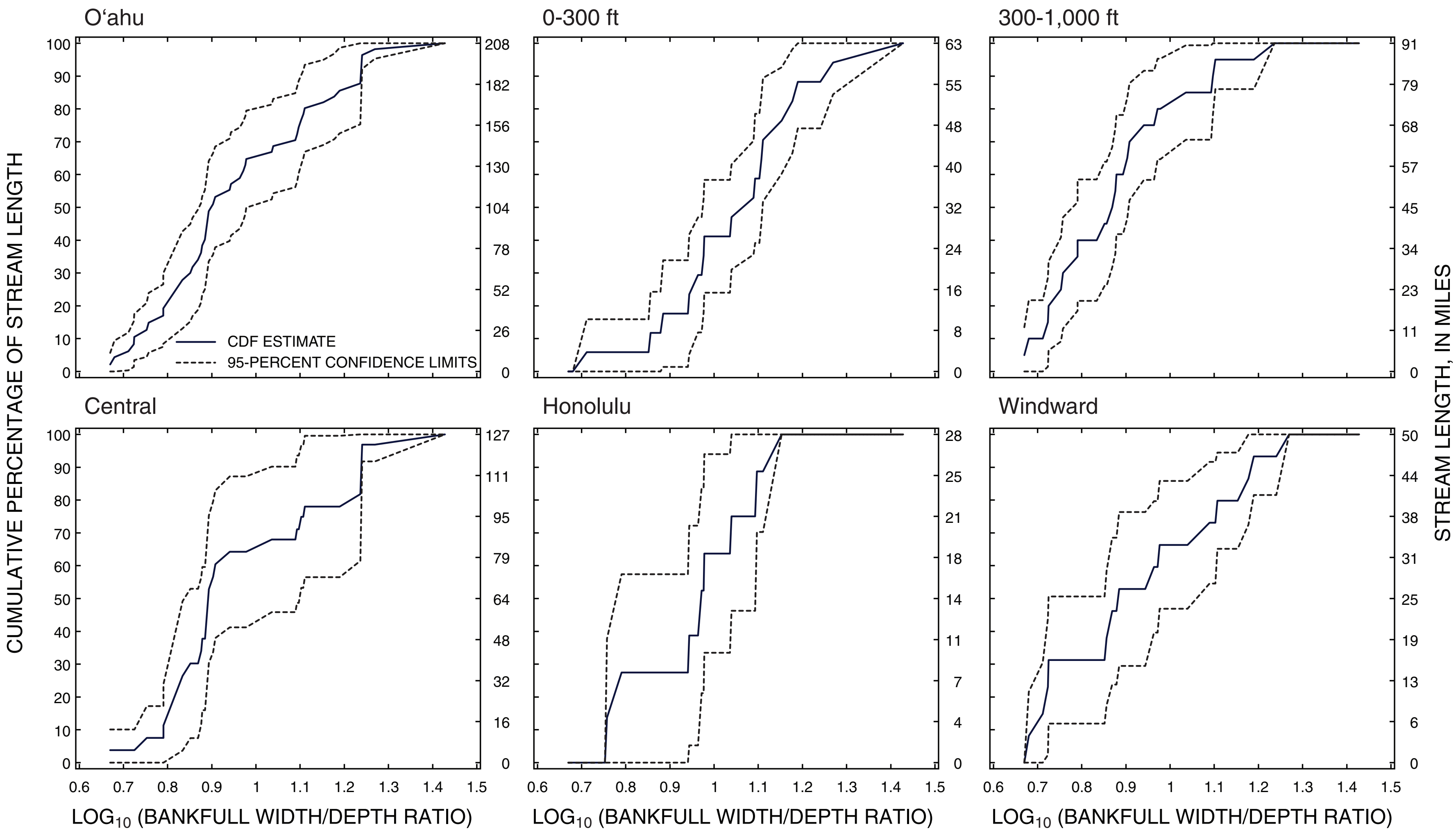

Figure D12. CDF plots of log10 of bankfull width / depth ratio (LBFWDRat).

