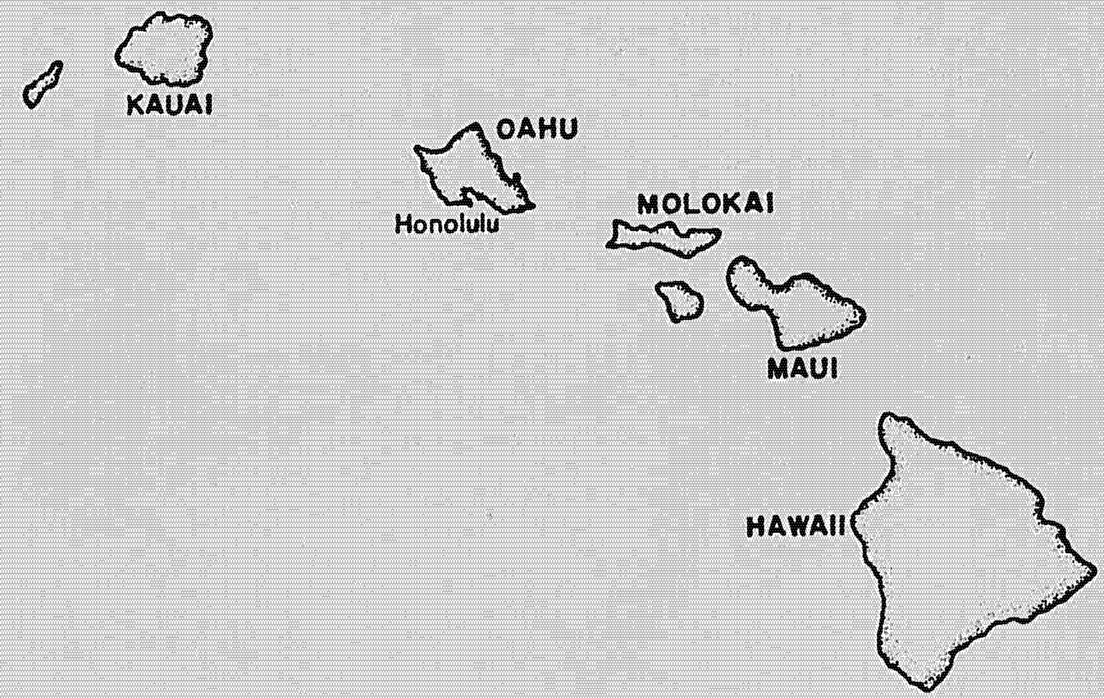
Biological Services Program

FWS/OBS-78/16
April 1978

Stream Channel Modification in Hawaii.

Part A: Statewide Inventory of Streams; Habitat Factors and Associated Biota



Fish and Wildlife Service
U.S. Department of the Interior

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FWS/OBS-78/16
April 1978

STREAM CHANNEL MODIFICATION IN HAWAII
PART A: STATEWIDE INVENTORY OF STREAMS, HABITAT FACTORS AND ASSOCIATED BIOTA

by

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Performed for:
Stream Alteration Project
Office of Biological Services
Fish and Wildlife Service
U.S. Department of the Interior

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PREFACE

This is the first of a four-part series on Stream Channel Modification (Channelization) in Hawaii and Its Effects on Native Fauna. Part A (and FWS/OBS-78/17, 18, and 19, later) was prepared for the National Stream Alteration Team to provide the much-needed baselines for evaluating future stream alteration proposals as well as ecological information applicable to the protection and preservation of native Hawaiian stream fauna. This report is an inventory of channel modifications on perennial streams and general biota survey. Stream alteration data include date of origin, type and distance from the stream mouth. Ecosystem data include discharges, stream profiles, and qualitative biota survey. Streams are classified according to ecological quality using the proposed status-use categories of the Hawaii State Department of Health. Inventory started in August 1975 and finished in September 1976. Refinement of inventory and report continued until February 1978.

Any suggestions or questions regarding Channel Modification in Hawaii should be directed to:

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EXECUTIVE SUMMARY

There are at least 366 perennial streams in the five largest islands of Hawaii. Fifteen percent of these streams have been altered. Six types of channel alteration have been identified: lined channel, channel realignment and riparian clearance, elevated culvert, revetment, filled-in channel, and extended culvert. A total length of 151 km of these modifications has been identified. The comparative "abundances" of these are: lined channel, 40%; realigned/cleared, 28%; revetment, 24%; filled-in channel, 5%; elevated culvert, 3%; and extended culvert, <1%. Eighty-nine percent of the total length of lined channel is located on Oahu.

On the basis of other human disturbances, only 14% of Hawaiian streams may be physically pristine, and none of these physically pristine streams is on Oahu, the most populous island in the State. There are apparently no longer any biologically pristine streams, since at least one exotic species was found in all streams sampled. Only 27% are of high ecological quality (pristine-preservation use), and none of these high ecological quality streams is on Oahu. Water is exported from 53% of all perennial Hawaiian streams.

Twenty-five species of fish and decapod crustaceans were collected statewide. Only eight of the species are native to the State. Both in numbers and biomass, native species are dominant in most unaltered streams, while exoitc species are dominant in altered streams.

This report was submitted in fulfillment of Contract No. 14-16-0008-1199 by the Hawaii Cooperative Fishery Research Unit under the sponsorship of the Office of Biological Services, U.S. Fish and Wildlife Service. Work was completed February 28, 1978.

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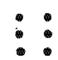
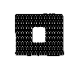
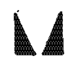
ABBREVIATIONS

cm	centimeters
cm^3/s	cubic centimeters per second
km	kilometers
km^2	square kilometers
m	meters
m^3/s	cubic meters per second
µmhos	micromhos
USGS	United States Geological Survey

SYMBOLS

A	channel altered
C	continuous stream
Ca	Calcium
$CaCO_3$	Calcium carbonate
I	interrupted
K	Potassium
Mg	Magnesium
N	channel not altered
Na	Sodium
●	abundant
◐	common
○	rare-occasional
	lined channel
	realigned/cleared
	elevated culvert
	revetment
	blocked or filled-in
	extended culvert

°C	degrees, Celsius
NW	northwest
SE	southeast
°N	degrees, North latitude
°W	degrees, West longitude

ACKNOWLEDGMENTS

The following made critical reviews and valuable suggestions: James M. Brown and Robert Little of the National Stream Alteration Team, Columbia, Missouri; Robert P. Hayden, Regional Activity Leader, Stream Alterations, Sacramento, California; James E. Maragos, U.S. Army Corps of Engineers, Honolulu, Hawaii; and Maurice H. Taylor, Field Supervisor, Ecological Services, Honolulu, Hawaii. James D. Parrish made critical reviews, valuable suggestions and supervised the preparation of the final camera-ready copy. Carl Couret, Lawrence Cowles, and Susan Norton of the Hawaii Cooperative Fishery Research Unit and Michael Nishimoto of Ecological Services, Honolulu, Hawaii, assisted in the field work. Sharon Honda did the typing and Ismael Trono prepared the illustrations.

INTRODUCTION

Numerous perennial streams occur on the five largest islands in the State, representing the principal environments of native freshwater animals. Most streams are small by continental standards, their drainage basins and flows being functions of the size, elevation, and geological age of the island, and of the nature of local rainfall. Characteristic flows are seasonally variable, with discharge fluctuations up to a thousandfold recorded from summer lows to winter freshets. Cultural modifications of natural stream ecosystems have been most severe at lower elevations. Channel modification is one of the three principal cultural changes, the others being dewatering (mainly for irrigation) and the introduction of exotic species.

Although perennial streams constitute Hawaii's principal type of inland aquatic ecosystem, no comprehensive list of streams nor descriptive inventory of channelization exists. The effects of channel modifications have been observed only superficially. The purposes of this study are: (1) to produce an inventory of all perennial streams of Hawaii that emphasizes significant channel modifications statewide by design type, size, age and geographic location; (2) to assess relevant environmental parameters that may influence the occurrence and abundance of native stream animals; (3) to make an inventory of stream macrofauna, particularly that associated with modified channels; and (4) to discern one or more species whose presence indicates reasonably pristine conditions.

BACKGROUND

STREAM FAUNA

Hawaii's native stream fauna is unique in several ways. It is particularly adapted to the rocky, precipitous, freshet-flow nature of Hawaiian streams. The number of species within a given taxon are few but most of them are endemic. Excluding insects, all larger native stream species are diadromous (having marine larval development) as a consequence of invasion from the oceanic ecosystem and incomplete adaptation to freshwater life. These diadromous animals include 6 fish species (5 of them endemic), 2 mollusks (1 endemic), 2 shrimps (both endemic), and a polychaete worm. Among the fishes, the goby, Lentipes concolor, is on the American Fisheries Society list of rare and endangered species, and three other species are considered as threatened (Miller 1972). Perhaps it is no coincidence that Lentipes, originally described in part from Oahu where today channel modification is most extensive, is now unknown on that island. Furthermore, unpublished surveys indicated that two other Hawaiian stream endemics, a freshwater limpet (Neritina granosa) and a prawn (Macrobrachium grandimanus), are becoming depleted.

Some native stream species provide an unmanaged fishery; goby (Awaous stamineus), freshwater limpet (N. granosa), atyid shrimp (Atya bisulcata), and prawn (M. grandimanus), are important locally as traditional food items and are marketed commercially. The impact of channelization on fauna of oceanic islands such as Hawaii can be especially severe inasmuch as the most extensive modifications are developed mainly on the lower reaches of streams. These reaches, in addition to being habitats of some species, are the essential migratory pathways for both seaward-moving larvae and returning juveniles of the native species inhabiting the upper reaches (see also Table 1).

Superimposed on the native animal communities are a large number of introduced aquatic species, most of which are highly successful competitors or predators. Within a group of nearly 50 foreign non-marine animals (decapod crustaceans, mollusks, amphibians, and mostly fishes) known to have been released in Hawaii, 36 species have become established. Among the 36 established exotics, 27 species are found in streams (Kanayama 1968). In addition, many species of foreign aquatic insects and lower invertebrates also occur in streams. Considering overall diversity of stream fauna and relative unobtrusiveness of many species, faunal inventory in this project

Table 1. Characteristic Fish and Decapod Crustacean Inhabitants of Hawaiian Streams[a]

Scientific name	Common name	Local name	Status[b]
Crustaceans			
Atya bisulcata	Atyid shrimp	Opae kalaole	Endemic
Macrobrachium grandimanus	Hawaiian prawn	Opae oehaa	Endemic
Macrobrachium lar	Tahitian prawn	--	Introduced
Procambarus clarkii	Crayfish	--	Introduced
Fishes			
Awaous genivittatus	Goby	O'opu naniha	Indigenous
Awaous stamineus	Goby	O'opu nakea	Endemic
Cichlasoma sp.	Cichlid	--	Introduced
Clarias fuscus	Chinese catfish	--	Introduced
Cyprinus carpio	Carp	Koi	Introduced
Eleotris sandwicensis	Eleotrid	O'opu okuhe	Endemic
Gambusia affinis	Mosquitofish	Medaka	Introduced
Kuhlia sandvicensis	Kuhliid	Aholehole	Endemic
Lentipes concolor	Goby	O'opu alamoo	Endemic
Lepomis macrochirus	Bluegill	--	Introduced
Micropterus dolomieui	Smallmouth bass	--	Introduced
Misgurnus anguillicaudatus	Oriental weatherfish Loach	Dojo	Introduced
Ophicephalus striatus	Snakehead	--	Introduced

Continued

Table 1 (Concluded)

Scientific Name	Common Name	Local Name	Status
Poecilia latipinna	Sailfin molly	--	Introduced
Poecilia mexicana	Shortfin molly	--	Introduced
Poecilia reticulata	Guppy	--	Introduced
Poecilia vittata	Topminnow	--	Introduced
Sicydium stimpsoni	Goby	O'opu nopili	Endemic
Tilapia (= Sarotherodon) mossambica[c]	Tilapia, Mossambique mouthbrooder	--	Introduced
Xiphophorus helleri	Green swordtail	--	Introduced
Xiphophorus maculatus	Southern platyfish	--	Introduced

[a]For a complete list of aquatic macrofauna in large Hawaiian streams, see Timbol, 1977.

[b]The terms "endemic" and "indigenous" are used to designate "occurring naturally in Hawaii only" and "occurring naturally in Hawaii and also elsewhere", respectively. According to Maciolek (MS) all five gobies (o'opu) and the Hawaiian prawn are "obligately diadromous, meaning they must travel twice between sea and stream habitats as a necessary part of their life cycles." The atyid shrimp is also diadromous but possibly can complete its life cycle entirely in the stream.

[c]Other tilapia species, T. macrochir, T. melanopleura, and T. zilli, are known to be established in Hawaii's streams.

was limited to the most representative taxa of large stream animals that were easiest to collect, identify, and observe: fishes and decapod crustaceans.

PHYSIOGRAPHY AND THE STREAM ENVIRONMENT

The inhabited (high) islands of the Hawaiian Archipelago are arranged in a NW → SE line 1,110 km long between latitudes 22° N and 19°N. This portion of the State is entirely within the Torrid Zone, but because of cooler winds flowing over it, it is considered as subtropical (Stearns 1946). The six major islands, from west to east, are: Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii (Fig. 1). The islands are successively younger from Kauai to Hawaii (Zimmerman 1948).

According to Blumenstock and Price (1967), Hawaii has only two seasons, a winter season of seven months (October through April) and a summer season of only five months (May through September). Persistent rainfall is associated with tradewinds (orographic) and seasonal storms with frontal systems. Rainfall distribution is highly variable, from less than 30 cm/yr in leeward coastal areas to over 760 cm/yr along the windward slopes of high mountains or near the summits of lower mountains. The temperature regime is not as variable as the rainfall pattern, at least in the lowlands. Daytime temperatures range from 20 to 26° C and nighttime temperatures from 15 to 20° C.

To provide a background for understanding the nature of stream and related ecosystems in Hawaii, the description of a representative stream is helpful. Kahana, on the windward coast of Oahu, which has been studied previously (Kubota 1972, Timbol 1972), is presented here as an example. It is one of the few unaltered Oahu streams to have permanent and unpolluted flow from headwaters to the sea. The Kahana mainstream averages about 8 m wide and has a depth range between 1 and 4 m, while Kawa tributary averages 4 m wide with a depth range between 0.3 and 1.2 m. Stream flow at elevations between 10 and 180 m is turbulent. Above 180 m, the stream is reduced to a series of pools and steep rivulets which flow intermittently. Kahana mainstream has a long-term mean discharge of 0.49 m^3/sec (Takasaki et al. 1969). Another 0.25 m^3/sec is exported from the valley (USGS 1968). Short-term data for Kawa tributary show an annual mean discharge between 0.07 m^3/sec (1914-1917) and 0.12 m^3/sec (1960-62) (USGS 1962). Daytime surface water temperature for the stream system in the year 1970-1971 averaged 22° C (range 18 - 24° C). Conductivity was low with a mean value of 106 µmhos (range 80 - 146).

CHANNELIZATION

Continued channel modification in Hawaii is certain, as evidenced by current channelization proposals for Kahoma and Iao Streams on Maui and Makaha Stream on Oahu. Presently on Oahu, a dam is being constructed across Kamooalii tributary of Kaneohe Stream. Environmental commentary is difficult because of the lack of definitive information on the effects of

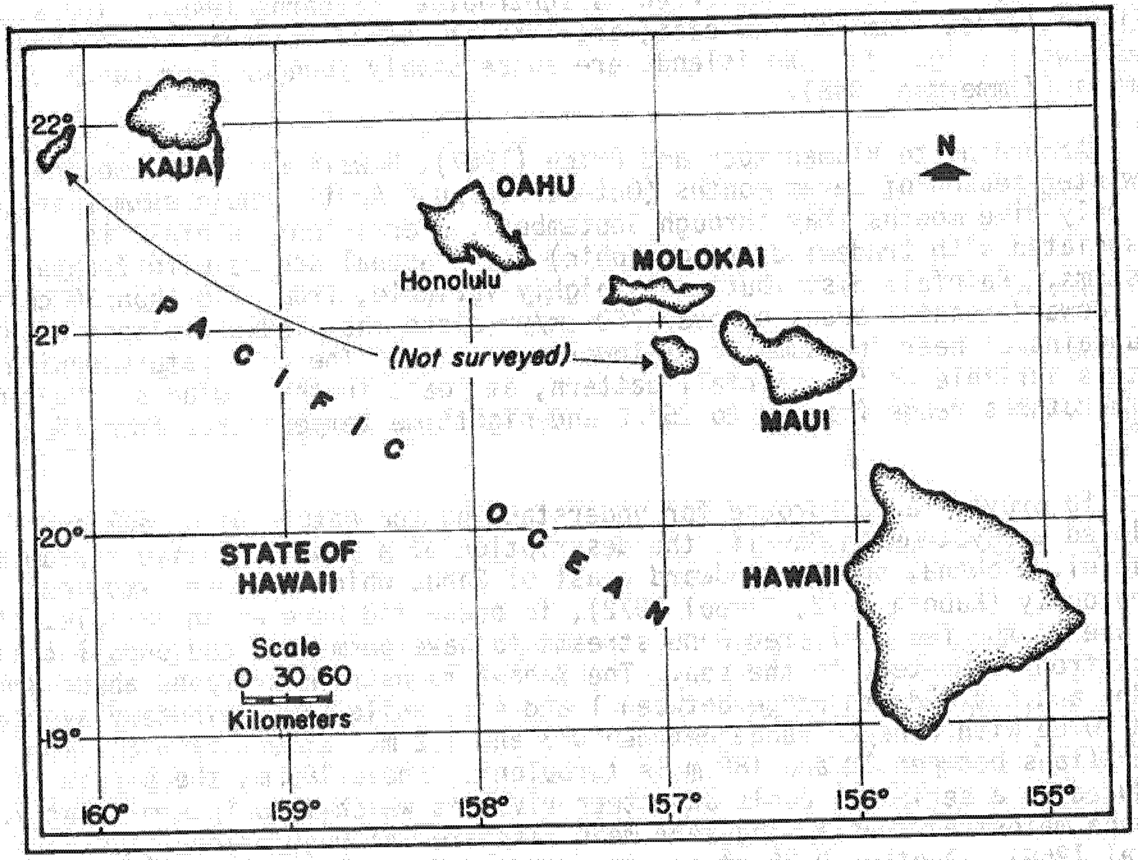


Figure 1. The State of Hawaii showing the five major islands surveyed for stream channel modification.

channelization either on total stream ecology or on individual native species. Past commentaries have been based on generalized information (mainland U.S. and limited ecological data on Hawaiian streams) and a few specific observations on local channelization effects. Concrete-lined flat-bottom channels, as shown in Fig. 2, obviously provide no habitat for native fishes and crustaceans, and expose water to excessive insolation. The effects of such lined channels on the quality and quantity of fauna upstream (i.e., effects on migration) or on the downstream environment (e.g., heating) are unknown. Such are examples of the principal informational needs today.

This report concerns that portion of the project involving a one-year (August 1975 - September 1976) statewide, exhaustive inventory of perennial streams with channel modifications, including a general survey of habitat factors and macrofauna. It includes the islands of Kauai, Oahu, Molokai, Maui, and Hawaii (Fig. 1). Niihau and Lanai, the remaining two inhabited islands in the State, were not surveyed. Niihau is small, relatively arid, and under private ownership that prohibits entry of non-residents. Lanai apparently has only one stream, and it is located in an area of difficult access. It is assumed that this lone stream is not channelized.

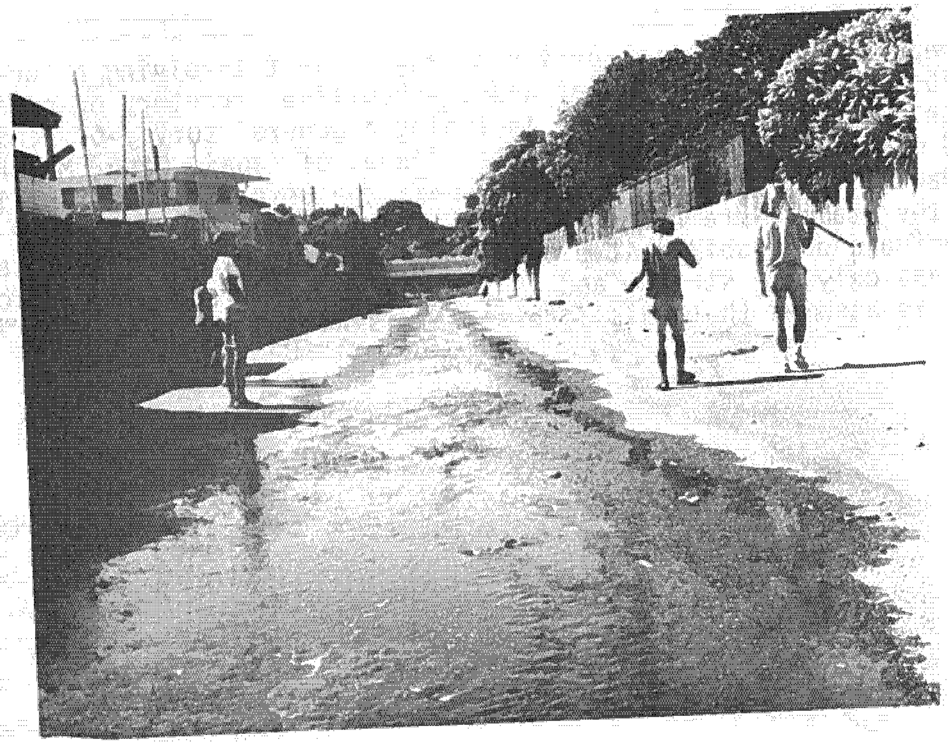


Figure 2. Lined channel of lower Palolo Stream, a tributary of Manoa Stream, Honolulu. Flat bed spreads low-flow water into a thin sheet that provides no shelter for native fishes or crustaceans and causes excessive solar heating.

METHODS

For project purposes, a stream is defined as surface water flowing in a discrete channel or channel system that discharges to the ocean at a single point. Thus, a given stream may have a single dominant channel or a complex of branching tributaries. Two classes of perennial streams are distinguished: Continuous streams flow naturally to the sea year-round under normal conditions; Interrupted streams have ecologically significant perennial water in their upper watercourses and intermittent flow in their channels at low elevations. Interrupted streams discharge into the sea occasionally during the wet seasons. These terms are applied both to mainstream and named tributaries.

STREAM SURVEY

A list of streams was prepared from USGS quadrangle maps of the various islands of the State. Channel modifications were identified from field surveys and from the 1975 Real Estate Atlas. The channel modifications and alterations considered in this report are defined in the legend for Appendix B. Total lengths of channelized streams were estimated by measurement of the watercourses drawn on the USGS quadrangle maps and field checked. Lengths of altered channel sections were determined by measurement from the Real Estate Atlas whenever possible. Dates of channel modifications were obtained from various governmental agencies. Maps of the drainages and channels of altered streams were prepared from USGS topographic maps for each island (scale = 1:62,500) and in some cases from topographic quadrangle sheets (scale = 1:24,000). Discharges are from USGS water-data reports. Water diversion information, which includes diversions by water tunnels, aqueducts, ditches, flumes, siphons, wells, pumps, and reservoirs, comes from USGS topographic quad sheets (1957, 1963). Roadways crossing stream channels, which include heavy-duty, medium-duty, light-duty, and unimproved dirt roads but not hiking trails, also come from these maps. Water quality standards are those proposed by the Hawaii Department of Health (Hawaii Department of Health 1977).

PHYSICOCHEMICAL

Water temperature and dissolved oxygen were determined with the use of a YSI Model 54 oxygen meter, conductivity with a YSI Model 33 S-C-T meter, and pH with an AM Model 107 analytical pocket pH meter. Additional information came from USGS and Hawaii State Department of Health publications.