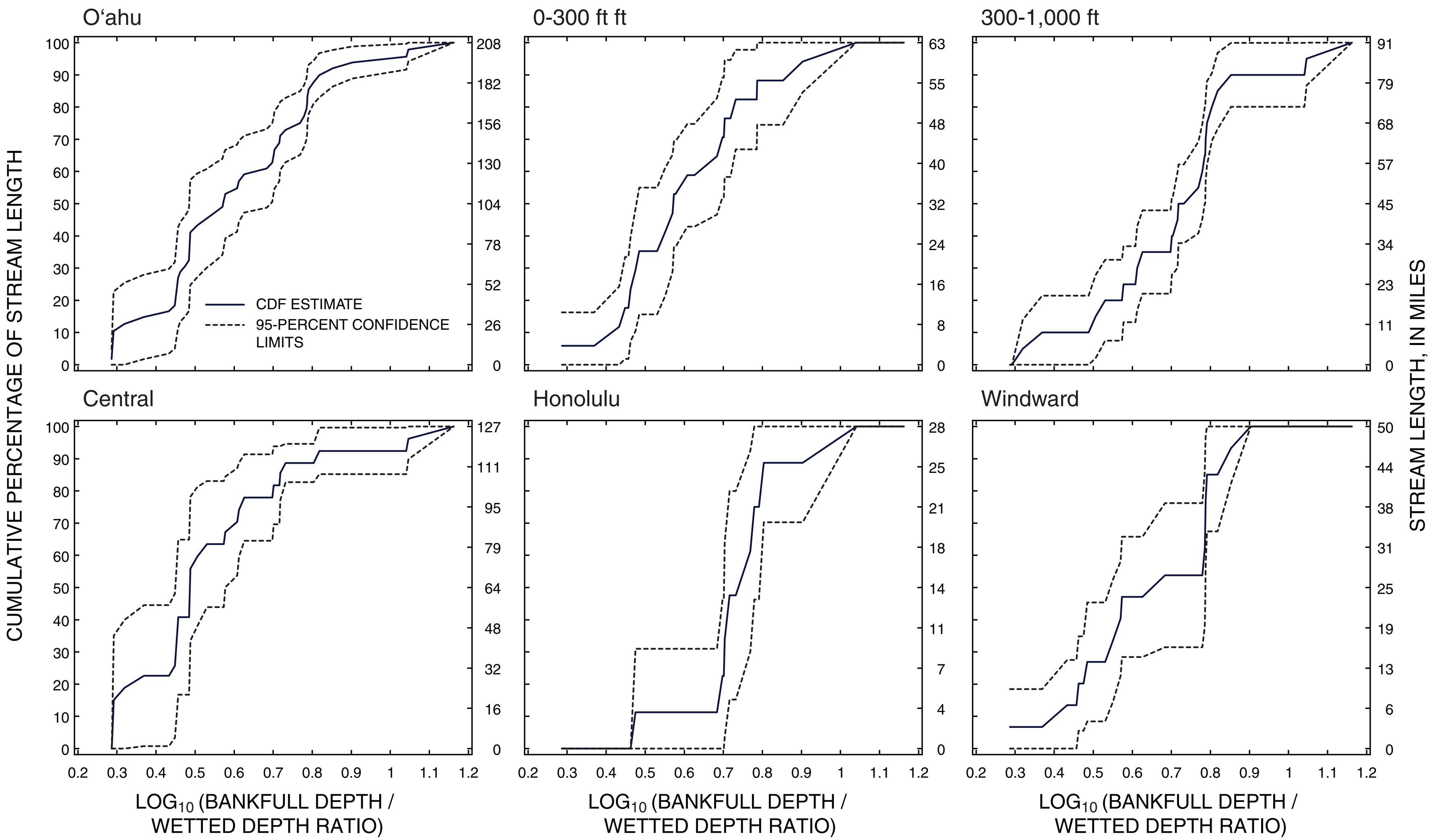

Figure D13. CDF plots of log10 of ratio of bankfull depth / wetted depth (LBFXDRat).