BIOLOGICAL

Stream macrofauna collections were made with battery- and generator-energized backpack electroshockers. Electrofishing was employed because it is the most effective and quickest method of sampling the principal stream animals: fishes and decapod crustaceans. The term "macrofauna" as used herein, is thus applied to include all species within those two major taxa. In most cases, collections from a given stream were made at three locations: in the freshwater portion nearest to the mouth, within the altered channel, and upstream from channel modifications. All specimens collected from a 20 m X 1 m sampling zone were counted, measured, and weighed for abundance and distribution data. Generally, electroshocking was continued beyond the 20-m zone to determine if additional species were present. Species found by sampling or sighting beyond the 20-m zone are included in the inventory of specimens. Because collections were made in small sections of channel, usually in lower stream reaches, faunal inventories here do not represent species complement or distribution of fishes and crustaceans in the entirety of any given stream (see comments under FAUNA OF OAHU STREAMS).

The inherent limitations of the electroshocking method should be considered when looking at the abundance and distribution results. The shocker effectiveness may be limited to shallow waters, and the stunned organisms may collect under any cover available (Riggs 1953). Furthermore, the efficiency of electrofishing in streams is directly affected by the behavior, habitats, and morphology of the species (Larimore 1961). However, since data are given here in relative terms of rare-occasional, common, and abundant, it can be safely assumed that the measured abundances and distributions of the macrofauna permit realistic comparisons. For project purposes, rare-occasional (O) indicates that either only one specimen was collected per sampling or it was sighted but not captured. Common (◐) indicates that the species is obtained every time a collection is made but not in abundance (usually between 2 and 5 specimens). Abundant (●) means many specimens are obtained in a collection (usually 6 to 100 or more).

References used in the identification of specimens were:

Fishes: Gosline and Brock 1960
Jordan and Evermann 1903

Crabs: Edmondson 1946
Rathbun 1906

Prawns and shrimps: Edmondson 1929
Holthuis 1950, 1951-1952
Rathbun 1906

Unfamiliar fish specimens were sent to the Smithsonian Institution and identified by Dr. William Fink.

HAWAIIAN STREAMS AND TYPES OF MODIFICATIONS

All perennial streams on the five islands surveyed are listed in Appendix A. In addition, Appendix A includes information on stream mouth locations by grid coordinates, topographic map name wherein located, water diversions, number of roadways crossing stream channels, and ecological quality status for each stream. Six types of channel modifications are distinguished (see also symbols, Fig. 11):

1. Lined channel. An artificial channel having both natural banks and stream bed replaced, usually with concrete. It may be flat bottom or v-shaped. Representative examples are in Palolo tributary of Manoa Stream and Ahuimanu tributary of Kahaluu Stream (Figs. 3 and 4).

2. Vegetation removed-channel realigned. Represented by Kapalama Stream (Fig. 5).

3. Elevated culvert. These are conduit structures that are comparatively short (typically <60 m), usually found under highways. Culverts placed in this category include only those where the culvert level is well above the water level immediately downstream, i.e., the culvert creates an artificial waterfall. An example of an elevated culvert is in Aolani tributary of Kaneohe Stream (Fig. 6). The numerous, short culverts at stream channel level were not inventoried.

4. Revetment. Where one or both banks of the stream are reinforced but the channel bed is not, as in Kalihi Stream (Fig. 7).

5. Blocked or filled-in channel. Where part of the original channel is blocked as in Pauoa tributary of Nuuanu Stream (Fig. 8).

6. Extended culvert. This is a longer version of modification type 3, usually found in residential areas as in Kawa Stream (Fig. 9).

Older examples of stream channel modification are the result of bridge building. The oldest forms of channel modification are clearing-realignment and revetments to reinforce stream banks. Most of these types of modifications on Oahu Island were done in the 1930 - 1950 period. The most significant form of modification ecologically and numerically is the lined

Figure 3. This flat-bottom lined channel (modification type 1) in Palolo tributary of Manoa Stream, Honolulu, is typical of lined channels found in streams on Oahu.

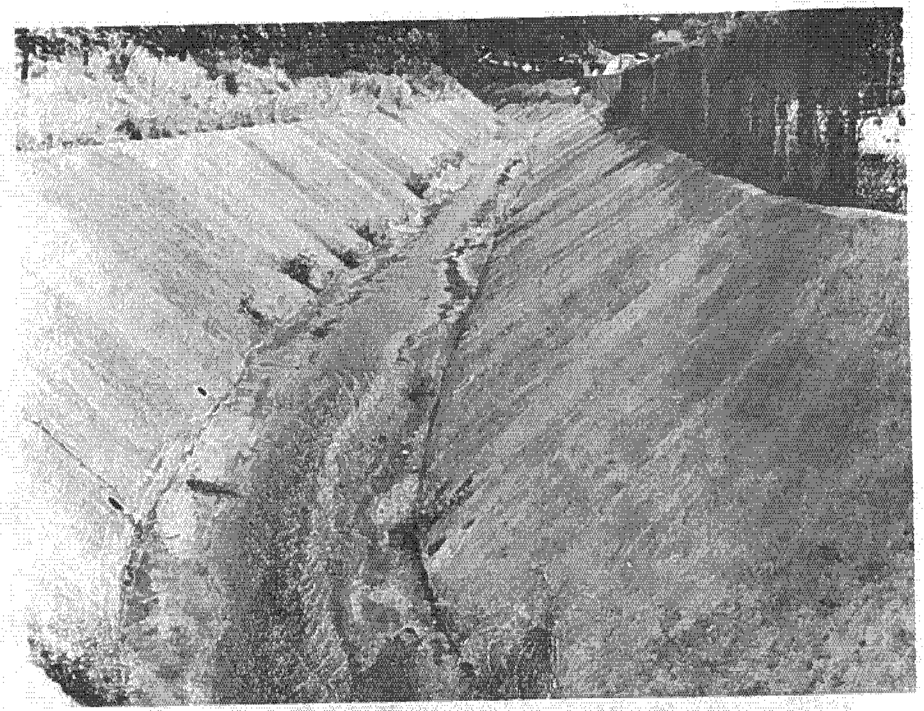


Figure 4. This lined channel in Ahuimanu tributary of Kahaluu Stream on windward Oahu, is representative of v-shaped construction with reduced flat-bottom area (modification type 1).

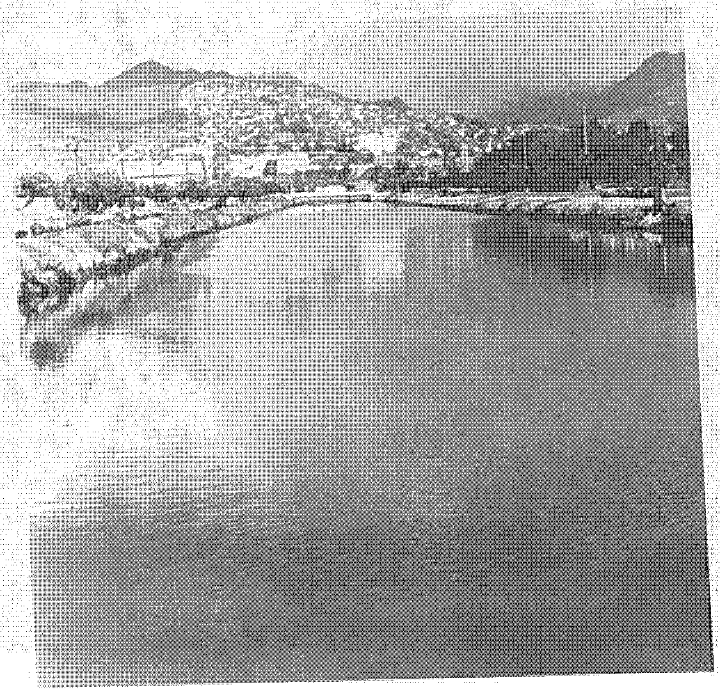


Figure 5. Kapalama Stream, between Dillingham Boulevard and North King Street in Honolulu, is an example of a realigned stream which has also been cleared of riparian vegetation (modification type 2).

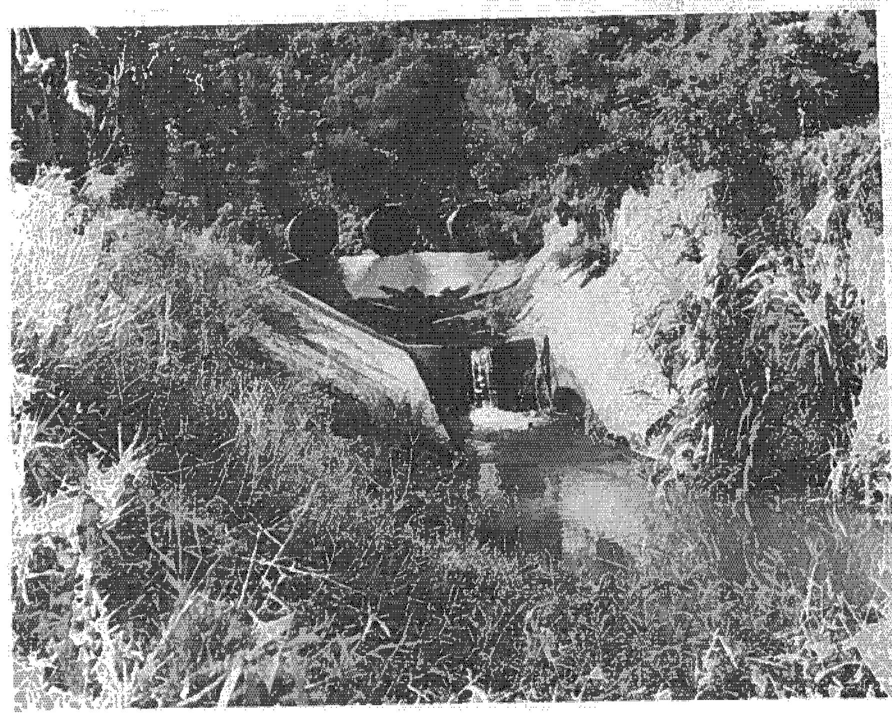


Figure 6. Road and highway crossings often involve elevated culverts (modification type 3). This elevated culvert arrangement was constructed where Kahekili Highway crosses Aolani tributary of Kaneohe Stream, windward Oahu.

Figure 7. Revetments in Kalihi Stream, Honolulu (modification type 4). Stream bed is natural material; revetted banks consist of mortared rock and concrete sections.

Figure 8. A filled-in portion of Pauoa tributary of Nuuanu Stream, Honolulu (modification type 5). View is "downstream" from former bridge crossing at Iliahi Lane. Foreground rock wall is part of original bridge; former channel extended from fence on left to right edge of photograph.

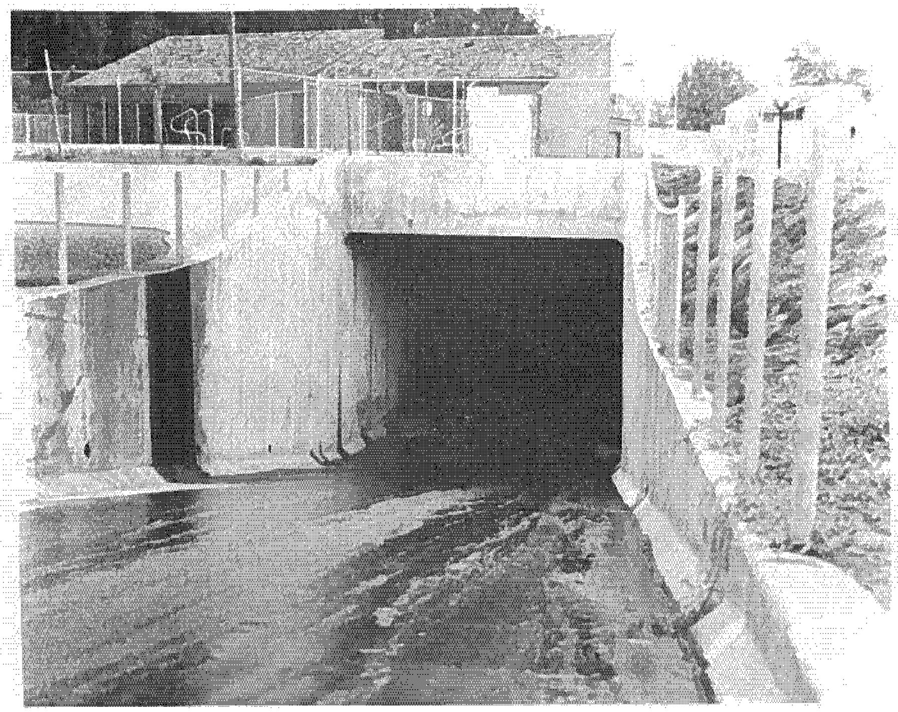


Figure 9. Upstream end of an extended culvert on Kawa Stream at Kaneohe (modification type 6). This structure is located in the Parkway subdivision.

channel, the earliest of which was built in 1938 at Kapalama Stream. Lined channels represent a majority of recently built flood-control structures.

For each stream surveyed with an altered channel, Appendix B contains a map showing watershed limits, mainstream channel and principal tributaries, the longitudinal gradient of mainstream, and the types and approximate locations of channel modifications. Locations of biological samples and relative abundances of species are also shown.

Pressures of an increasing population have a direct, mostly adverse effect on streams, especially small streams. An ever increasing amount of stream water is diverted both for agricultural purposes and domestic use to support the population. Also, new lands are opened for agricultural and housing purposes, resulting in more roads crossing over streams, less tree and grass cover, greater sediment loads, and stream channel alterations. The removal of natural vegetation inevitably alters the pattern of stream discharge (Hynes 1970). This report explores the extent to which Hawaiian streams have been degraded. For purposes of this report, a high quality stream is a completely natural stream that has not been changed detectably by human intervention, physically or biologically (Maciolek MS). A physically pristine stream is one where the stream channel has not been altered, its water is not diverted, and no roads (except foot trails) cross over it. A biologically pristine stream is one where only native species live.

STREAM AND FAUNA INVENTORY: OAHU ISLAND

STREAMS AND CHANNEL MODIFICATIONS

Oahu is the third largest island, measuring 71 by 48 km at its extreme dimensions and having an area of 1,564 km^2 (Foote et al. 1972). It emerged from the ocean during the Tertiary and possibly early Pleistocene (Stearns and Vaksik 1935). Two mountain ranges dominate the island's topography; Waianae rises to 1,227 m while Koolau reaches 960 m. Due to mountain configurations, rainfall gradients are steep, ca. 64 cm/km on the average. Rain varies from 50 to 635 cm/year on Oahu. Mean air temperature in Honolulu is 24° C with an absolute range of 11 - 32° C (Blumenstock and Price 1967).

Fifty-four perennial streams have been recognized on Oahu and are listed in Appendix A. Fifty-three percent of these are continuous and 47% are interrupted. Of the 54 streams, 31 (57%) are channelized. The locations of the altered (channelized) streams are shown in Fig. 10 and their features summarized in Table 2.

Among channelized streams, Waikele (Fig. 11) on the leeward side of Oahu, is the largest on the basis of stream length and watershed area. Keaahala (Fig. 12), on the windward side, is the smallest. Waiawa exhibited the highest discharge for a single day (663 m^3/s on January 5, 1958 per USGS 1975), and Waikele showed the highest long-term average discharge (1.1 m^3/s, 21-year average; USGS 1975). Watershed limits, stream channels, longitudinal gradient of mainstream, and approximate locations of the channelized portions in each stream are shown in Appendix B.

A total of 134 km of modified channels occurs among the 31 altered streams. The relative "abundance" of each type of channel modification is indicated by its combined length in all 31 altered streams. Expressed as a percentage of the 134 km total altered channel length for the island:

- Lined channel - 43%;
- Cleared and realigned - 27%;
- Revetment - 23%;
- Blocked - 6%;
- Elevated culvert - <1%
- Extended culvert - <1%.

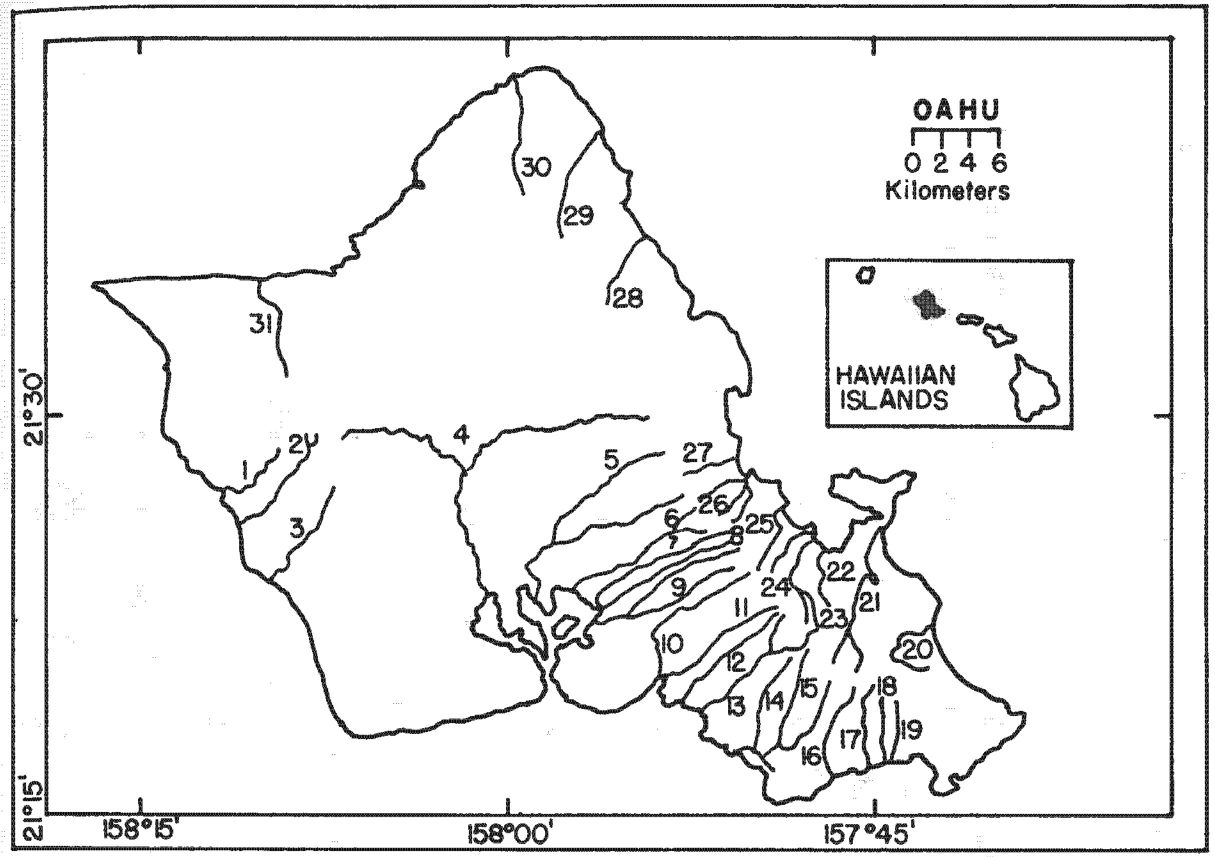


Figure 10. Location map for 31 Oahu streams having modified channels. Percentage of streams altered = 31/54 = 57%.

Legend:

1. Kaupuni Stream
2. Mailiili Stream
3. Ulehawa Stream
4. Waikele Stream
5. Waiawa Stream
6. Waimalu Stream
7. Kalauao Stream
8. Aiea Stream
9. Halawa Stream
10. Moanalua Stream
11. Kalihi Stream
12. Kapalama Stream
13. Nuuanu Stream
14. Makiki Stream
15. Manoa Stream
16. Waialaenui Stream
17. Wailupe Stream
18. Pia Stream
19. Kuliouou Stream
20. Waimanalo Stream
21. Maunawili Stream
22. Kawa Stream
23. Kaneohe Stream
24. Keaahala Stream
25. Heeia Stream
26. Kahaluu Stream
27. Kaalaea Stream
28. Kaipapau Stream
29. Malaekahana Stream
30. Oio Stream
31. Makaleha Stream

Table 2. Some Physical Characteristics of the 31 Oahu Streams Having Channel Modifications. See Fig. 3 for Locations.

	Stream - Class[a]	Length of Channel (km) Total	Length of Channel (km) Modified	Alteration Features Type[b]	Alteration Features Date[c]	Location Distance (km)[d]	Location Elevation (m)[e]
1.	Kaupuni Stream - I	37	3.7	1,3	1959, 1973	0	0
2.	Mailiili Stream - I	34	4.3	1,3	1966, 1974	0	0
3.	Ulehawa Stream - I	8	1.1	1,2,3	1963, 1966	0	0
4.	Waikele Stream - C	195	5.2	2,3,4,6	1935, 1971	0	0
5.	Waiawa Stream - C	93	4.3	2,3	1961, 1975	0	0
6.	Waimalu Stream - C	46	4.9	1,2,3	1963, 1975	0	0
7.	Kalauao Stream - C	13	1.2	2,3,4	1935, 1972	0	0
8.	Aiea Stream - I	11	2.7	1,2,3,4	1961, 1973	0	0
9.	Halawa Stream - C	40	4.1	1,3,4	1937, 1974	0	0
10.	Moanalua Stream - I	44	15.1	1,2,3,4	1959, 1975	0	0
11.	Kalihi Stream - C	18	4.8	3,4	1927, 1969	0	0
12.	Kapalama Stream - I	9	9.0	1,2,3,4,5,6	1938, 1965	0	0
13.	Nuuanu Stream - C	30	17.9	1,2,3,4,5	1932, 1975	0	0

Continued

Table 2 (Continued)

	Stream - Class[a]	Length of Channel (km) Total	Length of Channel (km) Modified	Alteration Features Type[b]	Alteration Features Date[c]	Location Distance (km)[d]	Location Elevation (m)[e]
14.	Makiki Stream - I	10	3.2	1,3,4,6	1920, 1972	0	0
15.	Manoa Stream - C	34	8.3	1,2,3,4	1960, 1973	0	0
16.	Waialaenui Stream - I	14	7.5	1,3,4	1961, 1975	0	0
17.	Wailupe Stream - I	13	3.2	2,3,4	1930, 1955	0.1	0
18.	Pia Stream - I	11	2.3	1,3	1964, 1969	0	0
19.	Kuliouou Stream - I	4	1.6	1	1969, 1973	0	0
20.	Waimanalo Stream - C	12	2.7	1,3,4	1963, 1976	0	0
21.	Maunawili Stream - C	29	5.5	1,2,3	1964, 1974	0	0
22.	Kawa Stream - C	5	2.3	1,2,3,6	1960, 1972	0	0
23.	Kaneohe Stream - C	28	6.9	1.2.3	1964, 1971	0	0
24.	Keaahala Stream - C	4	1.5	1,2,3	1966, 1968	0	12
25.	Heeia Stream - C	11	1.5	1,2,3	1966, 1968	3.1	45
26.	Kahaluu Stream - C	21	3.0	1,2,3	1963, 1972	0	0

Continued

Table 2 (Concluded)

Stream - Class[a]	Length of Channel (km) Total	Modified	Alteration Features Type[b]	Date[c]	Location Distance (km)[d]	Elevation (m)[e]
27. Kaalaea Stream - C	4	0.1	3,4	1923, 1964	0	0
28. Kaipapau Stream - I	11	0.2	3,4	1932, 1964	0.2	0
29. Malaekahana Stream - C	30	2.4	2	ca. 1930	1.0	6
30. Oio Stream - I	10	2.0	2	1931, 1970	0	0
31. Makaleha Stream - C	23	1.3	2	1975	0	0

[a]C = continuous, I = interrupted. See legend of Appendix A for definitions.

[b]1 = lined channel, 2 = vegetation removed-channel realigned, 3 = elevated culvert, 4 = revetment, 5 = blocked or filled-in channel, 6 = extended culvert. See legend of Appendix B for definitions.

[c]Year of earliest and most recent channel modification.

[d]Horizontal distance from mouth to lowest point of channel modification.

[e]Elevation of lowest modification.

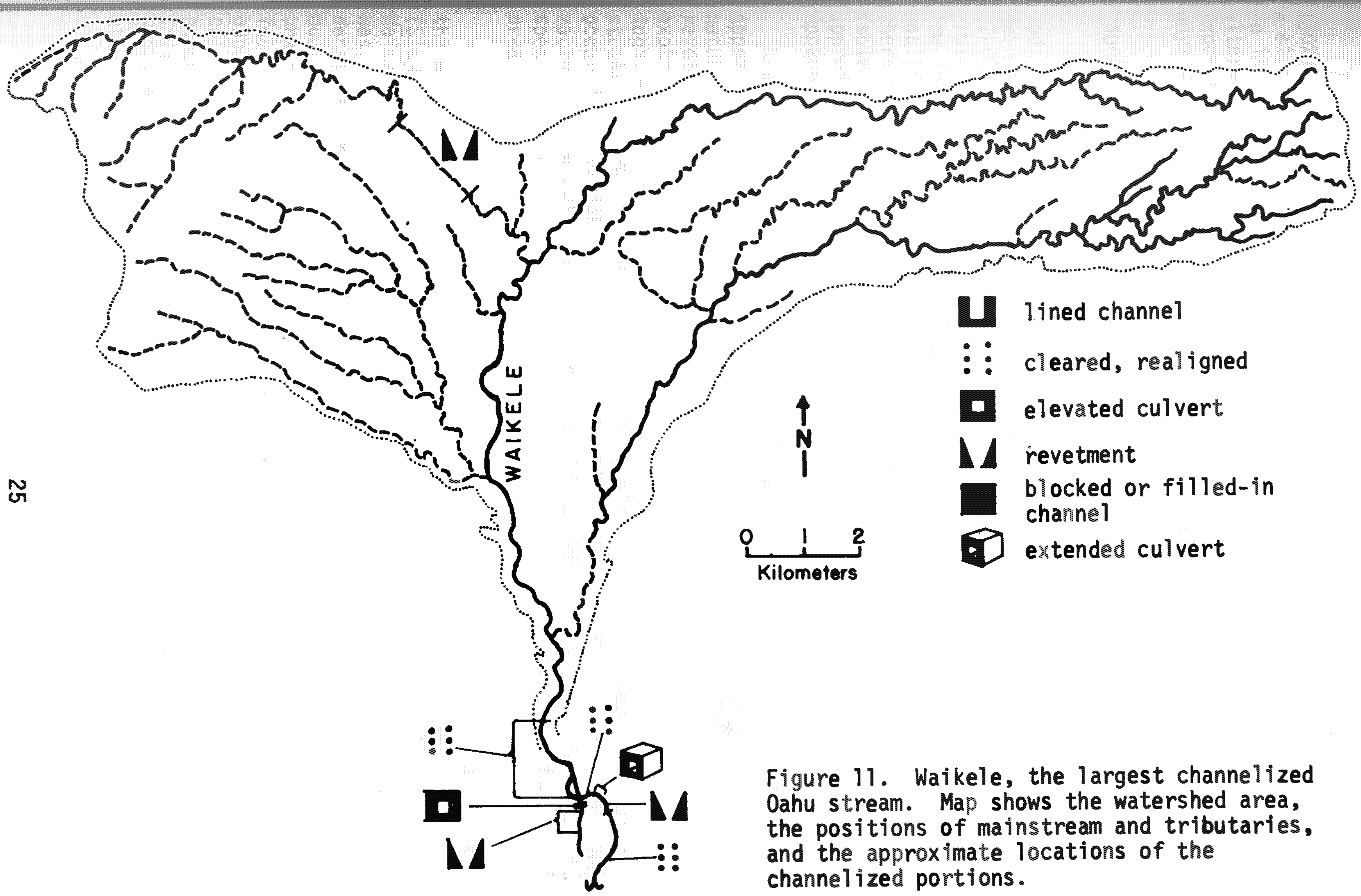


Figure 11. Waikele, the largest channelized Oahu stream. Map shows the watershed area, the positions of mainstream and tributaries, and the approximate locations of the channelized portions.

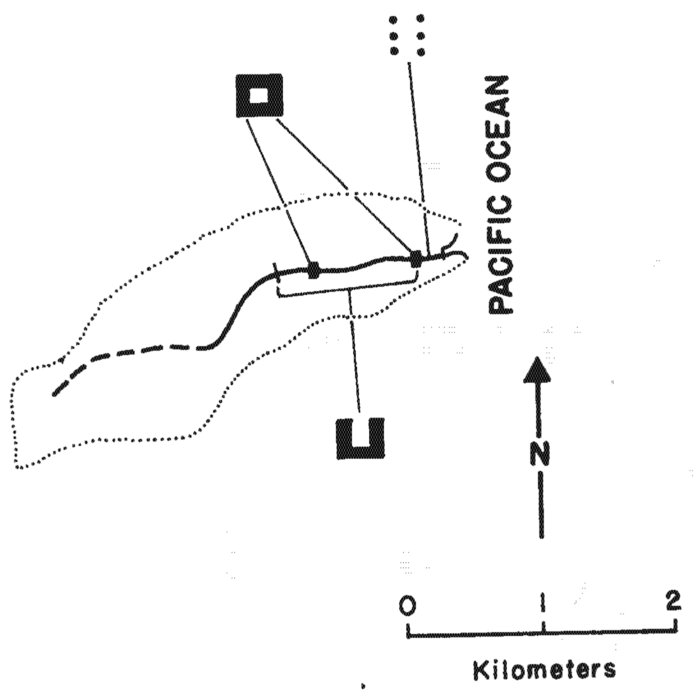


Figure 12. Keaahala, the smallest channelized Oahu stream. Map shows the watershed limits, the stream, and the approximate location of the channelized portions. See text and Figure 11 for symbol identification.

The altered sections of the channelized streams averaged 16% (range 2 - 100%) of total stream length. The water of one stream had been diverted into a storm drain and another was converted into a system of extended culverts in its upper and middle elevations. Fifty-seven percent of the streams have altered channels (discussed in detail in previous section), 58% have water exported, and all have roads crossing over them. (There are, therefore, no physically pristine streams on Oahu.) define

FAUNA OF OAHU STREAMS

One of the purposes of this study was to determine the effects of channel modification on the occurrence and quantity of native fishes and crustaceans. Results of faunal inventories showed that of 23 species found on Oahu (Table 3), only seven (30%) were native to Hawaii. Although native crustaceans were well represented, relative abundances of native fishes were low in Oahu streams. A breakdown of the species as to habitat type (e.g., unaltered, altered) showed that because of exotic species predominance, there were more species in altered streams than in unaltered ones (22 vs. 12, Table 3). Lists of animals collected, their relative abundances, and approximate locations of collecting sites in altered streams are shown in Appendix B.

Relative abundances of faunal groups in altered and unaltered streams appear in Table 4. Data for altered streams come from collections made on natural sites above and below channelized sections, cleared/realigned, revetment, and concrete-lined channels. These comparisons indicate that exotic fishes predominate strongly in altered streams and that this group, together with exotic crustaceans, form 87% of the faunal biomass in altered streams. Important numbers and biomasses of native shrimps and fishes occur only in unaltered streams. Additional analysis was made on the macrofauna in altered streams according to habitat types (Table 5). Exotic species dominated all habitat types while native species were absent in areas with lined channels.

Results of this survey confirm the long-suspected absence from Oahu of the endemic o'opu alamoo (Lentipes concolor). The endemic o'opu nopili (Sicydium stimpsoni) was still present in a few unaltered Oahu streams (e.g., Waimea Stream) in low abundances, while the o'opu nakea (Awaous stamineus) was found in most streams, both altered and unaltered, but in low population densities. The o'opu naniha (Awaous genivittatus), which lives near stream mouths, was more abundant than the other three gobies in both altered and unaltered streams. As will be seen later, only on Oahu is the o'opu naniha found in high population densities. Among the exotic fishes, the wild guppy (Poecilia reticulata) was ubiquitous and most abundant. It was collected in 16 of 17 channelized streams sampled and represented 44% by number and 25% by weight of the total faunal collection from altered streams. Tilapia mossambica and the swordtail (Xiphophorus helleri) were also prominent in altered streams. The Chinese catfish (Clarias fuscus) was ubiquitous in cleared-realigned channels and revetments but absent in lined

Table 3. Distributions and Abundances of Macrofauna[a] in Altered and Unaltered Streams[b] on Oahu. Abundances: - = Absent, 0 = Rare/Occasional, 0 = Common, and ● = Abundant

Stream Fauna - Species	Unaltered	Altered
Crustacea		
Native		
Atya bisulcata	●	●
Macrobrachium grandimanus	●	●
Exotic		
Macrobrachium lar	●	◐
Procambarus clarkii	-	●
Pisces		
Native		
Awaous genivittatus	◐	◐
Awaous stamineus	0	0
Eleotris sandwicensis	◐	0
Kuhlia sandvicensis	0	0
Sicydium stimpsoni	0	-
Exotic		
Cichlasoma sp.	-	●
Clarias fuscus	-	●
Cyprinus carpio	-	0
Gambusia affinis	0	●
Micropterus dolomieui	-	●
Misgurnus anguillicaudatus	0	●
Ophicephalus striatus	-	●
Poecilia latipinna	-	●
Poecilia mexicana	-	0
Poecilia reticulata	●	0
Poecilia vittata	-	●
Tilapia mossambica	-	●
Xiphophorus helleri	●	0
Xiphophorus maculatus	-	●

[a]Fishes and decapod crustaceans.

[b]Based on collections in 17 altered and six unaltered streams. Altered streams include Nos. 4, 5, 7, 9, 10, 11, 13, 14, 15, 17, 20, 21, 22, 23, 24, 25, and 26 on Fig. 10. Unaltered streams: Anahulu, Hakipuu, Kaukonahua, Waiahole, Waikane, and Waimea.

Table 4. Comparisons of Numbers and Weights Per 20 m X 1 m Station of Different Groups of Macrofauna in 17 Altered and 6 Unaltered Streams on Oahu (cf., Footnotes, Table 3). Native Species are Associated Mostly with Unaltered Streams, While Exotic Species Predominate in Altered Streams

Stream Fauna-Grouped	Unaltered % No. (No.)	Unaltered % Wt. (Wt., g)	Altered % No. (No.)	Altered % Wt. (Wt., g)
Native Crustaceans	53 (177)	13 (186.0)	7 (293)	2 (242.4)
Native Fishes	19 (64)	47 (646.8)	7 (262)	11 (1759.9)
Exotic Crustaceans	10 (32)	31 (424.5)	11 (434)	21 (3110.2)
Exotic Fishes	18 (62)	9 (126.2)	75 (2923)	66 (10094.1)

Table 5. Composition of Faunal Communities from Four Types of Habitats in Altered Streams on Oahu. No Native Species was Found in Lined Channels

	Natural Site Above and Below Channelization		Cleared-Realigned		Revetment		Lined Channel	
Stream Fauna-Grouped	% No	% Wt	% No	% Wt	% No	% Wt	% No	% Wt
Native Crustaceans	13	5	3	<1	2	<1	0	0
Native Fishes	3	8	5	9	17	13	0	0
Exotic Crustaceans	16	36	22	32	19	26	2	6
Exotic Fishes	68	51	70	58	62	60	98	94

channels. Among exotic Crustacea, Macrobrachium lar was ubiquitous in cleared-realigned channels, rare in revetments, and absent in lined channels. The crayfish (Procambarus clarkii) was distributed widely.

As noted earlier (METHODS), species abundance and distribution data presented here do not characterize the entire stream ecosystem. Among crustaceans, for example, the native prawn (Macrobrachium grandimanus) was found only in lower stream reaches, whereas the native shrimp (Atya bisulcata) was characteristic of upstream areas. The introduced prawn (Macrobrachium lar) ranged from brackish coastal habitats to upstream areas, often attaining greatest abundances in the midreaches of streams. Exotics were collected in both altered and unaltered streams.

STREAM AND FAUNA INVENTORY: OTHER ISLANDS

MAUI

Maui, the second largest island in the state, measures 77 by 42 km at its extreme dimensions and has an area of 1,886 km^2 (Sahara et al. 1967). It originated from two major volcanoes. Puu Kukui, West Maui, emerged in part from the ocean in Pliocene and early Pleistocene. Haleakala, East Maui, emerged in early and middle Pleistocene, with renewed volcanic activity in middle to late Pleistocene and Recent time (Stearns and MacDonald 1942). West Maui, the older of the two parts of the island, rises to 1,764 m altitude and is deeply eroded. East Maui attains 3,056 m and features relatively smooth slopes on its western and northern sides. The climate varies with altitude and to a lesser extent with position to windward or leeward. Large increases in rainfall occur over short distances when moving from low to high elevations or going from leeward to windward areas. In West Maui, the climate varies from dry and sunny Lahaina where the median annual rainfall is 40 cm/yr to 1,020 cm/yr at Puu Kukui, the highest point. The climate on the leeward slopes of Haleakala (East Maui) is warm and sunny with a median annual rainfall of 50 cm/yr; the windward and eastern slopes have a median annual rainfall up to 760 cm/yr (Sahara et al. 1967). Annual mean air temperature for the whole island at 60 m elevation is 23° C (22-25° C).

Ninety-six perennial streams have been recognized and are listed in Appendix A. Fifty-eight percent of these streams are continuous, the rest are interrupted. Seven streams (7%) were found to have altered channels, four in Lahaina District and three in Wailuku District. All seven channelized streams are usually dry at lower elevations because normal flows are diverted and exported from the drainages. Discharge to the ocean occurs irregularly, mainly during periods of heavy winter rainfall. The locations of these altered streams are shown in Fig. 13, and their features are summarized in Table 6.

Iao Stream, Wailuku District, is the largest of the altered streams on the basis of stream length and watershed area. Kauaula Stream, Lahaina District, is the smallest. Watershed limits, stream channels, longitudinal gradient of mainstream, and the approximate locations of the channelized portions in each stream are shown in Appendix B.

A total of 5 km of modified channels occurs among the seven altered streams. Modified sections of the altered streams averaged 3% (range <1 -

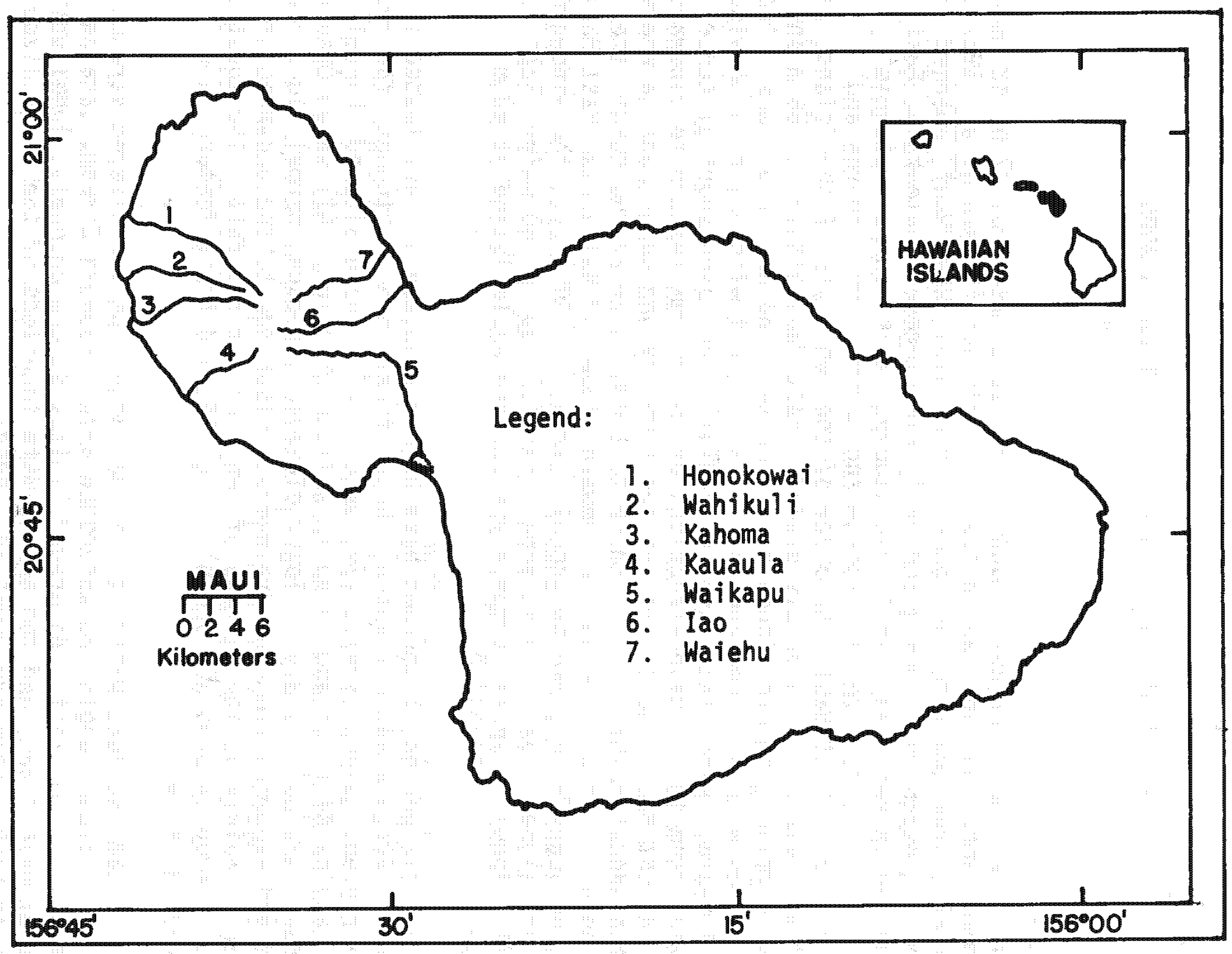


Figure 13. Location map for seven Maui streams having modified channels. Percentage of streams altered = 7/96 = 7%.

Table 6. Some Physical Characteristics of the Seven Maui Streams Having Channel Modifications. See Fig. 13 for Locations

Stream - Class[a]	Length of Channel (km) Total	Length of Channel (km) Modified	Alteration Features Type[b]	Alteration Features Date[c]	Location Distance (km)[d]	Location Elevation (m)[e]
1. Honokowai Stream - I	20	0.4	4	1962, 1964	0	0
2. Wahikuli Stream - I	19	0.4	4	1971	0	0
3. Kahoma Stream - C	25	1.0	3,4	ca. 1930, 1957	0	0
4. Kauaula Stream - C	10	0.3	1	1971	0	0
5. Waikapu Stream - C	25	2.8	2	1937, 1970	1.0	1
6. Iao Stream - C	38	0.2	1,3,4	1949	0.7	9
7. Waiehu Stream - C	23	0.1	3	1959	0.2	6

[a] C = continuous, I = interrupted. See legend of Appendix A for definitions.

[b] 1 = lined channel, 2 = vegetation removed-channel realigned, 3 = elevated culvert, 4 = revetment. See legend of Appendix B for definitions.

[c] Year of earliest and most recent channel modification.

[d] Horizontal distance from mouth to lowest point of channel modification.

[e] Elevation of lowest modification.

11) of total stream length. The relative "abundance" of each type of channel modification expressed as a percentage of the 5 km total is as follows:

- Cleared and realigned - 54%;
- Revetment - 34%;
- Lined channel - 8%;
- Elevated culverts - 4%.

Aside from the 7% channelized streams on Maui, diversions are found in 59% and road crossings on 96%. One percent of Maui streams (= one stream) is physically pristine.

Water from four Lahaina District streams has been diverted for agricultural use for a considerable time (e.g., Kahoma Stream, ca. 40 yrs.), making them dry at mid and low elevations. Collections from those streams (Honokowai, Wahikuli, Kahoma, and Kauaula), taken above the diversion points (elevations between 305 and 474 m), revealed an absence of fishes and crustaceans. Water was present at the mouths of these "dry" streams, due to tidal influence. A slight return flow of water from irrigation ditches in Wahikuli contained only Poecilia reticulata. On the other hand, nearby Ukumehame Stream is also dewatered, but its diversion is at a lower elevation (73 m). Collections above its diversion point contained two species of decapod crustaceans and three species of fishes. Included were the endemic shrimp, opae kalaole (Atya bisulcata), and the endemic goby, o'opu nopili (Sicydium stimpsoni). Lists of biota collected and approximate locations of collecting sites are shown in Appendix B.

Faunal inventory of Maui streams showed that there were more species in unaltered than in altered streams (Table 7), a condition opposite to that of Oahu. Moreover, more native species were found in unaltered than in altered streams. Population densities of native fishes were high in East Maui but low in West Maui streams. The o'opu nopili had high population density, o'opu nakea had medium density, but the o'opu naniha was not collected (Table 7). As on Oahu, the guppy (Poecilia reticulata) was widely distributed; it was collected in six of the seven streams sampled. At least one exotic species was present in all streams sampled.

MOLOKAI

The island of Molokai is the State's fifth largest island (673 km^2), measuring 61 by 16 km at its extreme dimensions. In geologic time, Molokai built upward from the sea during the Tertiary, possibly early Pleistocene (Stearns 1946, Stearns and MacDonald 1947). Molokai was formed by two volcanic domes, but only one remains a dominant feature, East Molokai, which rises to 1,515 m. West Molokai is characterized by rolling arid land rising to 721 m, while East Molokai is mountainous with many deep gulches and canyons. Mean annual air temperature of Molokai as a whole is 24° C with seasonal fluctuations ranging from 18 to 29° C. Median annual rainfall has

Table 7. Distributions and Abundances of Macrofauna[a] in Altered and Unaltered Streams[b] on Maui. Abundances: - = Absent, 0 = Rare/Occasional, ◐ = Common, and ● = Abundant

Stream Fauna - Species	Unaltered	Altered
Crustacea		
Native		
Atya bisulcata	●	●
Macrobrachium grandimanus	●	●
Exotic		
Macrobrachium lar	●	-
Procambarus clarkii	-	0
Pisces		
Native		
Awaous genivittatus[c]	●	0
Awaous stamineus	0	0
Eleotris sandwicensis	●	-
Kuhlia sandvicensis	●	0
Lentipes concolor	●	-
Sicydium stimpsoni	0	-
Exotic		
Clarias fuscus	-	●
Poecilia reticulata	0	0
Tilapia mossambica	●	●

[a]Fishes and decapod crustaceans.

[b]Based on collections in four unaltered (Waihee, Honokohau, Ukumehame, and Hanawi) and three altered (Iao, Waiehu, and Wahikuli) streams.

[c]Was not collected in this survey but collected previously by John A. Maciolek.

great areal variability: western and central Molokai receive from 38 to 76 cm per year depending upon elevation, while East Molokai receives from 38 to over 381 cm per year (Baker et al. 1968, Swain 1973).

Thirty-seven perennial streams have been recognized and are listed in Appendix A. All are on East Molokai. Only 43% of these streams are continuous. Only one, interrupted Kamalo Stream on the southeast side of Molokai, has been altered with an elevated culvert. Its location is shown in Fig. 14 and its features are summarized as follows (for explanation of symbols, see Table 6):

Stream - Class	Length of Channel (km)		Alteration Features		Location	
	Total	Modified	Type	Date	Distance (km)	Elevation (m)
Kamalo Stream - I	19	0.1	2	1930	0.3	0

Watershed limits, stream channels, longitudinal gradient of mainstream, and the approximate location of the channelized portion are shown in Appendix B. As a whole, streams in Molokai appear to have fared better than those in other islands. Only 3% of streams have channel alterations, 12% are diverted, and 38% have road crossings. Molokai has the largest percentage of physically pristine streams in the State - 49%.

Kamalo Stream is dry at the low and middle elevations. Collections were, however, made in two unaltered streams; Honouliwai Stream, which is in the general vicinity of Kamalo Stream, and Halawa Stream at the eastern end of Molokai. Nine decapod crustacean and fish species were collected (Table 8), eight (89%) of which were native species. Unlike Oahu, but like East Maui streams, native fish densities (except the endemic goby, Lentipes concolor) were high. The exotic Tahitian prawn (Macrobrachium lar) was found in both streams. The indigenous o'opu naniha was not collected in either Honouliwai or Halawa streams.