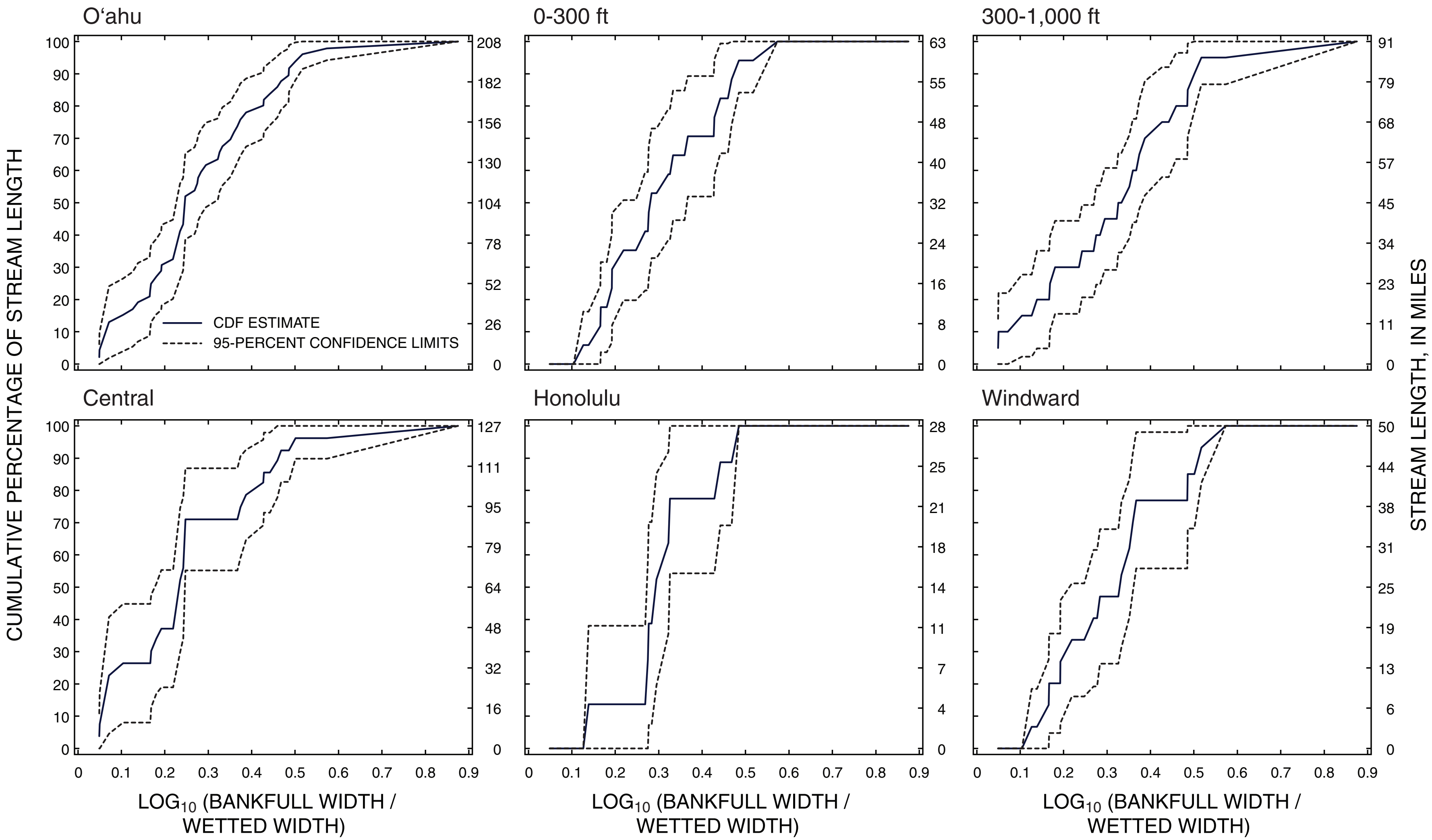

Figure D14. CDF plots of log10 of bankfull width / wetted width (LBXWRat).