HAWAII

The island of Hawaii is the largest (10,438 km^2) in the state, measuring 150 by 122 km at its extreme dimensions. It is the youngest geologically, having emerged from the ocean between late Pleistocene and Recent time (Zimmerman 1948). It is the result of five volcanoes (Baker et al. 1965), three of which are currently or recently active. The peaks of these volcanoes range in altitude from a few hundred to 4,206 m, resulting in about 80 percent of the island being 305 m in elevation. Topography is

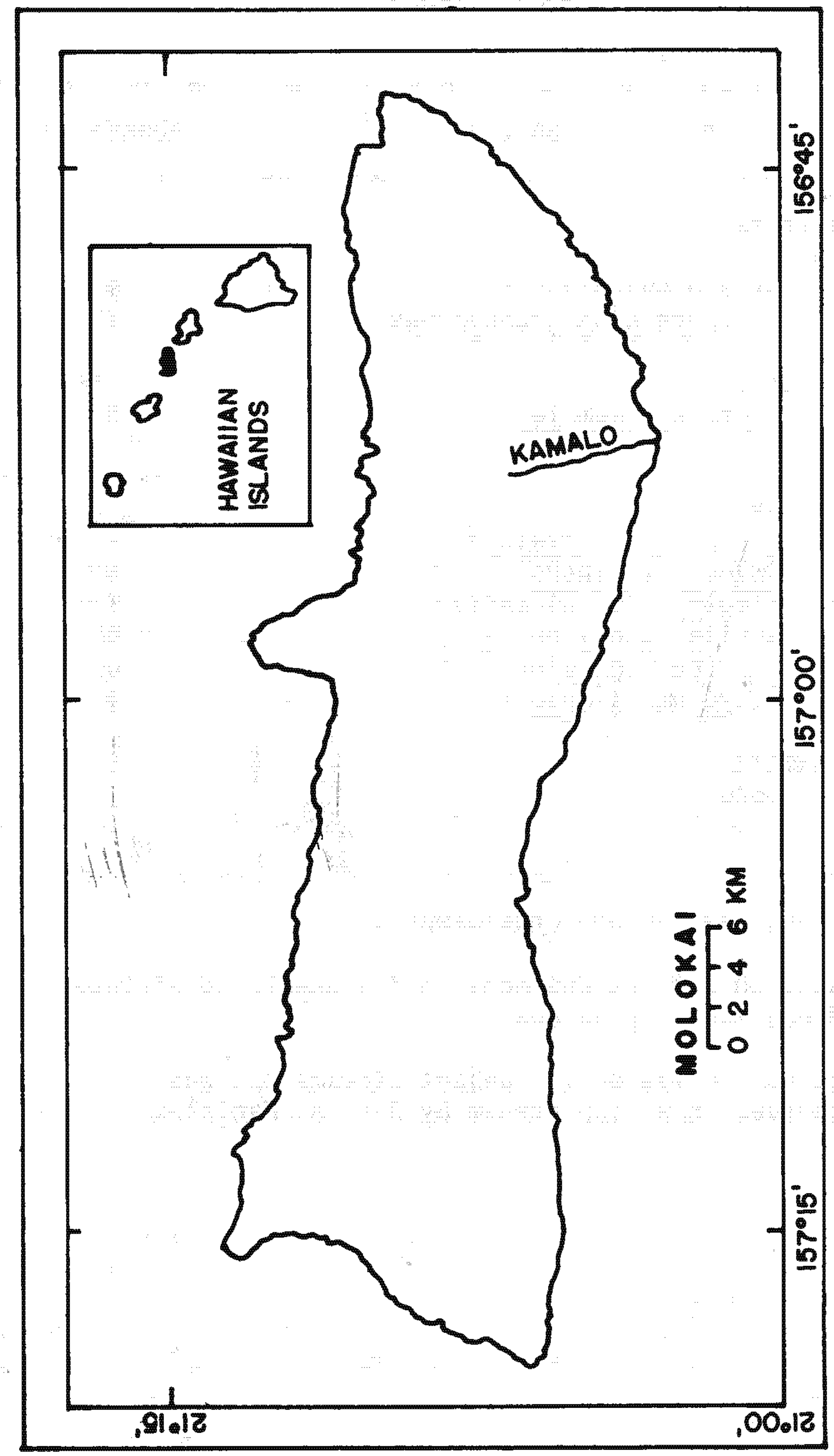


Figure 14. Location map for Kamalo Stream, the only stream with an altered channel on Molokai. Percentage of streams altered = 1/37 = 3%.

Table 8. Distributions and Abundances of Macrofauna[a] in Unaltered Streams[b] on Molokai. Abundances: - = Absent, O = Rare/Occasional, ◐ = Common, and ● = Abundant

Stream Fauna - Species	Abundance
Crustacea	
Native	
Atya bisulcata	●
Macrobrachium grandimanus	●
Exotic	
Macrobrachium lar	●
Pisces	
Native	
Awaous genivittatus[c]	-
Awaous stamineus	●
Eleotris sandwicensis	●
Kuhlia sandvicensis	●
Lentipes concolor	O
Sicydium stimpsoni	●
Exotic	
none	

[a]Fishes and decapod crustaceans.

[b]Based on collections made in two unaltered streams (Honouliwai and Halawa).

[c]Was not collected in subject streams but was observed in Wailau Stream by John A. Maciolek.

related to lava flows from the various volcanoes. It is generally smooth and sloping, uncarved by geologic erosion. However, at the northern corner of the island, the old Kohala mountains have been eroded into cliffs and canyons where they face the northeast trades. Extremes of rainfall and terrain produce a variety of climates, from the very humid rain forests on the windward slopes to the dry, hot desert-like climate of the leeward slopes. Rainfall ranges from 25 to 760 cm annually, depending upon location and altitude. Island-wide average annual rainfall is 130 cm. There is a broad range of air temperatures caused by the high mountains. At sea level, the annual temperature averages 24° C; the summits of the two highest mountains have freezing temperatures most of the year. All perennial streams are on the northeastern portion of the island. With few exceptions they are limited to the windward slopes of Mauna Kea and the Kohala mountains.

On Hawaii Island, 123 perennial streams have been recognized and are listed in Appendix A. Fifty-seven percent of these streams are continuous. Four streams (3%) have been altered. Three of the altered streams are interrupted. The locations of these streams are shown in Fig. 15 and their features are summarized in Table 9.

Wailoa River, Puna District, is the largest on the basis of stream length and watershed area. Lamimaumau Stream, north of Kamuela, is the smallest. The watershed limits, stream channels, mainstream, longitudinal gradients, and the approximate locations of the channelized portions of each stream are shown in Appendix B.

A total of 4 km of modified channel exists among the four altered streams. Modified sections of the altered streams averaged 7% (range 0.6 - 12%) of their combined channel length. The relative "abundance" of each type of channel modification expressed as percentage of the 4 km total is as follows:

Lined channel - 44%;
Cleared and/or realigned - 31%;
Revetment - 23%;
Elevated culvert - 2%.

Apart from the 3% of streams with channel alterations, water is diverted from 60% of the Hawaii Island streams, and 79% have road crossings. Only 11% of the streams are physically pristine.

Biological collections were made in eight streams in Puna, South Hilo, North Hilo, and North Kohala districts of Hawaii. Two of the streams are channelized but only one, the Wailoa River, has been significantly altered. The six unaltered streams are representative of Hawaii streams having continuous strong waterflow through deeply eroded, heavily vegetated gulches.

Eleven species of fishes and crustaceans were collected, eight (73%) of these are native to Hawaii. In another study (Timbol 1977), 11 species

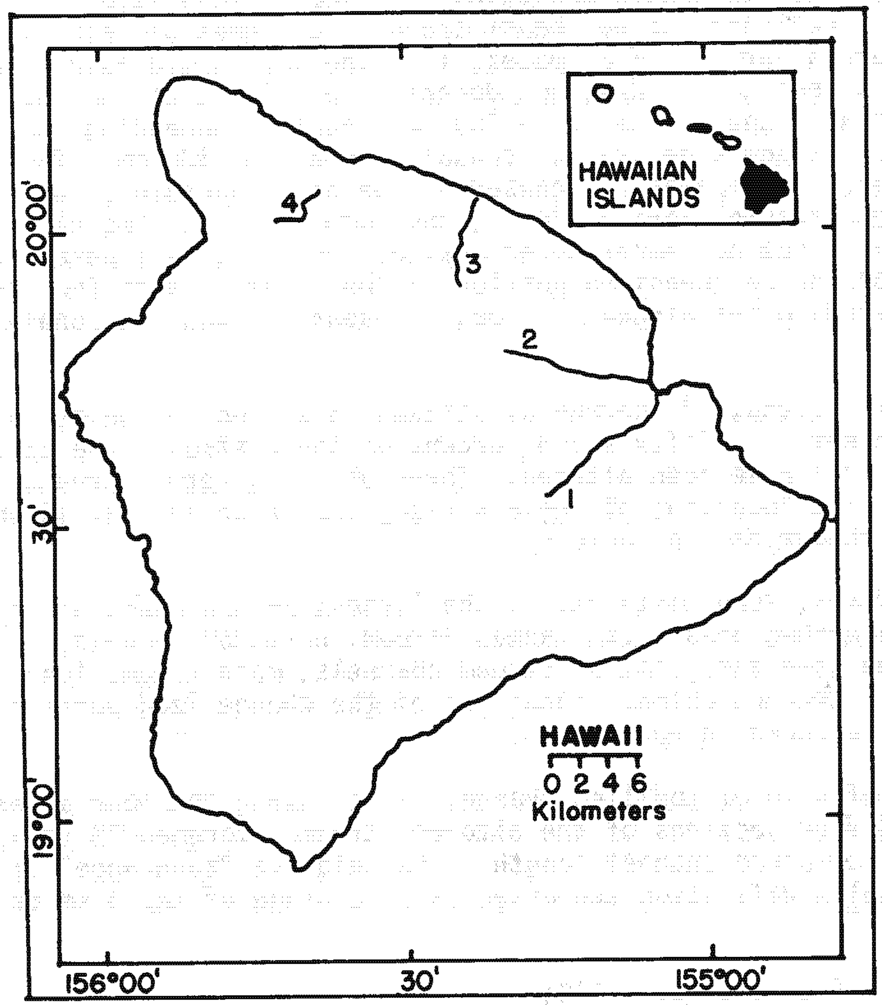


Figure 15. Location map for four Hawaii streams having modified channels. Percentage of streams altered = 4/123 = 3%.

Legend:

1. Wailoa River
2. Pukihae Stream
3. Papuaa Stream
4. Lamimaumau Stream

Table 9. Some Physical Characteristics of the Four Hawaii Streams Having Channel Modifications. See Fig. 15 for Locations

Stream - Class[a]	Length of Channel (km) Total	Length of Channel (km) Modified	Alteration Features Type[b]	Alteration Features Date[c]	Location Distance (km)[d]	Location Elevation (m)[e]
1. Wailoa River - I	26	3.2	1,2,4	ca. 1920, 1962	0.8	0.3
2. Pukihae Stream - C	16	0.1	3	ca. 1910	<0.1	0
3. Papuaa Stream - I	5	0.1	3,4	ca. 1930, 1972	2.5	330
4. Lamimaumau Stream - I	5	0.5	1	1968, 1969	16.5	866

[a]C = continuous, I = interrupted. See legend of Appendix A for definitions.

[b]1 = lined channel, 2 = vegetation removed-channel realigned, 3 = elevated culvert, 4 = revetment. See legend of Appendix B for definitions.

[c]Year of earliest and most recent channel modification.

[d]Horizontal distance from mouth to lowest point of channel modification.

[e]Elevation of lowest modification.

of fishes and decapod crustaceans were also collected in Wailoa Stream (Waipio Valley). There was no significant difference in the number of species present in altered and unaltered streams (see Table 10). However, population density of stream macrofauna was higher in unaltered streams than in altered ones. The population densities were high for o'opu nopili, expecially in Niulii and Waikama streams, medium for o'opu nakea, while the o'opu alamoo was not collected during this study. The indigenous o'opu naniha was of medium population density near the mouth of Wailoa River. The native crustaceans, A. bisulcata and M. grandimanus, the introduced crustacean, M. lar, and the introduced guppy, P. reticulata, were widespread in Hawaii streams. As was the case in the other islands, exotics were collected in all streams sampled.

KAUAI

Kauai, the fourth largest island (1,437 km^2) measures 54 by 40 km at its extreme dimensions. Geologically, it is the oldest, having emerged from the ocean during the Tertiary Period. The island contains rugged mountains and canyons at its center. Mount Waialeale is the dominant feature of the island, with its Kawaikini Peak the highest point at 1,587 m. Kauai's climate is generally mild. Rainfall is relatively high in windward areas but minimal in leeward areas; Mt. Waialeale receives over 1,000 cm/yr, while Kekaha, about 38 km leeward, receives only about 50 cm/yr (Foote et al. 1972). Mean annual air temperature is 24° C in the lowlands and 15° C at Kokee (elevation 1,067 m).

Fifty-six perennial streams have been recognized in Kauai and are listed in Appendix A. Seventy-seven percent of the Kauai streams are continuous, the highest percentage in the State. Twelve of these streams (21%) have altered channels. The locations of these altered streams are shown in Fig. 16 and their features are summarized in Table 11.

Waimea, a dendritic drainage on the southwest side of the island, is the largest on the basis of stream length and watershed area. Waikoko, in the north, is the smallest altered stream. The watershed limits, stream channels, mainstream longitudinal gradients, and the approximate locations of the channelized portions of each stream are shown in Appendix B. Modified sections of the altered streams averaged 1% (range 0.1 - 13). A total of 8 km of modified channels occur among the 12 altered streams. Three types of channel modifications occur; the relative "abundance" of each type of channel modification expressed as a percentage of the 8 km total is as follows:

Cleared and realigned - 51%;
Revetment - 35%;
Elevated culvert - 14%.

There are no lined channels among the altered Kauai streams. In addition to the 21% stream channel alterations on Kauai, 45% have water diverted from

Table 10. Distributions and Abundances of Macrofauna[a] in Altered and Unaltered Streams[b] on Hawaii. Abundances: - = Absent, ◐ = Rare/Occasional, ● = Common, and O = Abundant

Stream Fauna - Species	Unaltered	Altered
Crustacea		
Native		
Atya bisulcata	●	-
Macrobrachium grandimanus	●	●
Exotic		
Macrobrachium lar	●	●
Pisces		
Native		
Awaous genivittatus	-	◐
Awaous stamineus	◐	O
Eleotris sandwicensis	◐	◐
Kuhlia sandvicensis	O	◐
Lentipes concolor[c]	O	-
Sicydium stimpsoni	●	O
Exotic		
Gambusia affinis	-	O
Poecilia reticulata	●	●
Xiphophorus maculatus	-	O

[a]Fishes and decapod crustaceans.

[b]Based on collections made in two altered and six unaltered streams. Altered streams: Pukihae and Wailoa River (Alenaio tributary at Waialama Canal). Unaltered streams: Aamakao, Honolii (and Kaiwiki), Kolekole, Niulii, Paheehee, and Waikama.

[c]Not collected in this study but previously obtained by John A. Maciolek.

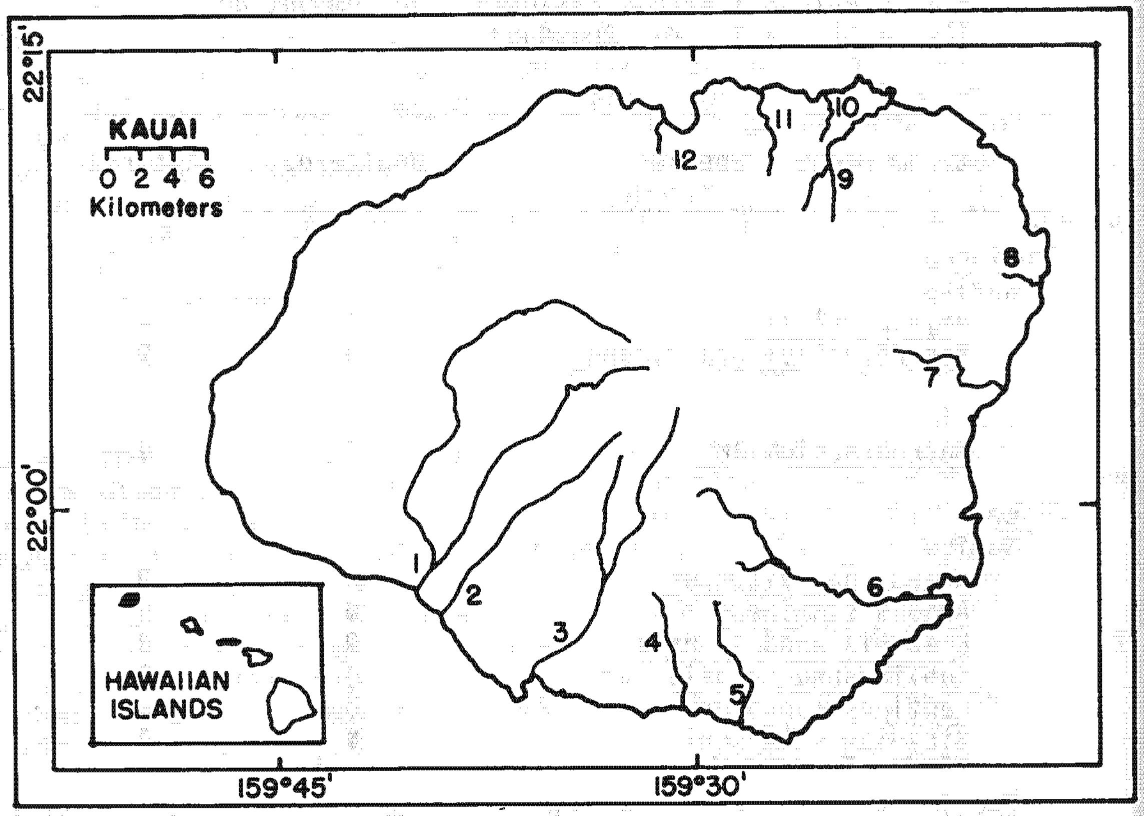


Figure 16. Location map for the 12 Kauai streams having modified channels. Percentage of streams altered = 12/56 = 21%.

Legend:

1. Waimea River
2. Waipao Stream
3. Hanapepe Stream
4. Lawai Stream
5. Waikomo Stream
6. Huleia Stream
7. Konohiki Stream
8. Kumukumu Stream
9. Kilauea Stream
10. Puukumu Stream
11. Anini Stream
12. Waikoko Stream

Table 11. Some Physical Characteristics of the Twelve Kauai Streams Having Channel Modifications. See Fig. 16 for Locations.

Stream - Class[a]	Length of Channel (km)		Alteration Features		Location	
	Total	Modified	Type[b]	Date[c]	Distance (km)[d]	Elevation (m)[e]
1. Waimea River - C	373	2.0	4	1952, 1953	0	0
2. Waipao Stream - C	33	0.1	4	1948	0.5	6
3. Hanapepe Stream - C	121	1.0	4	1962, 1963	0.7	6
4. Lawai Stream - C	27	0.6	2	1975, 1976	0.9	12
5. Waikomo Stream - C	28	0.1	3,4	1930, 1968	0.3	6
6. Huleia Stream - C	102	0.1	3	1937	12.0	122
7. Konohiki Stream - C	20	2.5	2	1946, 1948	0	0
8. Kumukumu Stream - C	3	0.6	2,3	1920, 1958	0	0
9. Kilauea Stream - C	56	0.1	3	1973	2.2	85
10. Puukumu Stream - C	7	0.1	3	1973	1.3	73
11. Anini Stream - I	14	0.1	3	1968	3.2	98
12. Waikoko Stream - C	2	0.6	2	1930	0.1	0

[a]C = continuous, I = interrupted. See legend of Appendix A for definitions.

Continued

Table 11 (Concluded).

[b]2 = vegetation removed-channel realigned, 3 = elevated culvert, 4 = revetment. See legend of Appendix B for definitions.

[c]Year of earliest and most recent channel modification.

[d]Horizontal distance from mouth to lowest point of channel modification.

[e]Elevation of lowest modification.

their channels, and 68% have road crossings. Kauai, however, is second only to Molokai in the proportion of physically pristine streams (32%).

Survey results showed that of the 16 species collected, seven (44%) are native to Hawaii (Table 12). In another study (Timbol 1977), eighteen species were collected from Wainiha, Hanalei, and Wailua Rivers, all unaltered Kauai streams. Comparison of altered and unaltered streams showed little difference in species richness or abundance of macrofauna. This may be due to the relatively innocuous channel modifications in Kauai streams, cleared and/or realigned channels (51%) being closest to unaltered conditions compared to other types of modifications. Exotics were also found in all streams sampled. (In contrast, exotic species in Oahu streams were predominant both in number and biomass in altered streams while native species were predominant in unaltered streams). In Kauai the o'opu nakea was found in more streams and in higher population density than the o'opu nopili. The o'opu naniha had low population density, while the o'opu alamoo was not collected during this study. The swordtail, Xiphophorus helleri, was ubiquitous in Kauai.

Table 12. Distributions and Abundances of Macrofauna[a] in Altered and Unaltered Streams[b] on Kauai. Abundances: - = Absent, 0 = Rare/Occasional, ◐ = Common, and ● = Abundant

Stream Fauna - Species	Unaltered	Altered
Crustacea		
Native		
Atya bisulcata	●	●
Macrobrachium grandimanus	●	●
Exotic		
Macrobrachium lar	0	0
Procambarus clarkii	0	0
Pisces		
Native		
Awaous genivittatus	0	0
Awaous stamineus	◐	◐
Eleotris sandwicensis	0	0
Kuhlia sandvicensis	●	◐
Lentipes concolor[c]	-	-
Sicydium stimpsoni	◐	◐
Exotic		
Clarias fuscus	0	0
Lepomis macrochirus	0	-
Micropterus dolomieui	0	-
Misgurnus anguillicaudatus	0	0
Poecilia reticulata	●	0
Tilapia mossambica	0	0
Xiphophorus helleri	●	◐

[a]Fishes and decapod crustaceans.

[b]Based on collections made in ten altered and seven unaltered streams. Altered streams include Nos. 1, 3, 4, 5, 6, 7, 8, 9, 10, and 11 on Fig. 16. Unaltered streams: Aakukui, Wailua at Opaekaa and Kalama tributaries, Wainiha, Hanalei, Manoa, Waioli, and Limahuli.

[c]Not collected in this study but previously obtained by John A. Maciolek.

PHYSICOCHEMICAL CHARACTERISTICS OF HAWAIIAN STREAMS

This section considers some physicochemical features and discharges of streams. Most of the data were obtained from USGS and Hawaii Department of Health publications. Additional data (e.g., water temperature from different types of channel alterations on Oahu) were obtained in this study.

SURFACE WATER DISCHARGES

By continental standards, even the largest of Hawaiian streams is minute. For example, the annual mean discharge of the Mississippi River measured near Vicksburg, Mississippi, is 19,633 times that of the largest river (Wailuku) in Hawaii (data from Leopold and Maddock 1953 and USGS 1977). Hawaiian streams are, however, of the magnitude of other Pacific high island streams.

Comparing the surface water discharges of three of the largest streams from each island of the State, Hawaii showed the highest mean for water year 1976 followed by Kauai. Maui and Oahu have about equal annual mean discharges while Molokai has the lowest (see also Table 13). Several of the perennial streams in each of the five islands surveyed do not discharge to the sea at various times of the year (see METHODS for definitions). In extreme cases, naturally strong, continuous flowing streams are rendered artificially interrupted due to diversions (e.g., Kahoma, Wahikuli, and Honokowai on West Maui). Water is diverted in more than half of Hawaii's streams with Hawaii having 60%, Maui and Oahu with 59% each, Kauai, 46%, and Molokai with 14 %. Appendix A shows which streams are diverted.

Kauai is the island with the largest percentage of its streams continuous, followed by Maui, Hawaii, Oahu, and Molokai in decreasing order. Additional water discharge data - annual mean, minimum and maximum discharges, USGS gaging station identification numbers, and presence of diversions above gaging stations - are presented in Appendix C.

COMPOSITION OF HAWAIIAN STREAM WATERS

Among the five major islands in the State, water in Oahu streams contains the highest total dissolved solids (Table 14). Maui (as represented by West Maui) and Kauai waters have the next highest dissolved solids (70% and 67% of Oahu waters, respectively) followed by Molokai (61%) and Hawaii

Table 13. Surface Water Discharges of the Three Largest Streams from Each of the Five Islands of Hawaii for Water Year 1976 (October 1975 - September 1976). Adapted from USGS (1977). Discharge Data are Annual Means and Instantaneous Maxima and Minima.

Island Stream	Discharge (m^3/s) Mean	Maximum	Minimum	Gaging Station No. and Remarks
A. Hawaii				
1. Honolii	3.9	100.3	0.3	16717000. No diversion above station.
2. Pohakupuka	0.9	11.0	0.02	16717800. No diversion above station.
3. Wailuku	9.7	271.0	0.2	16704000. Diversions above station.
(Average)	(4.8)	(127.4)	(0.2)	
B. Maui				
1. Honokohau	0.7	6.6	0.3	16620000. No diversions above station.
2. Palikea	1.2	21.5	0.001	16501000. No diversions above station.
3. W. Wailuku	0.6	31.2	0.1	16518000. No diversions above station.
(Average)	(0.8)	(20.0)	(0.1)	
C. Oahu				
1. Kahana	0.7	9.1	0.3	16296500. Diversion above station.
2. Waikele	1.1	27.4	0.04	16213000. Diversions above station.
3. Waimea	0.5	22.0	0	16330000. Kamananui Trib., no diversions above station.
(Average)	(0.8)	(19.5)	(0.1)	
D. Kauai				
1. Hanalei	5.3	73.3	0.7	16103000. Diversions above station.
2. Wailua	5.8	82.1	0.2	16060000, 16071000. South Fork Wailua Trib. plus North Fork Wailua Trib., several diversions above gaging stations.
3. Waimea	2.0	150.4	0.3	16031000, 16036000. Waimea mainstream plus Makaweli Trib., several diversions above stations.
(Average)	(4.4)	(101.9)	(0.4)	
E. Molokai				
1. Halawa	0.6	12.4	0.1	16400000. No diversion above station.
2. Pelekunu	0.4	3.4	0.1	16404000. No diversion above station.
3. Waikolu	0.2	4.3	0.1	16408000. Diversion above station.
(Average)	(0.4)	(6.7)	(0.1)	

Continued

Table 13 (Concluded)

Table 14. Dissolved Inorganic Ions and Selected Physicochemical Parameters of Hawaiian Streams[a]

Parameters	Annual Mean in mg/l				
	Hawaii[b]	Maui[c]	Oahu[d]	Kauai[e]	Molokai[f]
Calcium	2.0	9.0	9.1	5.7	6.5
Magnesium	1.6	3.6	7.2	6.2	2.3
Sodium	4.1	6.8	17.6	8.6	8.3
Potassium	1.0	0.9	1.3	0.8	1.0
Alkalinity as $CaCO_3$	7.8	31.3	43.0	34.4	22.3
Sulfate	2.7	7.3	9.4	3.5	5.9
Chloride	6.0	9.1	25.4	13.4	10.9
Dissolved Solids (sum of constituents)	31.0	78.7	112.2	75.5	68.5
pH (units)	6.2	7.5	7.2	7.3	7.2
Conductivity (μmhos)	43.0	107.4	180.0	131.0	93.0

[a]Data from USGS (1976) ranging from two readings/year in most streams to 10 in a few.

[b]Hawaii Island streams (Kohala District only): Alakahi, Lamimaumau (Kohakohau), and Waikoloa.

[c]Maui Island streams (West Maui only): Honokohau, Iao, Kahakuloa, and Olowalu.

[d]Oahu Island streams: Helemano, Kalauao, Kalihi, Kaluanui, Kaneohe, Kaukonahua, Makaha, Makiki, Manoa, Maunawili, Moanalua, Nuuanu, Opaeula, Punaluu, Waiawa, Waikane, Waikele, Waimanalo, and Waimea.

[e]Kauai Island streams: Anahola, Hanalei, Hanapepe, Huleia, Lawai, Wailua, Waimea, and Wainiha.

[f]Molokai Island streams: Halawa, Pelekunu, and Waikolu.

(34%) as represented by Kohala streams. Water temperature varies from 14 to 22° C depending upon season and elevation. In general, there is a direct relationship between total dissolved solids in water and its conductivity. Conductivity values obtained are as expected; water in Oahu streams has the highest conductivity, followed by Kauai, Maui, Molokai, and Hawaii. These values are well within the standards set by the Department of Health (1977).

In comparison with other natural waters, major cation contents of Hawaiian streams are nearer those of water from igneous rocks than those of rivers. Water in Hawaiian streams has more sodium than the mean fresh water of the world's river systems, as given by Clarke (in Hutchinson 1957) and water from igneous rocks as compiled by Conway (in Hutchinson 1957). This condition (Na> Ca> Mg> K, Table 15) is not unusual due to the insularity of Hawaii. By contrast, the proportions are Ca> Mg> Na> K in the world's river systems (Hutchinson 1957).

Table 15. Mean Equivalent Proportions of Cations in Hawaiian Streams Compared with Other Natural Waters

	Mean River[a]	Water From Igneous Rocks[a]	Mean, Hawaiian Streams[b]
Calcium	63.5	48.3	31.0
Magnesium	17.4	14.2	20.4
Sodium	15.7	30.6	43.7
Potassium	3.4	6.9	4.9

[a]From Hutchinson 1957, p. 555.

[b]From USGS 1976; see also Table 14.

EFFECT OF ALTERED CHANNELS ON WATER TEMPERATURE

The temperature regime of a shallow spring-fed stream such as those in Hawaii is affected by several factors: season, weather, time of day, elevation, length of channel, character of riparian vegetation, and others.

Manoa Stream is one example of an altered stream in which lined channels, revetments, cleared/realigned, as well as unaltered sections are found. Located in Manoa Valley, Oahu, it drains 27 km² and has a total of 34 km channel, 8 km of which has been altered. Water temperature was taken in altered and unaltered sections of the stream at various times of the year (1975-1976); results are summarized in Table 16. Allowing for a warming of 1.4° C (line 7 minus line 6) as water flows from mid-elevation to near the

See p58 too table 16

mouth, an average of more than 7° C (line 1 minus line 4) could be attributed to the warming effect of a lined channel, 4° C (line 2 minus line 5) for a revetment, and about 2° C (line 3 minus line 5) for a cleared and/or realigned section. Hathaway (personal communication), who is studying the effect of a lined channel on water temperature at Maunawili Stream as part of this channelization study, attributes only 2.5° C (range 0.8 - 4.4) to it but finds the warming effect of Waiahole Stream as it flows from 45 m to 1 m elevation to be 2.0° C (range 0.8 - 3.2). A more definitive study of this parameter will be available in the terminal report for Part C (FWS/OBS-78/18) of this contract study.

Table 16. Water Temperatures in Altered and Unaltered Sections of Manoa Stream[a] and Unaltered Waiahole Stream[b]

Type of Channel, Elevation	Mean Temperature (Range) °C
1. Lined channel, Manoa (Palolo tributary), 3 m	31.3 (26.5-35.0)
2. Revetment, Manoa, 1 m	26.6 (22.5-30.0)
3. Cleared/Realigned, Manoa, 12 m	24.4 (22.4-25.0)
4. Unaltered, Manoa (Pukele trib.), 110 m	22.1 (20.6-22.8)
5. Unaltered, Manoa (Waiakeakua trib.), 105 m	20.8 (20.5-21.3)
6. Unaltered, Waiahole[c], 45 m	21.2 (20.2-22.1)
7. Unaltered, Waiahole[c], 1 m	22.6 (22.0-23.8)

[a]Manoa Stream: drainage area = 27 km^2, mean flow = 0.25 m^3/s (USGS 1977).

[b]Waiahole Stream: drainage area = 10 km^2, mean flow = 0.24 m^3/s (USGS 1968).

[c]Norton (1977).

ECOLOGICAL QUALITY STATUS

An attempt was made to identify the ecological quality of all perennial streams. Quality status assignment was made on the basis of field observations whenever possible; ecological quality of streams not visited was estimated from the character of the locality wherein they occur. Assignment of ecological quality was done according to the status-use categories listed in the proposed State water quality standards (Hawaii Department of Health 1977) as follows:

(I) Pristine-preservation are streams of high quality;
(II) Limited consumptive are streams of moderate to high quality where use is controlled;
(III) Exploitive-consumptive are streams of moderate to low quality and well exploited; and
(IV) Construct-alter are streams of low quality. (see also Appendix A.)

Including both perennial and possibly perennial streams on an island-wide basis, Molokai has the largest percentage of high quality streams, with 81% of its streams belonging to the pristine-preservation status (Category I), 16% under limited consumptive (Category II), and only 3% (one stream) under exploitive-consumptive (Category III). There are no streams on Molokai that are classified as construct-alter (Category IV).

Maui has the next highest percentage of high quality streams, with 34% under Category I, 46% under Category II, 20% under Category III, and none under Category IV. Hawaii comes after Maui since 21% of its streams are of high quality (Category I), 74% under Category II, 5% under Category III, and none under Category IV.

Kauai has all four categories of ecological quality. Twenty percent of its streams are of high quality (Category I), 37% are under Category II, 39% under Category III, and 4% under Category IV. Oahu has the dubious distinction of having the poorest quality streams. There are no longer any streams which could be classified as pristine-preservation (Category I). The best streams (43%) are of limited consumptive quality (Category II). In addition, 44% of its streams are classified as exploitive-consumptive (Category III), and 13% (the highest statewide) are of the lowest quality (Category IV).

On a statewide basis, 51% of all perennial streams come under limited consumptive (Category II), 27% under pristine-preservation status (Category I), 20 % under exploitive-consumptive (Category III), and 2% under construct-alter (Category IV).

SUMMARY AND CONCLUSIONS

Although streams are Hawaii's most significant class of inland water (in area and numbers), no systematic statewide listing or description of them exists. Many are known to have been channelized, but the extent of channel alteration has not been documented. The effect of these alterations on the physicochemical features of the streams and the nature of the major fauna associated with inland water have not been explored. The purpose of this study was to compile a comprehensive index of perennial streams that is detailed with respect to locations, physical characteristics, and changes in aquatic ecology that have resulted.

STREAM SURVEY

Perennial Streams

At least 366 perennial streams have been recognized in the five major islands of the State. Fifty-nine percent of these streams are continuous, with Kauai having the highest percentage of its streams continuous and Molokai the lowest.

Altered Streams

Of the 366 streams identified, 15% have been channelized. More than half of these altered streams (8% of all perennial Hawaiian streams) are found in Oahu, followed by Kauai, Hawaii, Maui, and Molokai in decreasing order.

Types and "Abundances" of Alterations

Six types of channel modifications have been identified: lined channel, channel realigned and/or vegetation removed, elevated culvert, revetment, blocked or filled-in channel, and extended culvert. A total length of 151 km of these modifications have been identified statewide. The comparative "abundances" of these are: lined channel, 40%; realigned/cleared, 28%; revetment, 24%; blocked channel, 5%; elevated culvert, 3%; and extended culvert <1%. Eighty-nine percent of the total length of lined channel is located on Oahu.

ASSOCIATED MACROFAUNA

Electrofishing

Extent of the inventory necessitated a selective restriction of the faunal taxa surveyed. Collections were made primarily by electrofishing, an effective and adaptable method of stream sampling. This limited the survey to susceptible animals - fishes and decapod crustaceans - which are also the largest and most representative stream species exclusive of headwater areas.

Macrofaunal Inventory

Twenty-five species of fish and decapod crustaceans were collected statewide. Twenty-three of these species are found on Oahu, 17 on Kauai, 13 on Maui, 12 on Hawaii, and 9 on Molokai. Seventeen of these species are exotic. The proportion of native species relative to the total number is highest in Molokai (89%), followed by Hawaii (67%), Maui (62%), Kauai (47%), and Oahu (30%). This survey substantiated the absence of the endemic goby, *Lentipes concolor*, on Oahu--one of two islands from which it was described originally. The introduced guppy, *Poecilia reticulata*, was the most widely distributed and abundant species.

Macrofauna in Altered and Unaltered Streams

Both in numbers and biomass, native species are dominant in most unaltered streams, while exotic species are dominant in altered streams. No native species were collected from lined channels.

Indicator Species

Three endemic Hawaiian gobies (o'opu alamoo, *Lentipes concolor*; o'opu nopili, *Sicydium stimpsoni*; and o'opu nakea, *Awaous stamineus*) require clean fresh water in considerable volume flowing through comparatively unaltered stream channels. The population density of *Lentipes concolor* is now low where present at all. Both *Awaous stamineus* and *Sicydium stimpsoni* are present in comparatively high population density in most unaltered streams. However, *Awaous stamineus* is a food fish (there is a minor nakea fishery in Kauai) subject to fishing pressures in addition to pressures due to stream degradation. *Sicydium stimpsoni*, which is found in all five major islands (see Tables 3, 7, 8, 10, and 12) is not subject to harvesting. The decline in population density, or in extreme cases, the disappearance of the o'opu nopili from a stream, is a good indication of serious stream degradation.

PHYSICOCHEMICAL CHARACTERS

Discharge

The largest among Hawaiian streams is Wailuku on the island of Hawaii. On an island-wide basis, Hawaii and Kauai have the highest yearly mean discharge, followed by Maui, Oahu, and Molokai in decreasing order.

Composition of Stream Water

Oahu streams carry the highest total dissolved solids, followed by Maui, Kauai, Molokai, and Hawaii in decreasing order. Conductivity follows the same general pattern. There appears to be no significant difference in pH values on an island-wide basis. The major cation contents of Hawaiian stream water are nearer those of water from igneous rocks than of major rivers of the world.

Effects of Alterations on Water Temperature

Pending results of an on-going study, it can be said that the warming effect of a lined channel is about twice that of a revetment and about four times that of a clearing/realignment. Elevated temperatures appear to be related to shallowness, loss of vegetative cover, channel substrate, and strong insolation.

STREAM QUALITIES

Of the 366 perennial streams in the State, only 14% may be physically pristine. On an island basis, the order is as follows: Molokai> Kauai> Hawaii> Maui> Oahu. Oahu no longer has any physically pristine streams.

The presence of exotic macrofauna in all streams sampled indicates that there are apparently no longer any biologically pristine streams in the State, confirming earlier findings of Maciolek (1975, MS).

Only about 27% of the State's perennial streams may be of high ecological quality. On an island-wide basis, Molokai has the largest percentage of its streams belonging to the pristine-preservation category, followed by Maui, Hawaii, Kauai, and Oahu in decreasing order. Oahu has no stream which can be classified under pristine-preservation.

Fifty-three percent of the State's perennial streams have some form of water diversion. Hawaii, Maui, and Oahu each has about 60% of its streams diverted; Kauai has 46% and Molokai 14%.

STREAM ALTERATION, A CONTINUING PROCESS

This inventory of altered streams should not be considered final. Since this study was begun, alterations were started and completed in Waimanalo and Kahaluu Streams on Oahu, a dam is being constructed on a Kaneohe Stream tributary, and alteration is going on in Iao Stream on Maui. Plans are being processed for additional channel alterations in Kawa and Heeia Streams on Oahu.

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Appendix A. Comprehensive List of Perennial Hawaiian Streams and Tributaries as Named on USGS Quadrangle Maps (Undesignated Streams Named After Land Divisions or Adjacent Features).

Streams are listed alphabetically by island and located by grid coordinates determined from USGS topographic maps. Herein, a stream is defined as a single discharge to the ocean regardless of the number and length of tributaries.

Assignment of ecological quality was done according to the status-use categories listed in the proposed State water quality standards (Department of Health 1977) as described below. Quality status assignment was made on the basis of field observations wherever possible; ecological quality of streams not visited was estimated from the character of the locality in which they occur. In most cases, the ecological status of streams listed here agrees with that of the State Department of Health.

LEGEND FOR APPENDIX

Stream Name and Location

1. First word is stream name: second word is topographic quadrangle map, i.e., Aamakao (Stream): Hawi (second word of quadrangle sheet name, if any, is omitted to save space, e.g., Schofield = Schofield Barracks).
2. Grid coordinates indicate stream mouth location; latitude North, longitude West.

Ecological Quality Status

First Index.

(I) Pristine-Preservation. High environmental and biological quality: use range from no consumptive, degrading or modifying to special exploitive (but non-degrading). For purposes of this report, subcategories IA and IB proposed by the Department of Health (1977) are ignored.

(II) Limited Consumptive. Moderate to high quality water or natural values: controlled use to prevent excessive modification.

(III) Exploitive-Consumptive. Moderate to low natural and/or water quality (well exploited, modified or degraded): used for water related recreational activities.

(IV) Construct-Alter. Low environmental and biological quality: may be restricted to public for health or safety reasons.

Stream Characteristics

Second Index.

A = Channelized or stream channel altered.
N = Not channelized or stream channel not altered.

Third Index.

C = Continuous: naturally flowing to the sea year-round.
I = Interrupted: intermittent flow in a portion of channel, discharges into the sea during wet season.

Fourth Index.

DI = Water diverted (numeral indicates number of diversions in stream system).
U = No diversion(s).

Fifth Index.

Arabic numeral(s) indicates number of roadways of all kinds crossing all stream channels.

Example.

105.0[a] Wailoa R.[b]: Hilo[c]

(III)[d] A[e] I[f] D2[g] 22[h]

19°43'36", 155°04'25"[i]

105.1 Alenaio[j]

[a]Stream number.
[b]Stream name.
[c]Topographic map name.
[d]Ecological quality category.
[e]Altered stream channel.
[f]Interrupted stream.
[g]Diverted at two sites.
[h]Number of roadway crossings.
[i]Stream mouth location.
[j]Stream tributary.