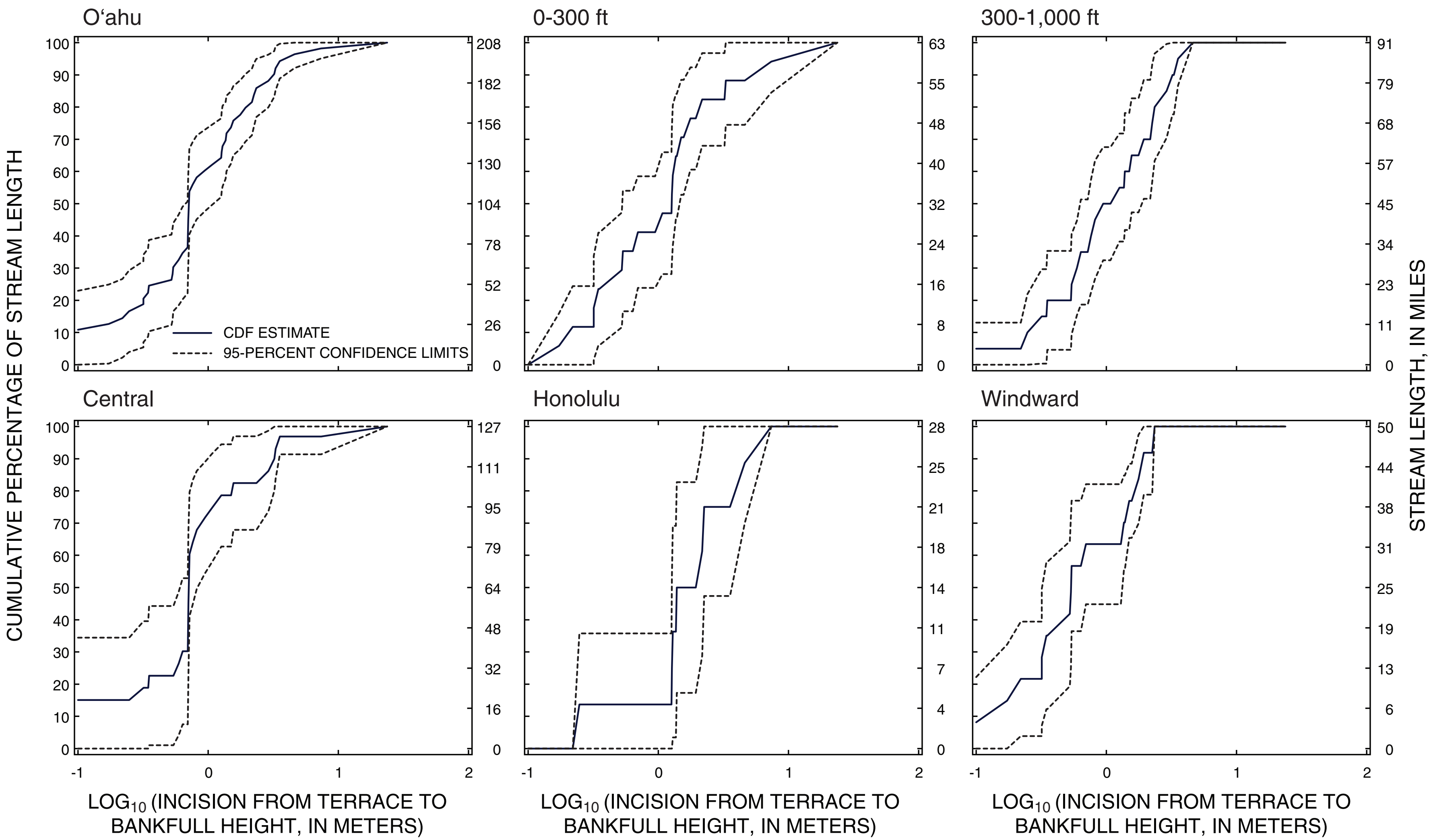

Figure D15. CDF plots of log10 of incision from terrace to bankfull height (LINCIS).