1. Hawaii Island.

001.0 Aamakao: Hawi
(II) N C D6 15
20°13'56", 155°45'17"

002.0 Aamanu: Kukaiau
(I) N C U 2
20°03'11", 155°21'25"

003.0 Ahole: Papaaloa
(II) N C U 3
20°57'10", 155°10'57"

004.0 Alakahi: Honomu
(II) N C D1 5
19°48'37", 155°05'41"

005.0 Alia: Honomu
(II) N C D2 15
19°51'16", 155°05'11"

006.0 Alilipali: Honokaa
(II) N I D1 5
20°04'17", 155°23'58"

007.0 Hakalau: Papaaloa
(II) N C D1 19
19°54'11", 155°07'54"

007.1 Hakalau segment
007.2 Kamaee
007.3 Waawaa

008.0 Halawa: Hawi
(II) N I D3 8
20°14'21", 155°45'42"

009.0 Hanaula: Hawi
(II) N I D3 9
20°15'04", 155°47'58"

010.0 Hanawi: Honomu
(II) N C D2 10
19°48'30", 155°05'37"

011.0 Hapahapai: Hawi
(II) N I D3 8
20°15'02", 155°47'33"

012.0 Heeka: Honomu
(II) N C D1 5
19°48'06", 155°05'22"

013.0 Honokane Iki: Honokane
(II) N C D2 0
20°11'45", 155°43'08"

014.0 Honokane Nui: Honokane
(II) N C D7 0
20°12'00", 155°43'14"

015.0 Honokea: Honokane
(II) N C D3 0
20°11'21", 155°42'08"

016.0 Honolii: Honomu
(II) N C D1 15
19°45'35", 155°05'37"

016.1 Honolii segment
016.2 Kaiwiki
016.3 Pohakupaa

017.0 Honomu: Honomu
(II) N C U 5
19°52'22", 155°06'28"

018.0 Honopue: Honokane
(II) N C D2 0
20°10'52", 155°41'28"

019.0 Kaaheiki: Papaaloa
(II) N C U 4
20° 56'38", 155°10'21"

020.0 Kaala: Kukaiau
(I) N I U 1
20°02'06", 155°19'08"

021.0 Kaalau: Papaaloa
(II) N I D1 8
20°58'26", 155°12'35"

021.1 Kaalau segment
021.2 Pahale

022.0 Kaapoko: Honomu
(II) N C D1 2
19°47'36", 155°05'34"

023.0 Kaawalii: Kukaiau
(I) N I U 2
20°00'31", 155°15'53"

024.0 Kahaupu: Honokaa
(II) N I D3 3
20°05'31", 155°26'20"

025.0 Kahawailiili: Honokaa
(II) N I D2 5
20°05'29", 155°26'08"

026.0 Kahoopuu: Kukuihaele
(I) N C U 0
20°08'21", 155°36'53"

027.0 Kahuku: Papaaloa
(II) N C U 2
20°56'11", 155°09'47"

028.0 Kaieie: Honomu
(II) N C D3 10
19°47'52", 155°05'34"

029.0 Kailikaula: Honokane
(II) N C D1 0
20°11'10", 155°41'43"

030.0 Kaimu: Honokane
(I) N C U 0
20°09'35", 155°38'59"

031.0 Kaiwiki: Kukaiau
(II) N C U 3
20°01'29", 155°17'39"

032.0 Kaiwilahilahi: Papaaloa
(II) N C D1 3
20°58'49", 155°13'20"

033.0 Kalaoa: Honomu
(II) N C D1 5
19°48'26", 155°05'34"

034.0 Kalopa: Honokaa
(II) N I D1 2
20°04'28", 155°24'46"

035.0 Kaohaoha: Kukaiau
(II) N C U 4
20°00'48", 155°16'11"

036.0 Kapehu: Papaaloa
(II) N C D1 5
20°58'14", 155°12'21"

037.0 Kapehu: Honomu
(II) N C D1 20
19°52'05", 155°05'53"

038.0 Kapue: Honomu
(II) N C D1 21
19°46'52", 155°05'26"

039.0 Kaula: Kukaiau
(II) N C D1 5
20°01'21", 155°17'18"

040.0 Kaumoali: Honokaa
(II) N I D1 4
20°04'09", 155°23'38"

041.0 Kawaikalia: Kukuihaele
(II) N I D2 3
20°07'06", 155°31'20"

042.0 Kawainui: Honomu
(II) N C U 10
19°49'24", 155°05'30"

043.0 Keahua: Honokaa
(II) N C D2 6
20°05'07", 155°25'14"

044.0 Kealakaha: Kukaiau
(I) N I U 2
20°01'55", 155°18'43"

045.0 Kihalani: Papaaloa
(II) N C D1 2
20°58'59"; 155°13'30"

046.0 Kilau: Papaaloa
(I) N C U 2
20°59'35"; 155°14'34"

047.0 Koholalele: Kukaiau
(II) N I D1 10
20°03'06", 155°03'06"

047.1 Kawaili
047.2 Koholalele segment

048.0 Kolealiilii: Honokane
(II) N C D2 0
20°10'50", 155°40'57"

048.1 Kolealiilii segment
048.2 Oniu

049.0 Kolekole: Honomu
(II) N C U 10
19°53'10", 155°07'17"

049.1 Kaahakini
049.2 Kalakoo
049.3 Kolekole segment

050.0 Kukaiau: Kukaiau
(II) N I U 5
20°02'30", 155°20'05"

051.0 Kukui: Honokane
(I) N C U 0
20°10'22", 155°39'57"

052.0 Kukuilamalamahii: Honokaa
(II) N C D1 5
20°04'24", 155°24'03"

053.0 Kumakua: Hawi
(II) N C D4 9
20°15'43", 155°49'11"

054.0 Kupapaulua: Kakaiau
(I) N I U 5
20°01'29", 155°17'46"

055.0 Kuwaikahi: Papaaloa
(II) N C D1 4
20°59'10", 155°13'53"

056.0 Laimi: Honomu
(II) N C U 11
19°52'16", 155°06'04"

057.0 Laupahoehoe: Papaaloa
(I) N I U 6
20°59'48", 155°14'39"

057.1 Kapili
057.2 Laupahoehoe segment

058.0 Maili: Honomu
(II) N C D1 5
19°45'35", 155°05'42"

059.0 Makahanaloa: Honomu
(II) N C D1 7
19°50'58", 155°05'12"

060.0 Makea: Honomu
(II) N C D2 12
19°51'25", 155°05'26"

061.0 Malanahae: Kukuihaele
(II) N I D2 3
20°06'54", 155°31'00"

062.0 Manoloa: Papaaloa
(I) N C U 2
20°56'51", 155°10'37"

063.0 Manowaiopae: Papaaloa
(II) N C D1 2
20°59'16", 155°14'00"

064.0 Manuwaikaalio: Kukuihaele
(I) N C U 0
20°08'41", 155°37'25"

065.0 Maulua: Papaaloa
(I) N I U 1
20°57'29", 155°11'49"

065.1 Makahiloa
065.2 Maulua segment

066.0 Moanalulu: Papaaloa
(II) N C D1 6
20°58'41", 155°12'58"

066.1 Ahoa
066.2 Haakoa
066.3 Moanalulu segment

067.0 Nakooko: Honokane
(II) N C D1 0
20°10'38", 155°40'33"

068.0 Naluea: Kukuihaele
(I) N C U 0
20°08'24", 155°37'01"

069.0 Nanue: Papaaloa
(II) N C U 3
20°55'53", 155°09'30"

069.1 Kaahina
069.2 Nanue segment
069.3 Painiu

070.0 Nienie: Honokaa
(II) N I D4 6
20°06'17", 155°28'26"

071.0 Ninole: Papaaloa
(II) N C U 3
20°56'42", 155°10'25"

072.0 Niulii: Honokane
(II) N C D3 9
20°13'33", 155°44'55"

073.0 Ohiahuea: Honokane
(II) N C D1 0
20°10'39", 155°40'39"

074.0 Onomea: Honomu
(II) N C D2 9
19°48'43", 155°05'42"

075.0 Opea: Papaaloa
(II) N C U 7
20°55'39", 155°09'14"

076.0 Paauilo: Kukaiau
(II) N I U 3
20°03'12", 155°21'30"

077.0 Pae: Honokane
(I) N C U 0
20°09'27", 155°38'39"

078.0 Paeohe: Papaaloa
(I) N C D2 5
20°57'29", 155°11'53"

079.0 Paheehee: Honomu
(II) N C U 14
19°52'46", 155°06'47"

080.0 Pahoehoe: Honomu
(II) N C D1 4
19°46'36", 155°05'32"

080.1 Pahoehoe segment
080.2 Waikoana

081.0 Pali Akamoa: Hawi
(II) N I D1 4
20°14'42", 155°46'46"

082.0 Paopao: Honokane
(I) N C U 0
20°10'09", 155°39'39"

083.0 Papaikou: Honomu
(II) N C D1 6
19°47'12", 155°05'20"

084.0 Papuaa: Honokaa
(II) A C D1 8
20°06'12", 155°28'12"

085.0 Paukaa: Honomu
(II) N C D2 5
19°46'16", 155°05'37"

086.0 Peleau: Papaaloa
(II) N C U 4
20°55'14", 155°08'39"

087.0 Pohakupuka: Papaaloa
(II) N C U 7
20°57'22", 155°11'16"

087.1 Huliilii
087.2 Kaoheanu
087.3 Pohakupuka segment

088.0 Pololu: Honokane
(II) N C D5 0
20°12'26", 155°44'01"

088.1 Kapoloa
088.2 Pololu segment
088.3 Waiakalae

089.0 Poupou: Papaaloa
(I) N C U 2
20°56'53", 155°10'41"

090.0 Pukihae: Hilo
(II) A C D1 7
19°44'09", 155°05'30"

091.0 Pukoa: Honokane
(I) N C U 0
20°08'45", 155°37'33"

092.0 Punalulu: Honokane
(I) N C U 0
20°09'55", 155°39'06"

093.0 Puuokalepa: Honomu
(II) N C D1 10
19°47'45", 155°05'33"

093.1 Kumuawane
093.2 Puuokalepa segment

094.0 Umauma: Papaaloa
(II) N C D1 12
20°54'37", 155°08'17"

094.1 Hanapueo
094.2 Umauma segment

095.0 Waiaalala: Honokane
(I) N C U 0
20°10'05", 155°39'29"

096.0 Waiaama: Honomu
(II) N C U 3
19°49'45", 155°05'22"

097.0 Waiapuka: Honokane
(II) N C D2 0
21°10'35", 155°40'21"

097.1 Kamoloumi
097.2 Waiapuka segment

098.0 Waiehu: Papaaloa
(II) N C U 4
20°56'06", 155°09'38"

099.0 Waikaalulu: Honokaa
(II) N I D1 5
20°04'46", 155°24'28"

100.0 Waikaloa: Honokane
(II) N C D1 0
21°10'31", 155°40'14"

101.0 Waikama: Honokane
(II) N C D1 3
20°13'17", 155°44'11"

102.0 Waikaumalo: Papaaloa
(II) N C U 3
20°56'14", 155°09'48"

103.0 Waikoloa: Kukuihaele
(II) N I D3 7
20°07'30", 155°32'32"

104.0 Waikolu: Papaaloa
(II) N C U 4
20°56'32", 155°10'14"

105.0 Wailoa R.: Hilo
(III) A I D2 22
19°43'36", 155°04'25"

105.1 Alenaio
105.2 Kaluiiki
105.3 Waiakea
105.4 Wailoa R. segment
105.5 Waipahoehoe

106.0 Wailoa: Kukuihaele
(II) N C D7 1
20°07'21", 155°35'28"

106.1 Alakahi
106.2 Hiilawe
106.3 Kawaiki
106.4 Kawainui
106.5 Koiawe
106.6 Nanaue
106.7 Wailoa segment
106.8 Waima
106.9 Waipio

107.0 Wailuku R.: Hilo
(II) N C D2 39
19°43'55", 155°05'24"

107.1 Aale
107.2 Awehi

107.3 Hookelekele
107.4 Kahoama
107.5 Kalohewahewa
107.6 Kapehu
107.7 Kipi
107.8 Laualu
107.9 Mokupau
107.10 Nakakauila
107.11 Pakaluahine
107.12 Waiau
107.13 Wailuku R. segment

108.0 Waimaauou: Honomu
(II) N C U 12
19°50'00", 155°05'12"

109.0 Waimaile: Honokane
(I) N C U 0
20°10'29", 155°49'04"

110.0 Waimanu: Honokane
(I) N C U 0
20°08'45", 155°38'14"

110.1 Kakaauki
110.2 Waihilau
110.3 Waiilikahi
110.4 Waimanu segment

111.0 Wainaia: Hawi
(II) N I D6 7
20°14'43", 155°46'42"

112.0 Waipahi: Honokane
(II) N C D1 0
20°11'37", 155°42'37"

113.0 Waipahoehoe: Kukuihaele
(I) N C U 0
20°08'02", 155°36'22"

114.0 Waipunahina: Honokaa
(II) N I D3 15
20°03'41", 155°22'29"

115.0 Waipunahoe: Kukuihaele
(II) N I D4 10
20°07'47", 155°33'07"

116.0 Waipunalei: Keanakolu
(II) N C U 4
20°00'00", 155°15'09"

117.0 Waiulili: Kukuihaele
(II) N C D3 7
20°07'26", 155°34'47"

Possible Interrupted Streams:

118.0 Haloa: Kamuela
(III) N I U 2
20°01'50", 155°38'21"

119.0 Hilea: Naalehu
(III) N I U 6
19°07'00", 155°31'41"

120.0 Kiilae: Honaunau
(II) N I U 1
19°24'48", 155°54'27"

121.0 Lamimaumau: Kamuela
(III) A I D1 13
20°00'56", 155°40'25"

122.0 Waiaha: Kailua
(III) N I D2 4
19°37'46", 155°58'26"

123.0 Waiulaula: Kawaihae
(III) N I D2 15
20°01'01", 155°49'21"

123.1 Keanuiomano
123.2 Kohakohau
123.3 Waikoloa
123.4 Waiulaula segment

2. Maui Island.

001.0 Alaalaula: Kipahulu
(I) N C U 1
20°41'14", 156°01'15"

002.0 Alelele: Kaupo
(I) N C U 1
20°39'04", 156°05'13"

003.0 East Wailuaiki: Keanae
(II) N C D1 1
20°50'21", 156°07'36"

004.0 Hahalawe: Kipahulu
(I) N C U 2
20°40'24", 156°02'30"

004.1 Hahalawe segment
004.2 Maluhianaiwi

005.0 Haipuaena: Keanae
(II) N C D3 1
20°52'37", 156°10'28"

006.0 Hanawana: Haiku
(II) N C D1 0
20°54'21", 156°12'47"

007.0 Hanawi: Nahiku
(II) N C D3 1
20°49'41", 156°06'13"

008.0 Hanehoi: Nahiku
(II) N C D5 3
20°54'39", 156°13'01"

008.1 Hanehoi segment
008.2 Huelo

009.0 Heleleikeoha: Hana
(I) N I U 1
20°48'38", 156°03'36"

010.0 Hoalua: Haiku
(II) N C D3 1
20°54'25", 156°12'59"

011.0 Honokahua: Honolua
(II) N C D2 2
21°00'29", 156°39'07"

012.0 Honokowai: Lahaina
(III) A I D5 6
20°57'13", 156°41'33"

012.1 Amalu
012.2 Honokowai segment
012.3 Kapaloa

013.0 Honokohau: Honolua
(III) N C D2 2
21°01'29", 156°36'43"

014.0 Honolewa: Kipahulu
(I) N C U 1
20°41'01", 156°01'46"

015.0 Honolua: Honolua
(III) N C D2 3
21°01'00", 156°38'29"

016.0 Honomaele: Hana
(I) N I U 4
20°48'30", 156°02'19"

017.0 Honomanu: Keanae
(II) N C D3 1
20°51'56", 156°10'12"

17.1 Honomanu segment
17.2 Uluini

018.0 Honopou: Haiku
(II) N C D6 2
20°56'20", 156°14'29"

018.1 Honopou segment
018.2 Puniawa

019.0 Hoolawa: Haiku
(II) N C D5 1
20°56'00", 156°14'30"

019.1 Hoolawa segment
019.2 Hoolawaliilii
019.3 Hoolawanui

020.0 Iao: Wailuku
(II) A C D9 6
20°54'43", 156°29'07"

020.1 Ae
020.2 Iao segment
020.3 Kinihapai
020.4 Nakalaloa
020.5 Poohahoahoa

021.0 Kaaiea: Keanae
(II) N C D4 1
20°53'17", 156°11'32"

022.0 Kaapahu: Kipahulu
(I) N C U 1
20°39'15", 156°04'55"

023.0 Kahakuloa: Kahakuloa
(II) N C U 1
21°00'05", 156°33'07"

024.0 Kahana: Honolua
(II) N I D3 7
20°58'50", 156°40'50"

024.1 Kahana segment
024.2 Mailepai

025.0 Kahoma: Lahaina
(III) A C D6 3
20°53'20", 156°41'21"

025.1 Halona
025.2 Kahoma segment
025.3 Kanaha

026.0 Kailua: Keanae
(II) N C D4 1
20°54'07", 156°12'27"

026.1 Kailua segment
026.2 Oanui

027.0 Kakipi: Haiku
(II) N C D17 4
20°56'10", 156°15'32"

027.1 Kakipi segment
027.2 Kapalaalaea
027.3 Kaulu
027.4 Koale
027.5 Makaa
027.6 Papalua
027.7 Piiloi
027.8 Waihee

028.0 Kakiweka: Kipahulu
(I) N C U 1
20°40'26", 156°02'22"

029.0 Kapaula: Nahiku
(II) N C D1 1
20°49'25", 156°06'34"

030.0 Kapia: Hana
(I) N I U 1
20°42'59", 155°59'30"

031.0 Kauaula: Lahaina
(III) A C D7 5
20°51'42", 156°40'18"

032.0 Kaupakulua: Haiku
(II) N I D8 4
20°56'41", 156°18'06"

033.0 Kawaipapa: Hana
(II) N I D2 1
20°45'51", 155°59'22"

034.0 Kawakoe: Hana
(I) N I U 2
20°48'34", 156°03'13"

034.1 Kawakoe segment
034.2 Mokulehua

035.0 Keaaiki: Hana
(I) N I U 1
20°49'05", 156°04'03"

036.0 Kolea: Keanae
(II) N C D1 1
20°53'06", 156°11'11"

037.0 Kopiliula: Keanae
(II) N C D2 2
20°50'10", 156°07'16"

037.1 Kopiliula segment
037.2 Puakaa

038.0 Koukouai: Kipahulu
(III) N I U 1
20°39'07", 156°03'45"

039.0 Kuhiwa: Nahiku
(I) N C U 1
20°49'40", 156°05'08"

040.0 Kuiaha: Haiku
(III) N I D13 6
20°56'45", 156°18'49"

040.1 Kuiaha segment
040.2 Ohia

041.0 Kukuiula: Kipahulu
(I) N C U 1
20°39'12", 156°04'42"

042.0 Laniupoko: Lahaina
(III) N C D1 2
20°50'12", 156°38'53"

043.0 Leleka: Kaupo
(I) N C U 1
22°39'14", 156°05'00"

044.0 Makamakaole: Kahakuloa
(II) N C D1 1
20°58'05", 156°31'41"

045.0 Makapipi: Nahiku
(II) N C D1 2
20°49'49", 156°05'49"

046.0 Maliko: Paia
(II) N I D6 8
20°56'20", 156°20'32"

047.0 Manawaiiao: Haiku
(II) N I D2 2
20°56'46", 156°17'50"

048.0 Manawaikeae: Hana
(I) N I U 1
20°49'24", 156°04'37"

049.0 Manawainui: Kaupo
(II) N I D1 1
20°38'17", 156°06'59"

049.1 Healani
049.2 Manawainui segment

050.0 Moomoonui: Hana
(I) N I U 1
20°44'39", 155°59'07"

051.0 Nailiilihaele: Keanae
(II) N C D2 1
20°54'06", 156°12'26"

052.0 Nuaailua: Keanae
(III) N C D1 1
20°51'46", 156°09'40"

053.0 Nuanuaaloa: Kaupo
(I) N I U 2
22°38'43", 156°06'08"

054.0 Olowalu: Olowalu
(III) N C D4 3
20°48'58", 156°37'48"

055.0 Oopuola: Keanae
(III) N C D6 2
20°53'31", 156°11'55"

055.1 Makanali
055.2 Oopuola segment

056.0 Paakea: Nahiku
(II) N C D1 1
20°49'50", 156°07'04"

057.0 Palikea: Kipahulu
(II) N C U 1
20°39'59", 156°02'38"

057.1 Palikea segment
057.2 Pipiwai

058.0 Papaahawahawa: Kipahulu
(I) N C U 1
20°41'21", 156°00'41"

059.0 Piinau: Keanae
(II) N C D3 3
20°51'50", 156°08'50"

059.1 Kuo
059.2 Palauhulu

059.3 Piinau segment
059.4 Pokakaekane

060.0 Punalau: Keanae
(III) N C D3 1
20°51'55", 156°10'12"

060.1 Kolea
060.2 Punalau segment

061.0 Puohokamoa: Keanae
(II) N C D5 1
20°52'35", 156°10'38"

062.0 Uaoa: Haiku
(II) N I D3 2
20°56'14", 156°16'29"

063.0 Ukumehame: Olowalu
(II) N C D2 3
20°48'09", 156°33'44"

063.1 Hokuula
063.2 Ukumehame segment

064.0 Wahikuli: Lahaina
(III) A I D7 8
20°54'50", 156°41'34"

064.1 Hahakea
064.2 Wahikuli segment

065.0 Waiehu: Wailuku
(II) A C D5 8
20°55'17", 156°29'40"

065.1 North Waiehu
065.2 South Waiehu
065.3 Waiehu segment

066.0 Waieli: Kipahulu
(III) N C U 1
20°40'37", 156°02'12"

067.0 Waihee R.: Wailuku
(II) N C D5 5
20°57'05", 156°30'43"

067.1 Huluhulupueo
067.2 Mananole
067.3 Waihee segment

068.0 Waihole: Nahiku
(I) N I U 2
20°49'26", 156°04'42"

069.0 Waikamoi: Keanae
(III) N C D4 0
20°52'56", 156°11'00"

069.1 Alo
069.2 Waikamoi segment

070.0 Waikapu: Maalaea
(II) A C D9 9
20°47'40", 156°28'51"

071.0 Wailua: Kipahulu
(I) N C U 2
20°41'02", 156°01'42"

072.0 Waiohonu: Kipahulu
(I) N I U 1
20°42'26", 155°59'51"

073.0 Waiohue: Nahiku
(II) N C D1 1
20°49'51", 156°07'05"

074.0 Waiokamilo: Keanae
(III) N C D1 1
20°51'06", 156°07'52"

075.0 Waioni: Hana
(I) N I U 1
20°48'55", 156°03'58"

076.0 Waipio: Haiku
(III) N C D3, 2
20°55'04", 156°13'48"

077.0 West Wailuaiki: Keanae
(II) N C D1 1
20°50'25", 156°07'42"

078.0 West Wailuanui: Keanae
(II) N C D2 1
20°50'37", 156°07'51"

078.1 East Wailuanui
078.2 West Wailuanui segment

Possible Interrupted Streams.

079.0 Haneoo: Hana
(I) N I U 1
20°43'52", 155°59'14"

080.0 Holoinawawae: Hana
(I) N I U 1
20°45'50", 155°59'39"

081.0 Honanana: Kahakuloa
(I) N I U 1
21°00'56", 156°34'09"

082.0 Kahawaihapapa: Hana
(I) N I U 1
20°49'18", 156°04'24"

083.0 Kalena: Kipahulu
(III) N I U 11
20°39'08", 156°03'41"

084.0 Kalepa: Kaupo
(I) N I U 1
20°39'08", 156°05'20"

085.0 Kealii: Haiku
(II) N I D1 0
20°56'24", 156°16'09"

086.0 Lanikele: Hana
(I) N I U 1
20°48'50", 156°03'45"

087.0 Maalo: Kaupo
(I) N I U 1
20°38'37", 156°06'43"

088.0 Ohia: Keanae
(I) N I U 0
20°51'40", 156°08'30"

089.0 Opelu: Kipahulu
(I) N I U 1
20°39'10", 156°04'36"

090.0 Poelua: Kahakuloa
(I) N I U 1
21°01'11", 156°34'57"

091.0 Pohakea: Maalaea
(II) N I D3 6
20°47'59", 156°29'48"

092.0 Puaaluu: Kipahulu
(I) N I U 1
20°40'11", 156°02'37"

093.0 Puehu: Keanae
(II) N I D1 1
20°53'51", 156°11'55"

094.0 Wahinepee: Keanae
(I) N I U 1
20°52'50", 156°10'53"

095.0 Waiaaka: Nahiku
(III) N I D1 1
20°49'40", 156°06'57"

096.0 Waiolai: Kahakuloa
(II) N I D1 2
20°58'24", 156°31'45"

3. Oahu Island.

001.0 Aiea: Waipahu
(IV) A I D1 6
21°22'16", 156°56'15"

002.0 Anahulu R.: Haleiwa
(II) N C D10 13
21°35'50", 156°06'31"

002.1 Anahulu R. segment
002.2 Kawaiiki
002.3 Kawainui

003.0 Hakipuu: Kahana
(II) N I U 2
21°30'33", 157°51'16"

004.0 Halawa: Puuloa
(III) A C U 10
21°22'08", 156°56'25"

004.1 Halawa segment
004.2 North Halawa
004.3 South Halawa

005.0 Heeia: Kaneohe
(II) A C D1 9
21°26'23", 157°48'46"

006.0 Honouliuli: Ewa
(III) N I D10 54
21°21'57", 158°01'30"

007.0 Kaaawa: Kahana
(II) N I U 4
21°32'55", 157°50'49"

008.0 Kaalaea: Kaneohe
(III) A C U 3
21°28'13", 157°50'43"

009.0 Kahaluu: Kaneohe
(II) A C D2 14
21°27'51", 157°50'30"

009.1 Ahuimanu
009.2 Kahaluu segment
009.3 Waihee

010.0 Kahana: Kahana
(II) N C D7 7
21°33'35", 157°52'18"

010.1 Kahana segment
010.2 Kawa

011.0 Kahawainui: Kahuku
(III) N C U 8
21°39'31", 157°55'51"

012.0 Kaipapau: Hauula
(II) A I U 2
21°37'13", 157°54'53"

013.0 Kalauao: Waipahu
(III) A C D2 5
21°21'57", 157°56'46"

014.0 Kalihi: Honolulu
(IV) A C D1 19
21°20'00", 157°53'38"

014.1 Kalihi segment
014.2 Kamanaiki

015.0 Kaluanui: Hauula
(II) N C D1 4
21°36'05", 157°53'57"

016.0 Kaneohe: Kaneohe
(III) A C D3 20
21°24'56", 157°47'09"

016.1 Aolani
016.2 Kamooalii
016.3 Kaneohe segment
016.4 Kuou
016.5 Luluku

017.0 Kapalama: Honolulu
(IV) A I U 7
21°19'21", 157°52'50"

018.0 Kaukonahua: Haleiwa
(III) N C D18 26
21°35'05", 158°07'10"

018.1 Kaukonahua segment
018.2 North Poamoho
018.3 Poamoho
018.4 South Kaukonahua

019.0 Kaupuni: Waianae
(IV) A I D10 13
21°27'08", 158°11'44"

019.1 Hiu
019.2 Honua
019.3 Punanaula
019.4 Kalalula
019.5 Kanewai
019.6 Kauaopuu
019.7 Kaupuni segment
019.8 Kawiwi
019.9 Kukaki
019.10 Kumaipo

020.0 Kawa: Kaneohe
(III) A C U 4
21°24'44", 157°47'11"

021.0 Keaahala: Kaneohe
(IV) A C U 4
21°25'17", 157°47'23"

022.0 Kuliouou: Koko
(III) A I U 4
21°17'18", 157°43'26"

023.0 Maakua: Hauula
(II) N I U 2
21°36'50", 157°54'43"

024.0 Mailiili: Waianae
(III) A I D3 52
21°25'59", 158°11'05"

025.0 Makaha: Waianae
(II) N I D5 7
21°28'38", 158°13'22"

026.0 Makaleha: Kaena
(III) A C D3 9
21°34'57", 158°10'11"

027.0 Makiki: Honolulu
(IV) A I U 14
21°17'24", 157°50'51"

027.1 Kanaha
027.2 Kanealole
027.3 Makiki segment
027.4 Maunalaha
027.5 Moleka

028.0 Makua: Kaena
(II) N I D2 1
21°31'12", 158°13'57"

029.0 Malaekahana: Kahuku
(III) A I D4 9
21°40'36", 157°56'14"

030.0 Manoa: Honolulu
(II) A C D2 30
21°17'24", 157°49'51"

030.1 Aihualama
030.2 Luaalaea
030.3 Manoa segment
030.4 Naniuapo
030.5 Palolo
030.6 Pukele
030.7 Waaloa
030.8 Waiakeakua
030.9 Waihi
030.10 Waiomao

031.0 Maunawili: Mokapu
(II) A C D8 15
21°25'43", 157°44'40"

031.1 Ainoni
031.2 Kahanaiki
031.3 Makawao
031.4 Maunawili segment
031.5 Olomana
031.6 Omao
031.7 Palapu

032.0 Moanalua: Honolulu
(III) A I U 39
21°20'05", 157°53'46"

032.1 Kahauiki

032.2 Manaiki
032.3 Moanalua segment

033.0 Nanakuli: Schofield
(II) N I U 1
21°22'18", 158°08'40"

034.0 Nuuanu: Honolulu
(II) A C D3 41
21°19'58", 157°52'07"

034.1 Lulumahu
034.2 Makuku
034.3 Moole
034.4 Niniko
034.5 Nuuanu segment
034.6 Pauoa
034.7 Waolani

035.0 Oio: Kahuku
(III) A I D1 11
21°42'33", 157°59'26"

036.0 Paukauila: Haleiwa
(II) N C D10 8
21°35'05", 158°07'10"

036.1 Helemano
036.2 Opaeula
036.3 Paukauila segment

037.0 Paumalu: Waimea
(III) N I U 3
21°40'38", 158°02'38"

037.1 Kaleleiki
037.2 Paumalu segment

038.0 Pia: Koko
(III) A I U 4
21°17'04", 157°44'26"

038.1 Kupaua
038.2 Pia segment

039.0 Punaluu: Kahana
(II) N C D8 6
21°34'55", 157°53'16"

040.0 Ulehawa: Waianae
(III) A I U 7
21°23'43", 158°09'38"

041.0 Waiahole: Kaneohe
(II) N C D3 4
21°29'14", 157°51'45"

041.1 Waiahole segment
041.2 Waianu
041.3 Uwau

042.0 Waialaenui: Honolulu
(III) A I U 6
21°16'20", 157°46'48"

042.1 Kapakahi
042.2 Waialaenui segment

043.0 Waiawa: Waipahu
(IV) A C D6 19
21°22'02", 157°58'50"

043.1 Manana
043.2 Waiawa segment
043.3 Waimano

044.0 Waikane: Kaneohe
(II) N C D2 3
21°29'34", 157°51'06"

044.1 Waikane segment
044.2 Waikeekee

045.0 Waikele: Waipahu
(III) A C D14 65
21°22'05", 158°00'45"

045.1 Kapakahi
045.2 Kipapa
045.3 Waikakalaua
045.4 Waikele segment

046.0 Wailupe: Koko
(III) A I U 4
21°16'52", 157°45'09"

046.1 Kului
046.2 Wailupe segment

047.0 Waimalu: Waipahu
(III) A C D6 9
21°21'52", 156°57'20"

048.0 Waimanalo: Koko
(II) A C D9 13
21°22'05", 157°42'41"

049.0 Waimea R.: Waimea
(II) N C U 7
21°38'40", 158°04'01"

049.1 Elehaha
049.2 Kamananui
049.3 Kawaiwikoele
049.4 Waimea R. segment

Possible Interrupted Streams.