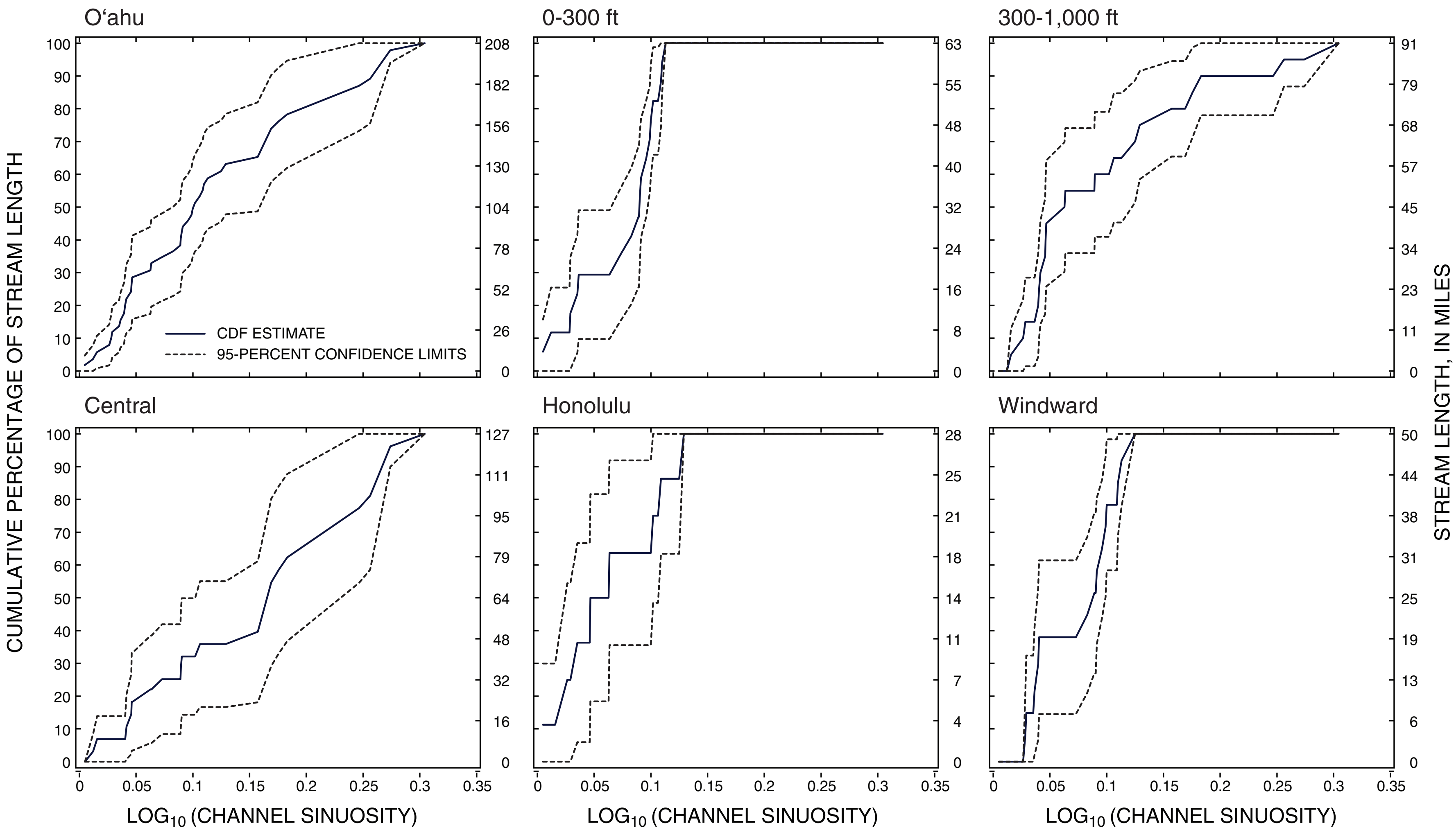

Figure D16. CDF plots of log10 of channel sinuosity (LSINU).

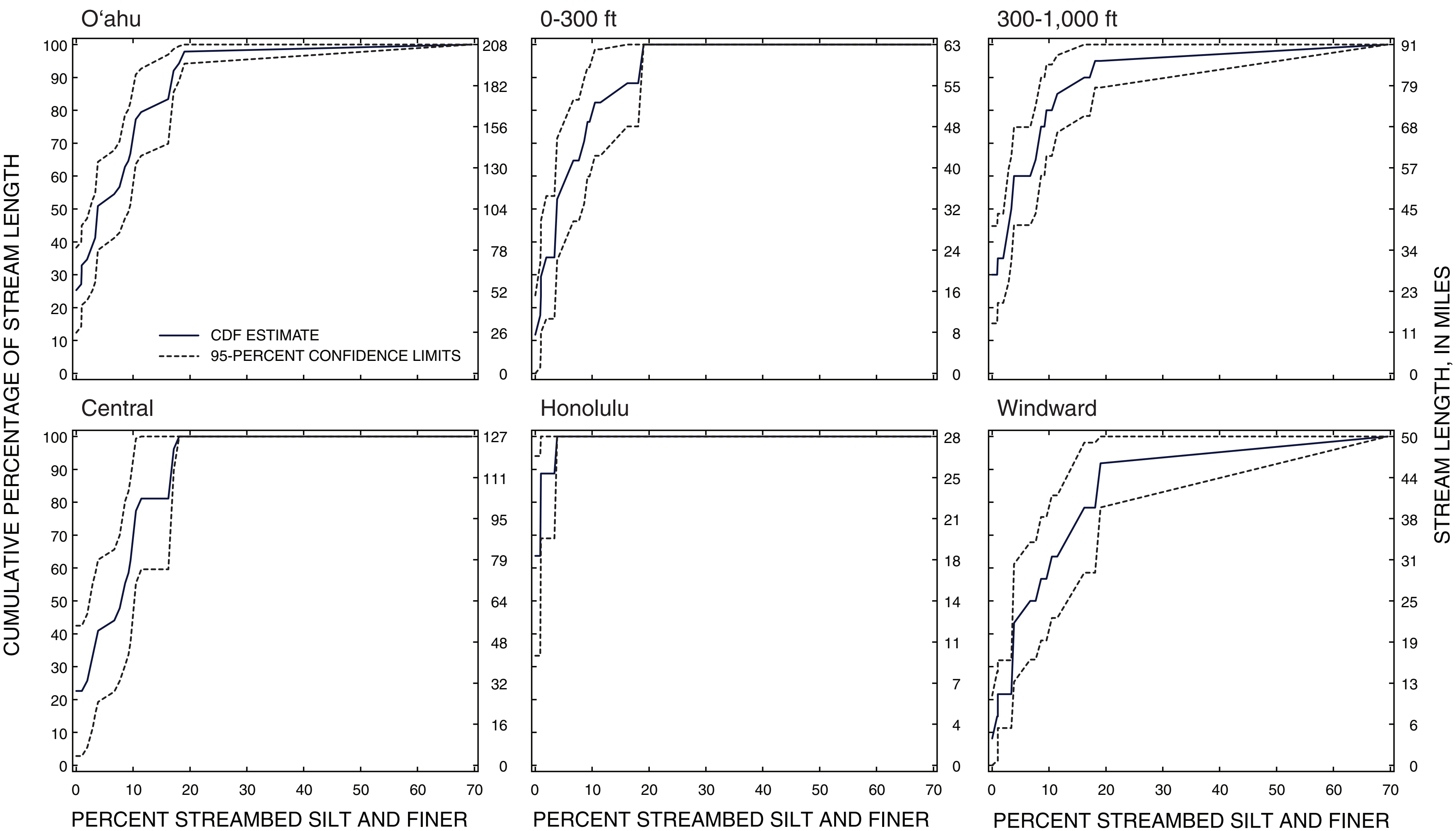

Figure D17. CDF plots of percent streambed silt and finer (PCT_FN).