050.0 Kalunawaikaala: Waimea
(III) N I D1 2
21°39'42", 158°03'42"

051.0 Kawaihapai: Kaena
(III) N I D1 3
21°35'01", 158°10'45"

052.0 Kawela: Kahuku
(III) N I D1 4
21°43'05", 158°00'50"

053.0 Pakulena: Waimea
(II) N I U 2
21°39'55", 158°03'24"

054.0 South Makaha: Waianae
(II) N I U 4
21°27'40", 158°12'28"

4. Kauai Island.

001.0 Aakukui: Hanapepe
(III) N I D4 6
21°56'31", 159°39'12"

002.0 Anahola: Anahola
(III) N C D6 6
22°09'11", 159°18'30"

002.1 Anahola segment
002.2 Kaalula
002.3 Kahoopulu
002.4 Kaupaku
002.5 Keaoopu

003.0 Anini: Hanalei
(III) A C U 3
22°13'34", 159°28'00"

004.0 Awaawapuhi: Makaha
(I) N C U 0
22°09'59", 159°41'27"

005.0 East Waiakalua: Anahola
(II) N C D1 4
22°13'07", 159°22'33"

006.0 East Waipake: Anahola
(III) N C U 1
22°12'53", 159°21'06"

007.0 Haeleele: Makaha
(II) N I U 0
22°05'51", 159°45'05"

008.0 Hanakapiai: Haena
(II) N C U 0
22°12'46", 159°36'01"

009.0 Hanakoa: Haena
(I) N C U 0
22°11'53", 159°37'36"

010.0 Hanalei R.: Hanalei
(II) N C D6 6
22°13'05", 159°30'01"

010.1 Hanalei R. segment
010.2 Kaapoko
010.3 Waipunaea

011.0 Hanamaulu: Kapaa
(III) N C D13 10
21°59'21", 159°20'34"

012.0 Hanapepe: Hanapepe
(III) A C D14 10
21°54'24", 159°35'36"

012.1 Hanapepe segment
012.2 Hauhili
012.3 Kalai
012.4 Kapohakukilomanu
012.5 Kawaipuua
012.6 Koula
012.7 Wainonoia

013.0 Hoolulu: Haena
(I) N C U 0
22°12'30", 159°36'41"

014.0 Honopu: Makaha
(I) N C U 0
22°10'46", 159°40'36"

015.0 Hikimoe: Makaha
(II) N I U 0
22°06'24", 159°44'46"

016.0 Huleia: Lihue
(III) A C D40 38
21°57'03", 159°21'52"

016.1 Halenanahu
016.2 Hoinakaunalehua
016.3 Huleia segment
016.4 Kamooloa
016.5 Kuia
016.6 Paohia
016.7 Papakolea
016.8 Papuaa
016.9 Puakukui
016.10 Puhi
016.11 Weoweopilau

017.0 Kaaweiki: Makaha
(II) N I U 0
22°06'47", 159°44'36"

018.0 Kalalau: Haena
(I) N C U 0
22°10'53", 159°39'18"

019.0 Kalihiwai R.: Hanalei
(II) N C D3 2
22°13'11", 159°24'53"

019.1 Kalihiwai R. segment
019.2 Kaumoku
019.3 Pouli

020.0 Kapaa: Kapaa
(III) N C D10 13
22°05'46", 159°18'00"

020.1 Kapaa segment
020.2 Kapahi
020.3 Kealia
020.4 Maiakii
020.5 Makaleha
020.6 Moalepe
020.7 Mimino

021.0 Kauhao: Makaha
(II) N I U 0
22°07'16", 159°44'27"

022.0 Kaulaula: Makaha
(II) N I U 0
22°05'35", 159°45'22"

023.0 Kilauea: Anahola
(II) A C D12 7
22°13'22", 159°23'20"

023.1 Halaulani
023.2 Kahiliholo
023.3 Kaluamakua
023.4 Kilauea segment
023.5 Pohakuhonu
023.6 Puu Ka Ele
023.7 Wailapa

024.0 Konohiki: Kapaa
(III) A C D2 12
22°04'26", 159°19'02"

025.0 Kulihaili: Anahola
(II) N C U 1
22°13'08", 159°22'38"

026.0 Kumukumu: Kapaa
(IV) A C D4 8
22°06'38", 159°17'58"

027.0 Lawai: Koloa
(II) A C D3 10
21°53'30", 159°30'20"

028.0 Limahuli: Haena
(II) N C U 1
22°13'41", 159°34'37"

029.0 Lumahai R.: Hanalei
(II) N C U 1
22°13'12", 159°32'06"

030.0 Mahinauli: Hanapepe
(III) N C D7 8
21°55'56", 159°38'52"

031.0 Makaha: Makaha
(II) N I U 0
22°08'34", 159°44'00"

032.0 Manoa: Haena
(II) N C D1 1
22°13'29", 159°34'06"

033.0 Maunapuluo: Haena
(II) N C U 0
22°12'56", 159°35'55"

034.0 Milolii: Makaha
(I) N C U 0
22°09'10", 159°43'31"

035.0 Moloaa: Anahola
(III) N C U 3
22°11'54", 159°20'12"

035.1 Kaluaa
035.2 Moloaa segment

036.0 Nahomalu: Kekaha
(II) N I D4 2
22°02'43", 159°46'30"

037.0 Nakeikionaiwi: Haena
(I) N C U 0
22°10'33", 159°39'46"

038.0 Nawiliwili: Lihue
(IV) N C D8 16
21°57'47", 159°21'16"

039.0 Nualolo: Makaha
(I) N C U 0
22°09'56", 159°41'49"

040.0 Papaa: Anahola
(III) N C D1 7
22°10'38", 159°19'00"

041.0 Pilaa: Anahola
(II) N C U 1
22°12'52", 159°22'02"

042.0 Pohakuao: Haena
(I) N C U 0
22°11'24", 159°38'18"

043.0 Puali: Lihue
(II) N C D7 9
21°57'17", 159°21'50"

043.1 Halehaka
043.2 Puali segment

044.0 Puukumu: Hanalei
(III) A C U 5
22°13'11", 159°24'53"

045.0 Wahiawa: Hanapepe
(III) N C D4 4
21°53'38", 159°34'41"

046.0 Waiahuakua: Haena
(I) N C U 0
22°12'12", 159°37'04"

047.0 Waikoko: Hanalei
(III) A I U 1
22°12'36", 159°31'08"

048.0 Waikomo: Koloa
(III) A C D9 17
21°52'59", 159°28'16"

048.1 Omao
048.2 Poeleele
048.3 Waihohonu
048.4 Waikomo segment

049.0 Wailua R.: Kapaa
(III) N C D32 27
22°02'55", 159°20'19"

049.1 Halii
049.2 Iliiliula
049.3 Iole
049.4 Kalama
049.5 Kaulu
049.6 Kawi
049.7 Keahua
049.8 North Fork Wailua
049.9 Opaekaa
049.10 Palikea
049.11 South Fork Wailua
049.12 Uhau Iole
049.13 Waiahi
049.14 Waiaka
049.15 Waikoko
049.16 Wailua R. segment

050.0 Waimea R.: Kekaha
(III) A C D28 10
21°57'16", 159°40'07"

050.1 Awini
050.2 Elekeniiki
050.3 Elekeninui
050.4 Halehaha
050.5 Halekua
050.6 Halemanu
050.7 Halepaakai
050.8 Kauaikinana
050.9 Kawaikoi
050.10 Koale
050.11 Koholoina
050.12 Kokee
050.13 Loli
050.14 Makaweli
050.15 Maluapopoki
050.16 Mohihi
050.17 Mokihana
050.18 Mokuone
050.19 Nawaimaka
050.20 Noe
050.21 Olokole
050.22 Poomau
050.23 Waiahulu
050.24 Waiakoali
050.25 Waialae
050.26 Waianuenue

050.27 Waiau
050.28 Waimea R. segment

051.0 Wainiha R.: Haena
(II) N C D19 9
22°13'03", 159°32'29"

051.1 Hiaupe
051.2 Makawea
051.3 Maunahina
051.4 Wainiha segment

052.0 Waipa: Hanalei
(III) N C U 1
22°12'25", 159°30'58"

053.0 Waipao: Hanapepe
(III) A C D5 5
21°56'39", 159°39'23"

054.0 Waioli: Hanalei
(III) N C U 1
22°12'22", 159°30'47"

055.0 West Waipake: Anahola
(III) N C D3 6
22°13'00", 159°21'10"

Possible Interrupted Stream.

056.0 Aliomanu: Anahola
(III) N I U 4
22°09'52", 159°18'30"

5. Molokai.

001.0 Anapuhi: Kamalo
(I) N C U 0
21°10'02", 156°54'34"

002.0 Halawa: Halawa
(I) N C U 0
21°09'46", 156°44'23"

002.1 Halawa segment
002.2 Hipuapua
002.3 Moalua
002.4 Nawaihulili

003.0 Haloku: Kamalo
(I) N I U 0
21°09'57", 156°51'42"

004.0 Honoulimaloo: Halawa
(I) N I U 1
21°07'01", 156°44'36"

005.0 Honouliwai: Halawa
(I) N C U 1
21°06'51", 156°44'54"

006.0 Kahananui: Kamalo
(I) N I U 1
21°03'30", 156°50'16"

007.0 Kahiwa: Halawa
(I) N C U 0
21°10'36", 156°48'33"

008.0 Kailiili: Kamalo
(I) N C U 0
21°09'52", 156°53'08"

009.0 Kainalu: Halawa
(I) N I U 1
21°05'22", 156°46'35"

010.0 Kalaemilo: Halawa
(I) N C U 0
21°10'31", 156°49'12"

011.0 Kaluaaha: Kamalo
(I) N I U 0
21°03'54", 156°49'37"

012.0 Kamalo: Kamalo
(I) A I U 1
21°03'02", 156°56'07"

013.0 Kawainui: Halawa
(II) N C U 0
21°10'15", 156°47'53"

013.1 Kapea
013.2 Kawainui segment

014.0 Kawela: Kaunakakai
(II) N I D4 1
21°04'00", 156°57'11"

015.0 Keawanui: Kamalo
(I) N C U 0
21°10'10", 156°53'42"

016.0 Mapulehu: Halawa
(I) N I U 1
21°04'12", 156°48'18"

017.0 Ohia: Kamalo
(I) N I U 1
21°03'26", 156°50'36"

018.0 Oloupena: Kamalo
(I) N I U 0
21°09'57", 156°51'32"

019.0 Pelekunu: Kamalo
(I) N C U 0
21°09'51", 156°52'59"

019.1 Kapuhi
019.2 Kawaiiki
019.3 Kawailena
019.4 Kawainui
019.5 Kawaipaka
019.6 Lanipuni
019.7 Pelekunu segment
019.8 Pilipililau

020.0 Pipiwai: Halawa
(I) N I U 0
21°10'41", 156°45'45"

021.0 Pohakupili: Halawa
(I) N I U 1
21°07'45", 156°43'57"

022.0 Puukaoku: Kamalo
(I) N I U 0
21°09'58", 156°51'20"

023.0 Waiahookalo: Kamalo
(I) N C U 0
21°10'32", 156°48'55"

024.0 Waialeia: Kamalo
(II) N C D1 0
21°10'33", 156°56'43"

025.0 Waialua: Halawa
(II) N C U 1
21°05'56", 156°45'46"

026.0 Waihanau: Kaunakakai
(II) N I D1 1
21°11'20", 156°59'14"

027.0 Waikolu: Kamalo
(III) N C D1 0
21°10'22", 156°55'59"

Possible Interrupted Streams.

034.0 Ahaino: Halawa
(I) N I U 1
21°05'00", 156°47'14"

035.0 Honomuni: Halawa
(I) N I U 1
21°05'09", 156°46'53"

028.0 Wailau: Kamalo
(I) N C U 0
21°10'06", 156°49'52"

028.1 Kahawaiiki
028.2 Pulena
028.3 Waiakeakua
028.4 Wailau segment
028.5 Waiokeela

029.0 Wailele: Kamalo
(I) N I U 0
21°10'02", 156°51'12"

030.0 Wainene: Kamalo
(I) N C U 0
21°10'15", 156°55'01"

031.0 Waiohookalo: Halawa
(I) N C U 0
21°09'55", 156°54'00"

032.0 Waipu: Kamalo
(I) N I U 0
21°09'50", 156°52'03"

033.0 Wawaia: Kamalo
(I) N I U 1
21°03'07", 156°52'12"

036.0 Kaunakakai: Kaunakakai
(II) N I D3 1
21°05'26", 157°01'52"

037.0 Manawai: Kamalo
(I) N I U 1
21°03'29", 156°50'28"

Appendix B. Maps of Altered Hawaiian Streams Showing Extent of Watersheds, Positions of Mainstreams and Tributaries, Longitudinal Gradients, Types and Approximate Locations of the Alterations, and Locations of Collection Sites with List of Faunal Species Collected

Stream maps are arranged by island. Streams for each island are preceded by a locator map of the island showing stream locations. The arrangement of maps is:

Locator map for Hawaii - Figure B1;
Hawaii stream maps - Figures B2 through B5;
Locator map for Maui - Figure B6;
Maui stream maps - Figures B7 through B13;
Locator map for Oahu - Figure B14;
Oahu stream maps - Figures B15 through B47;
Locator map for Kauai - Figure B48
Kauai stream maps - Figures B49 through B61;
Locator map for Molokai - Figure B62;
Molokai stream map - Figure B63.

LEGEND FOR APPENDIX

Symbols for Alteration Types (Maps)

(1) Lined channel. An artificial channel having both natural banks and stream bed replaced, usually with concrete. May be flat bottom or v-shaped.

(2) Channel realigned and/or vegetation removed.

(3) Elevated culvert. Conduit structures that are comparatively short (typically <60 meters), usually found under highways. Culverts that discharge at stream level have been excluded.

(4) Revetment. One or both banks of the stream are reinforced but the channel bed is not.

(5) Blocked or filled-in channel. Part of the original channel is blocked.

(6) Extended culvert. A longer version of modification type 3, usually found in residential areas.

Abbreviation Coding for Faunal Species

Crustacea.

Ab = *Atya bisulcata*
Mg = *Macrobrachium grandimanus*
Ml = *Macrobrachium lar*
Pc = *Procambarus clarkii*

Pisces.

Ag = *Awaous genivittatus*
As = *Awaous stamineus*
Cc = *Cyprinus carpio*
Cf = *Clarias fuscus*
Cs = *Cichlasoma* sp
Es = *Eleotris sandwicensis*
Ga = *Gambusia affinis*
Ks = *Kuhlia sandvicensis*
Lc = *Lentipes concolor*
Lm = *Lepomis macrochirus*
Ma = *Misgurnus anguillicaudatus*
Md = *Micropterus dolomieui*
Os = *Ophicephalus striatus*
Pl = *Poecilia latipinna*
Pm = *Poecilia mexicana*
Pr = *Poecilia reticulata*
Pv = *Poecilia vittata*
Ss = *Sicydium stimpsoni*
Tm = *Tilapia mossambica*
Xh = *Xiphophorus helleri*
Xm = *Xiphophorus maculatus*

Symbols for Species Abundances

O = Rare or occasional, not more than one specimen collected per sampling or only occasionally collected; sometimes sighted but not captured.
◐ = Common, between two and five specimens obtained per sampling.
● = Abundant, more than five specimens per sampling.

Symbols for Stream Channels and Watershed

——— = Continuous portion of channel of a perennial stream.
- - - = Interrupted portion of channel of a perennial stream.
······ = Boundary of stream watershed.

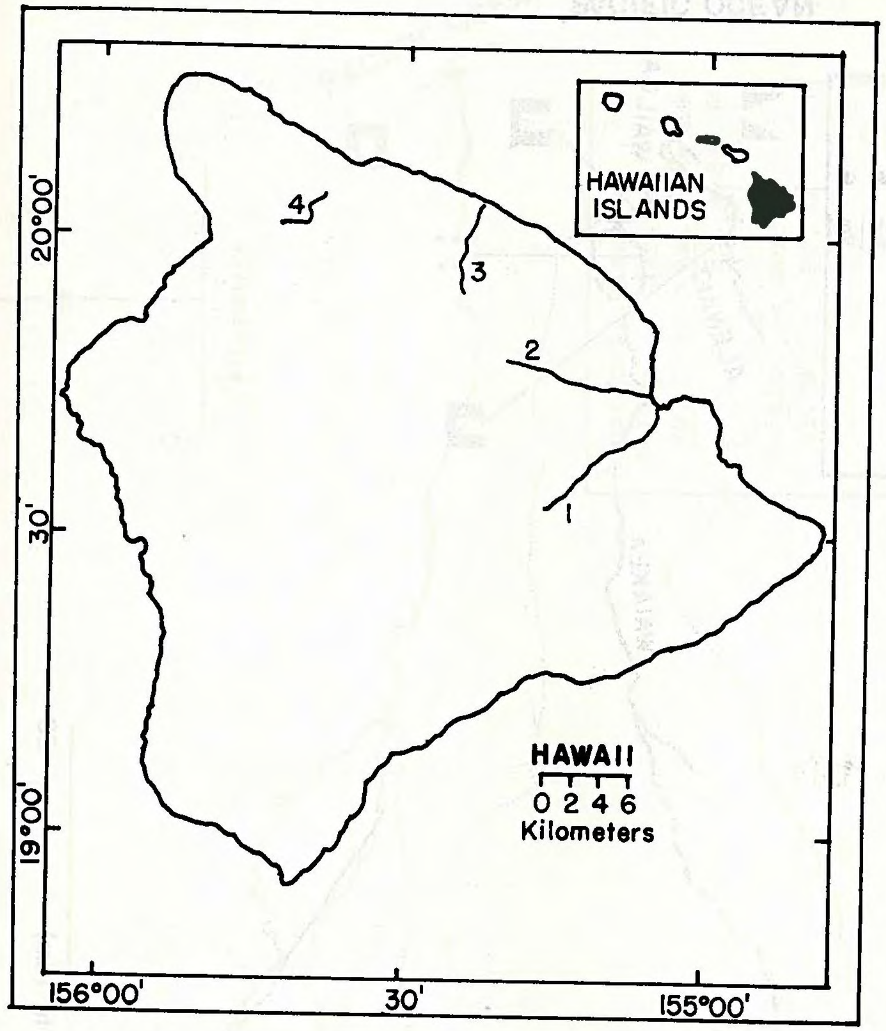


Figure B1. Locator map for four Hawaii streams having modified channels.

Legend:

1. Wailoa River
2. Pukihae Stream
3. Papuaa Stream
4. Lamimaumau Stream

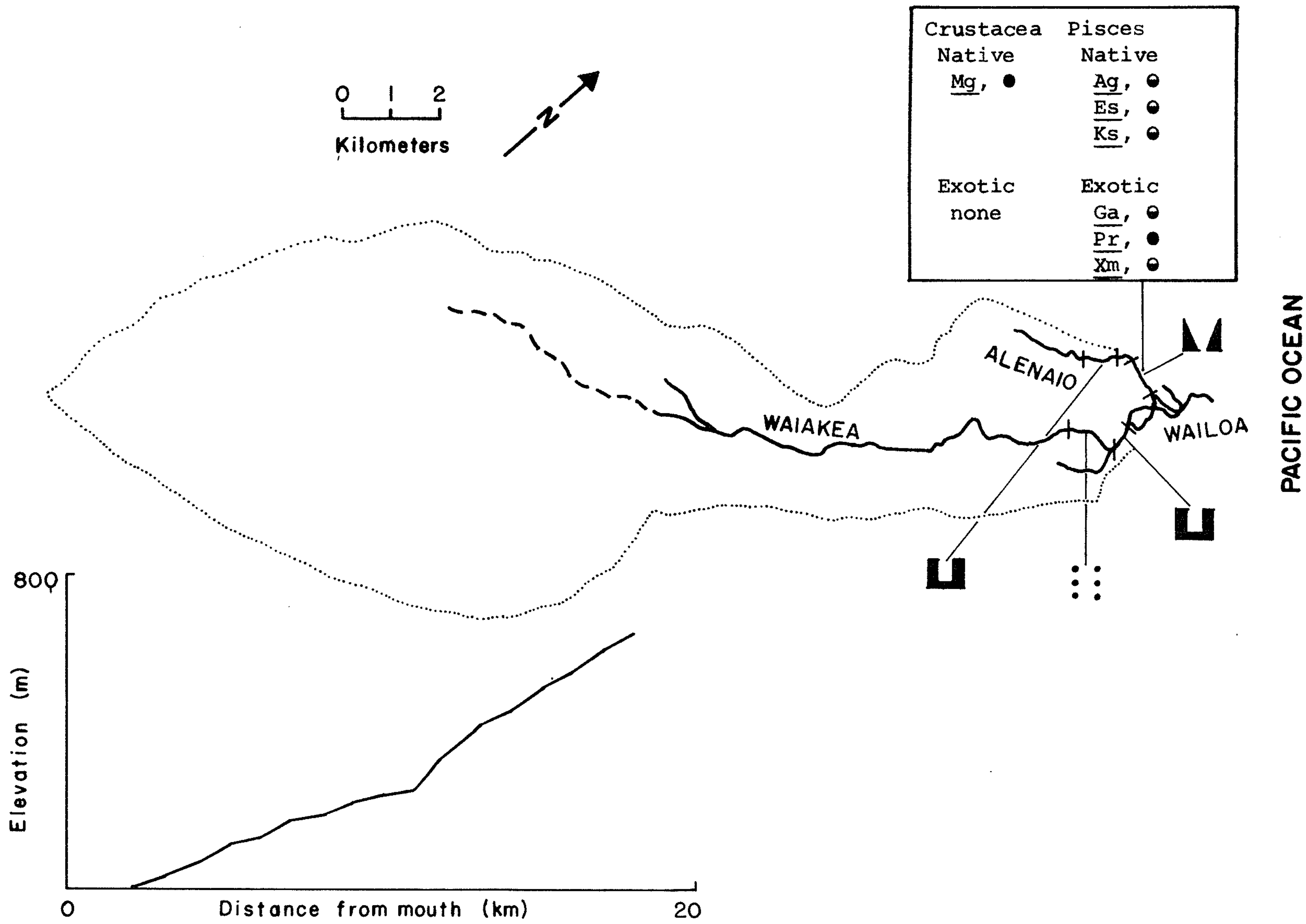


Figure B2. Wailoa River, Hawaii: 12% of channel altered. Longitudinal gradient (m/km) = 36.