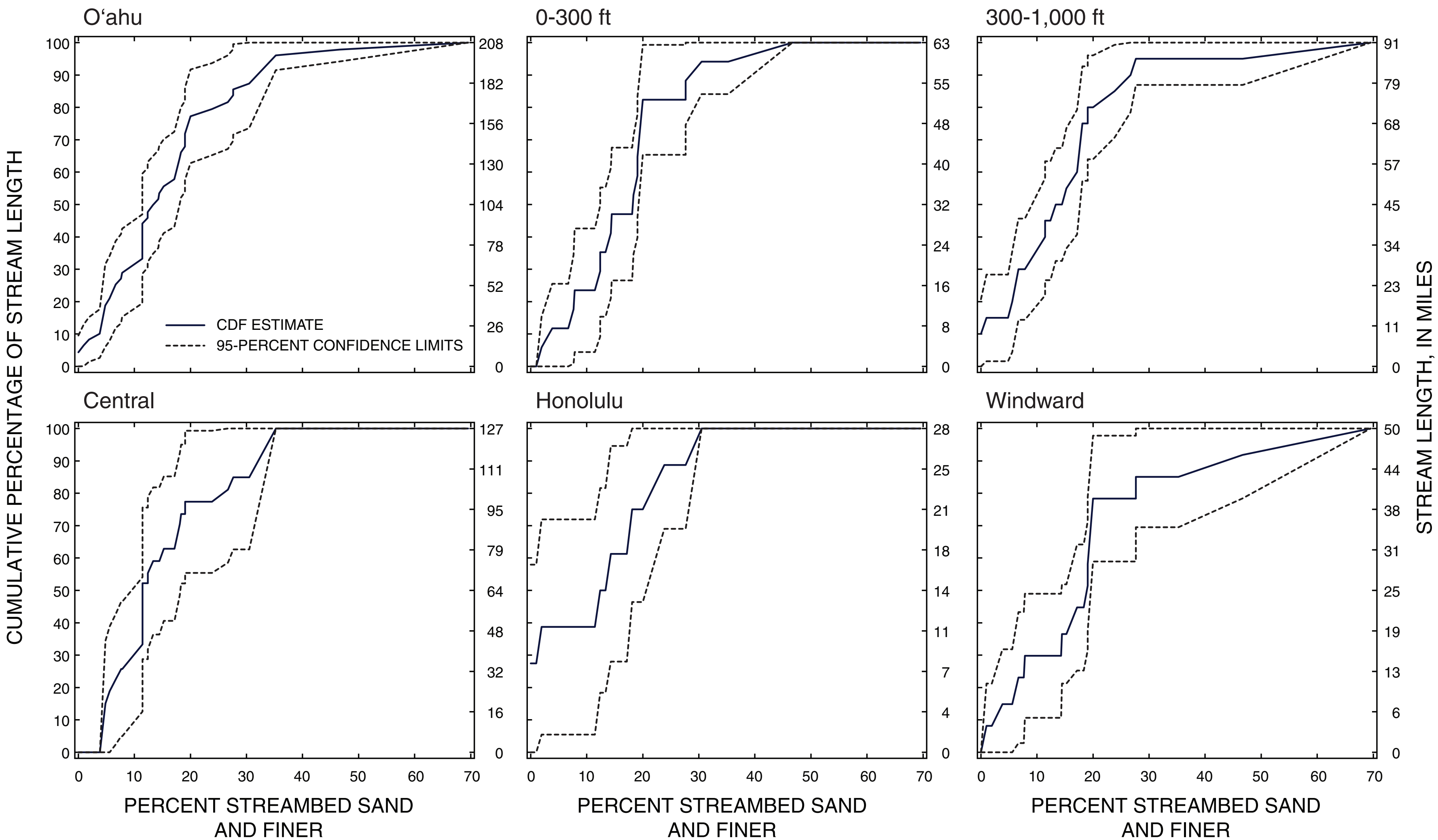

Figure D18. CDF plots of percent streambed sand and finer (PCT_SAFN).

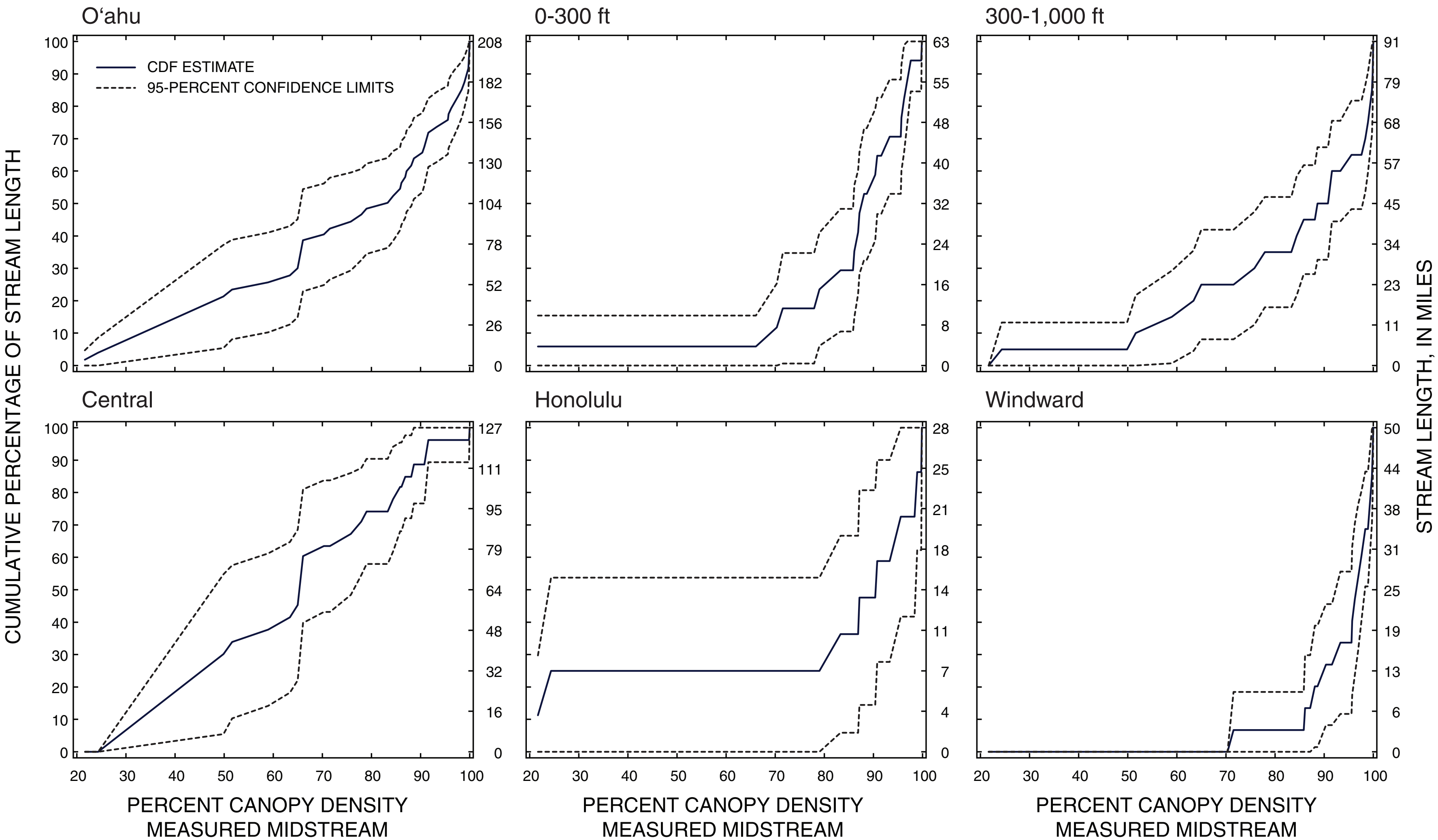

Figure D19. CDF plots of percent canopy density measured midstream (XCDENMID).

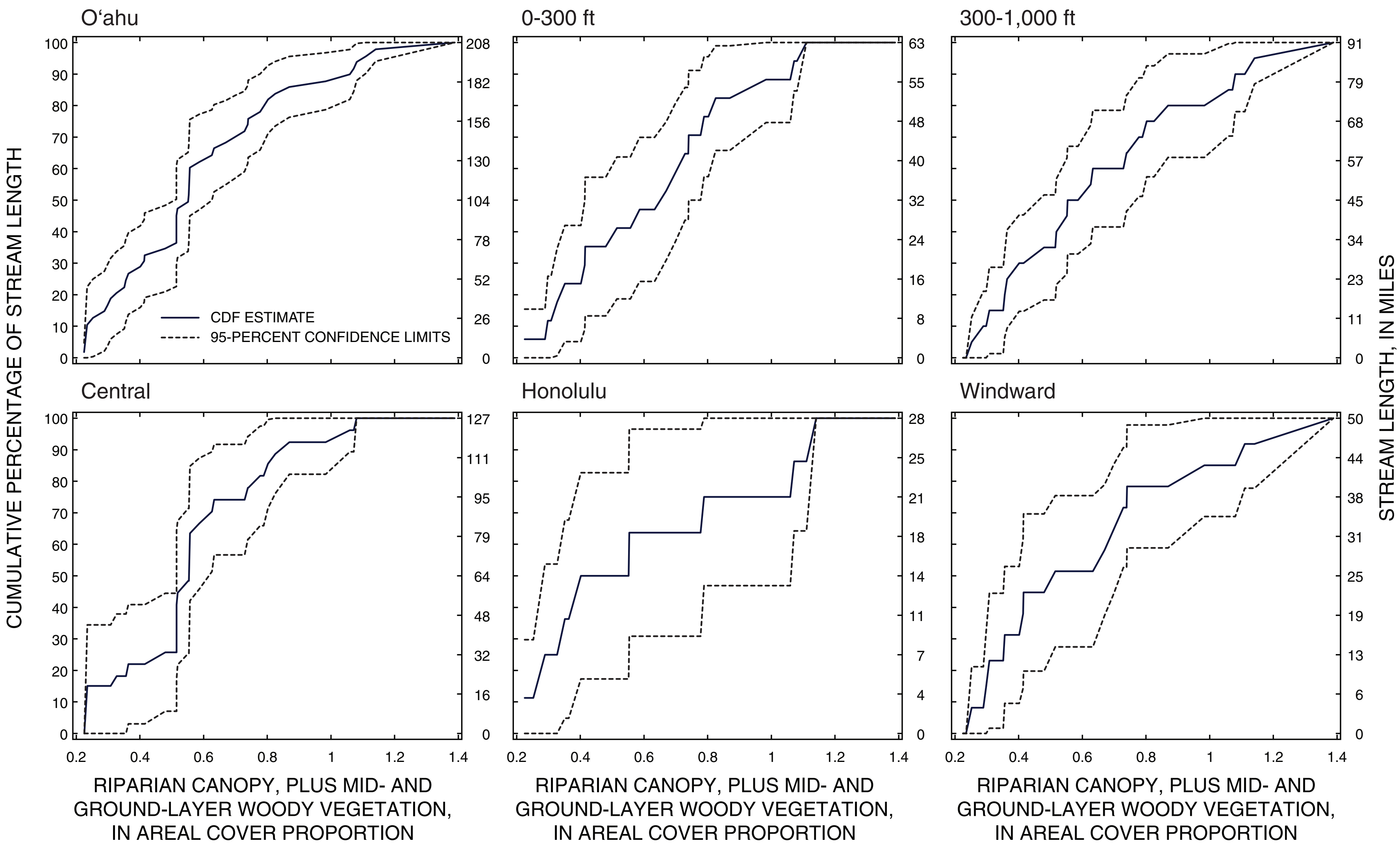

Figure D20. CDF plots of areal cover proportion of riparian canopy, plus mid- and ground-layer woody vegetation (XCMGW).

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