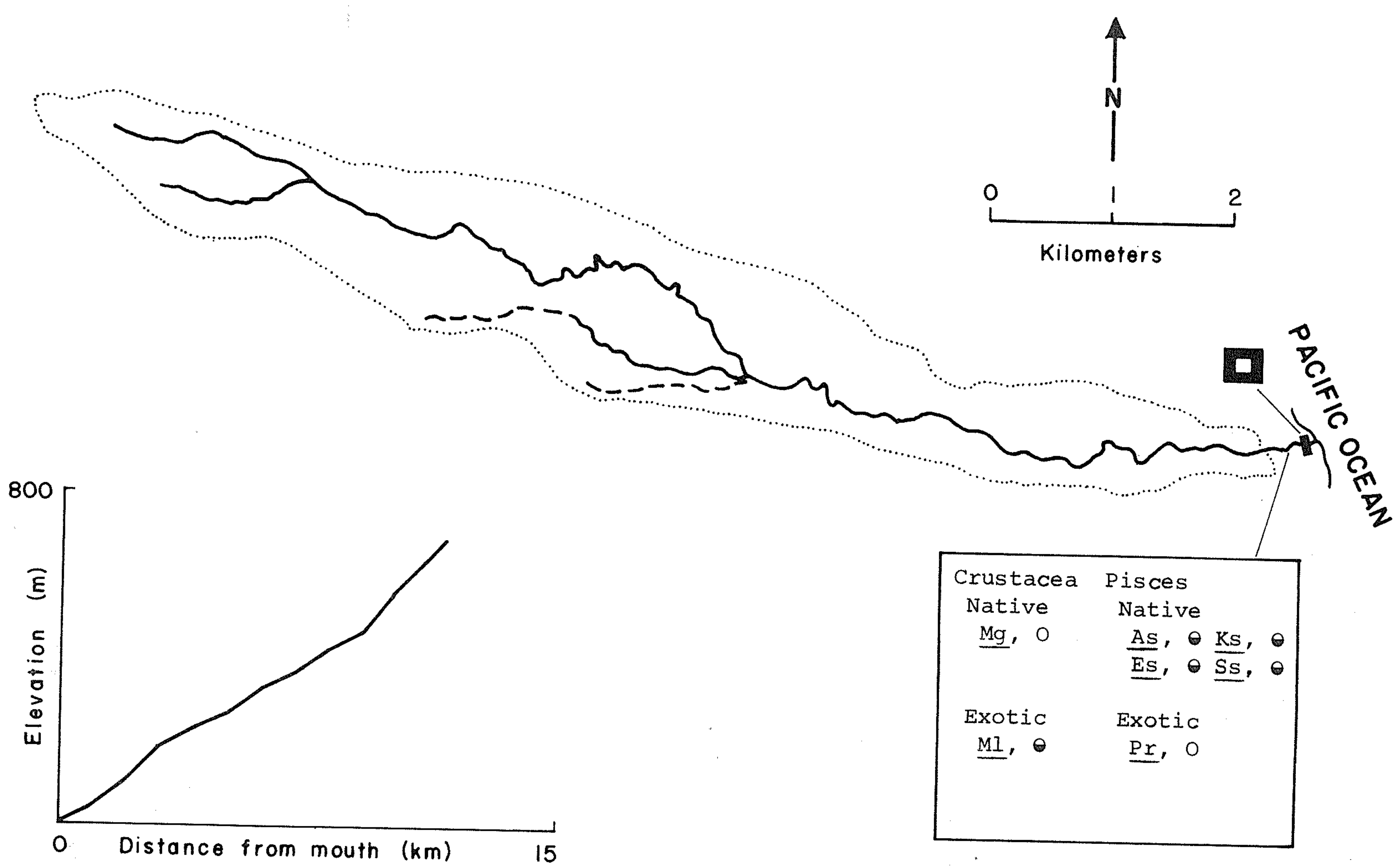


Figure B3. Pukihae Stream, Hawaii: <1% of channel length altered. Longitudinal gradient (m/km) = 58.

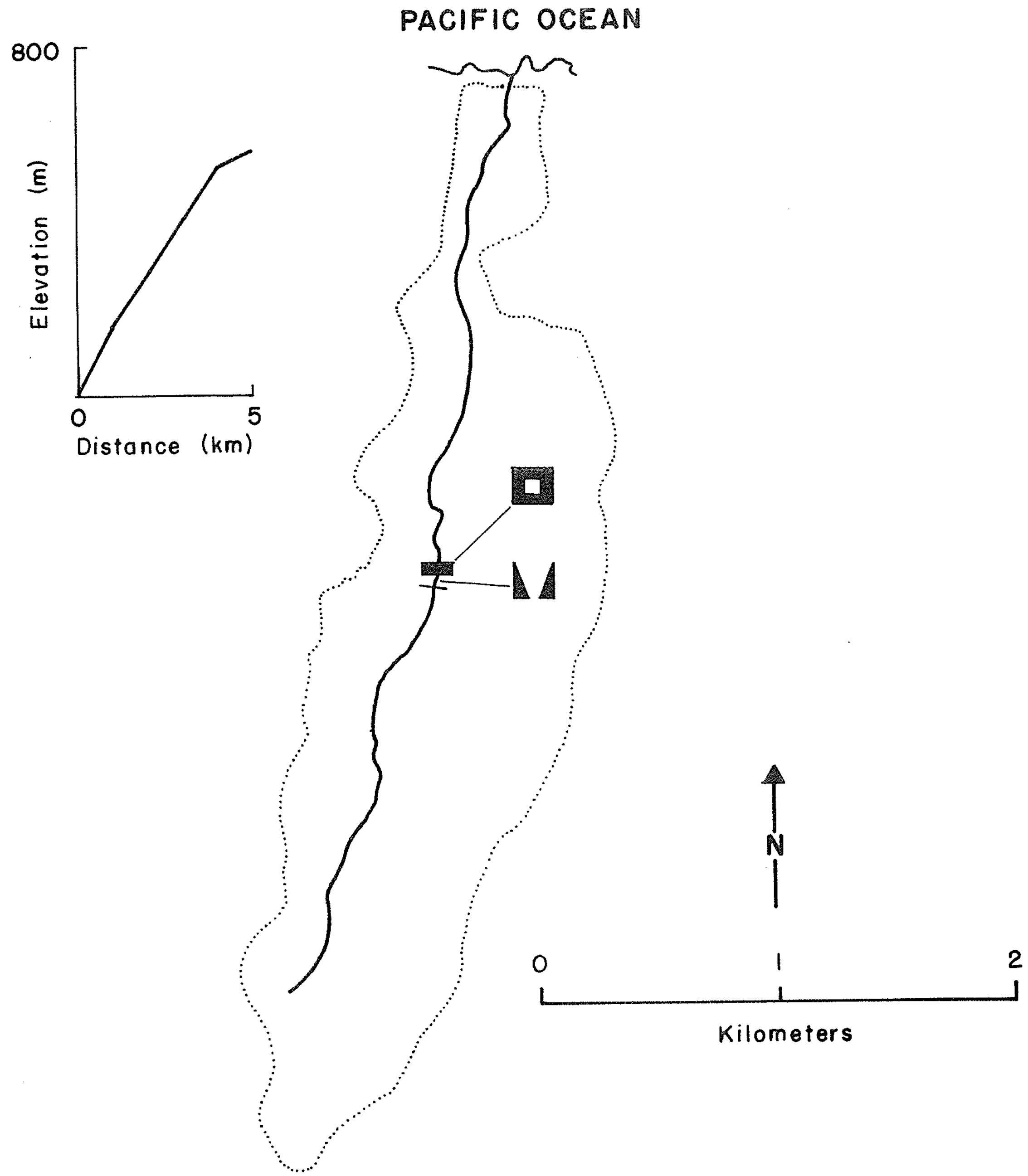


Figure B4. Papuaa Stream, Hawaii: 2% of channel length altered. Longitudinal gradient (m/km) = 123.

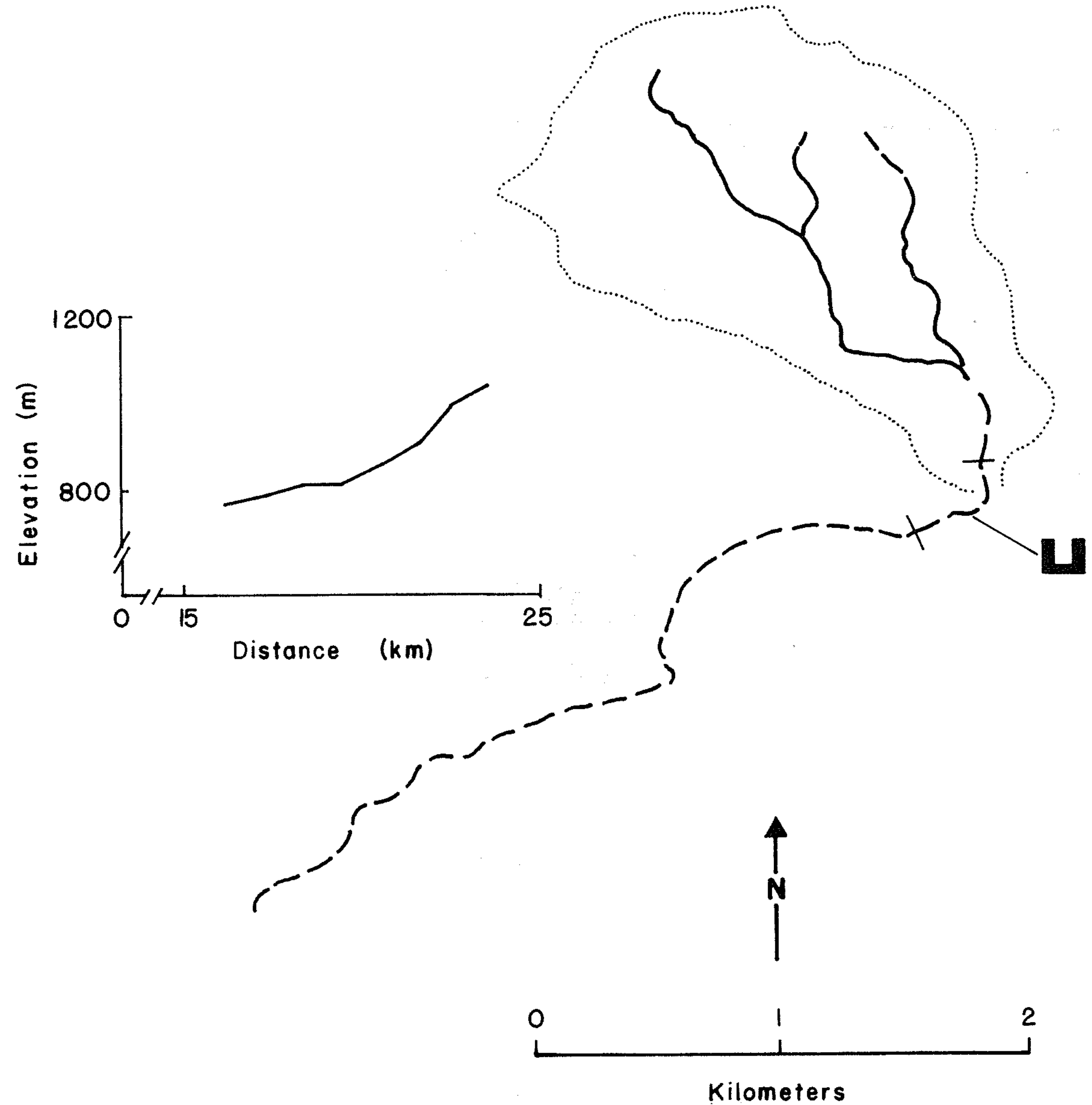


Figure B5. Lamimaumau Stream, Hawaii: 10% of channel length altered. Longitudinal gradient (m/km) = 36.

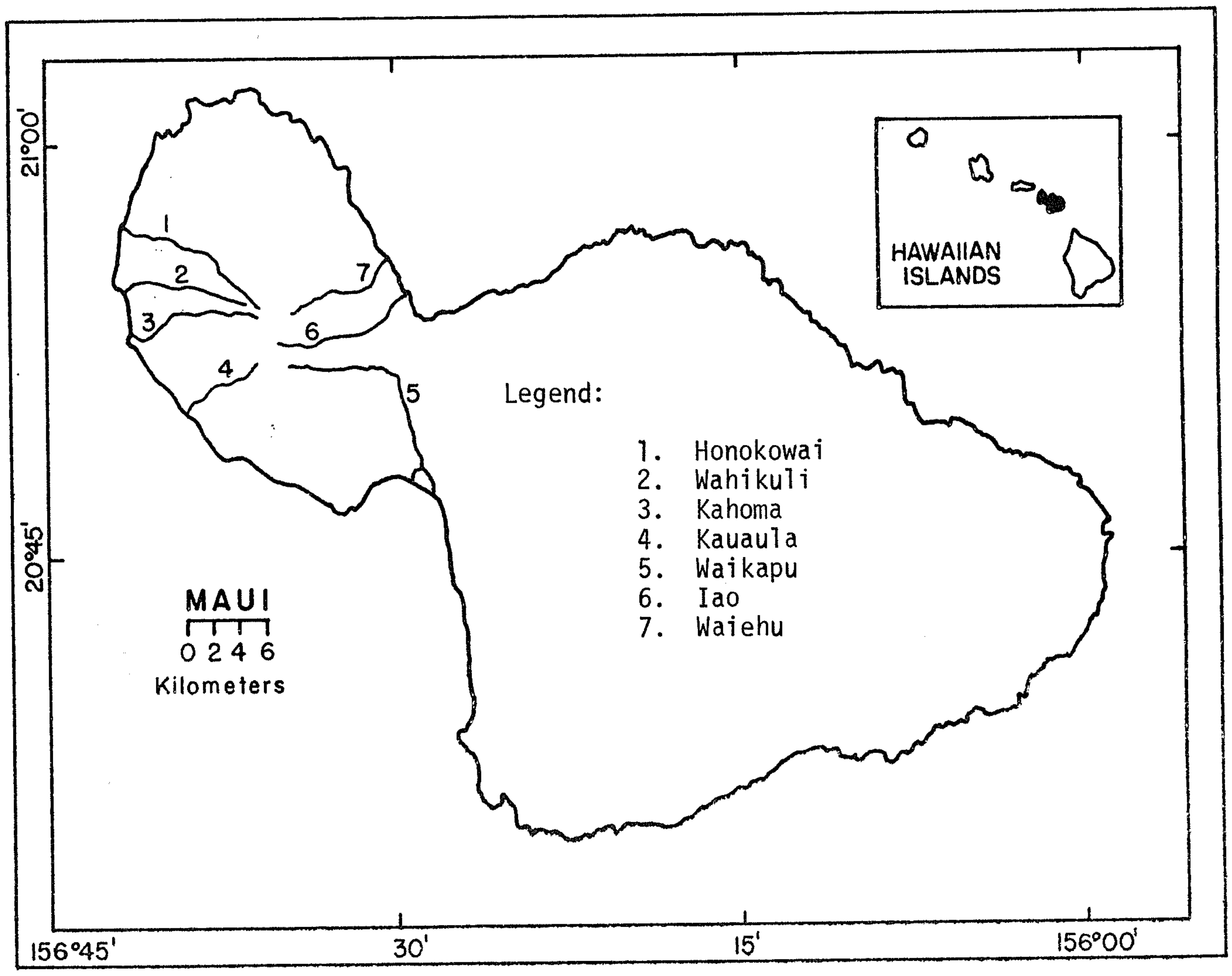


Figure B6. Locator map for seven Maui streams having modified channels.

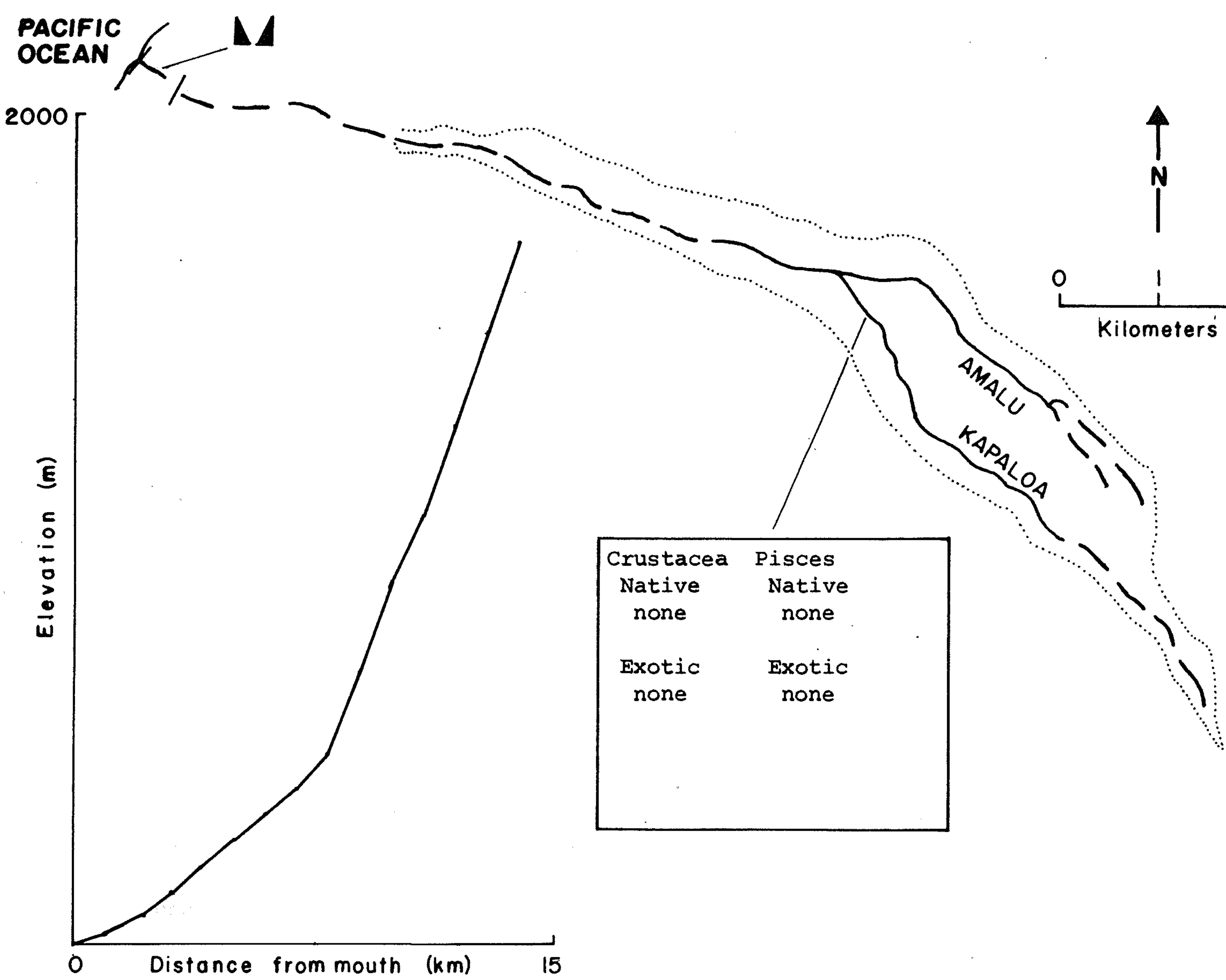
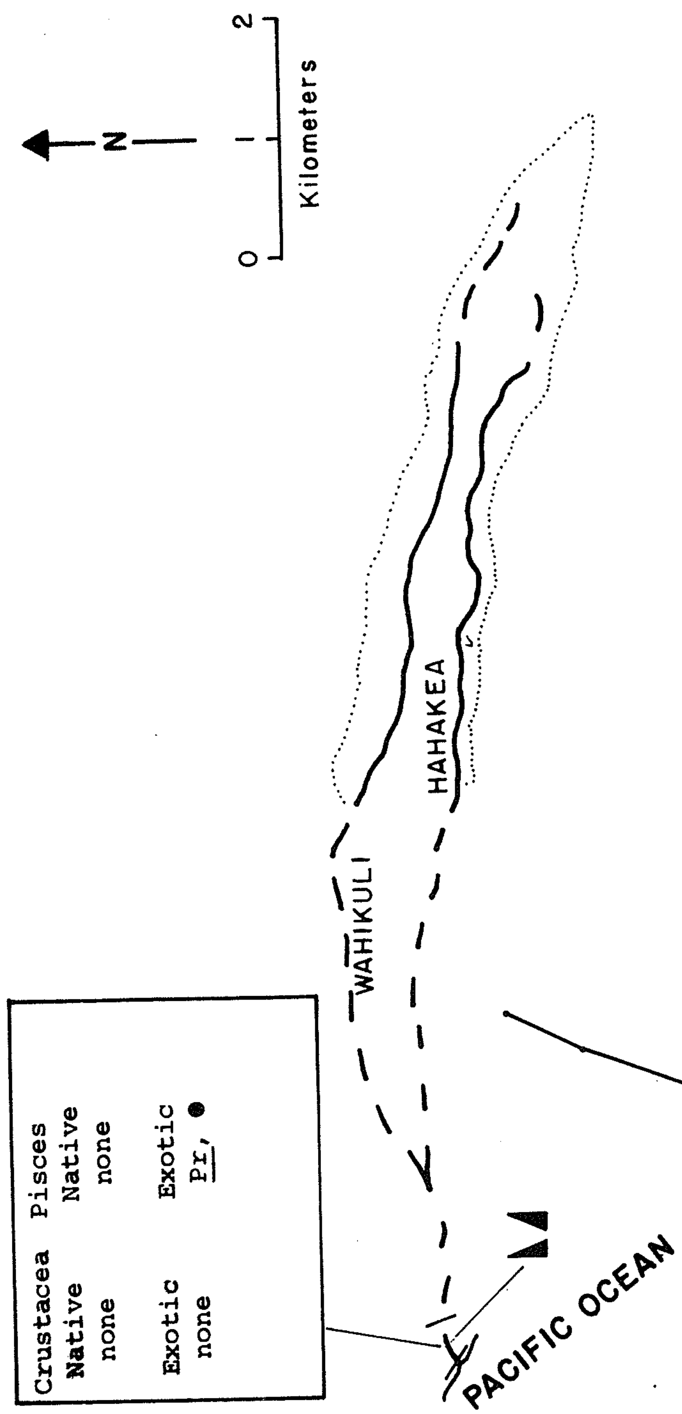


Figure B7. Honokowai Stream, Maui: 2% of channel length altered. Longitudinal gradient (m/km) = 120.



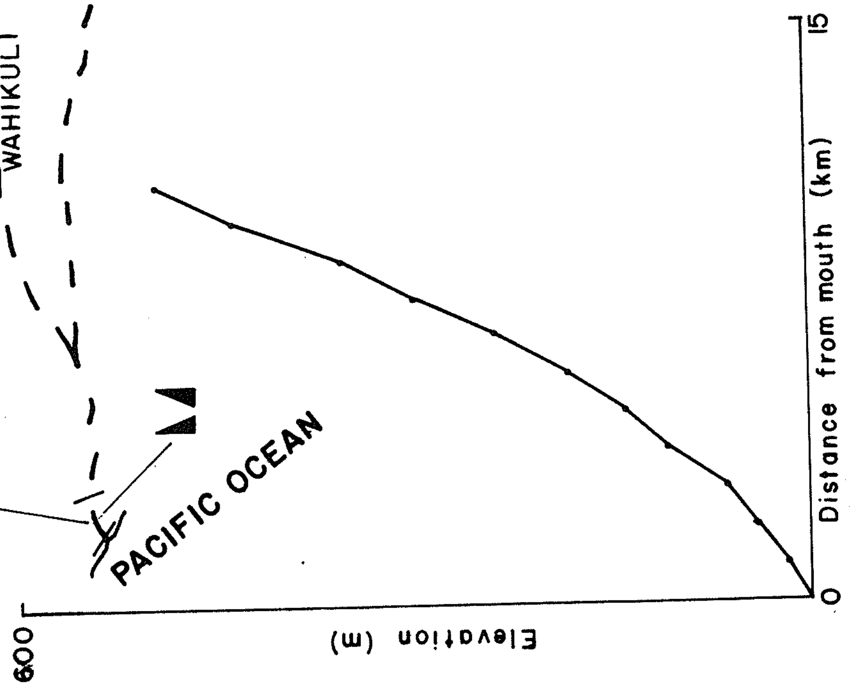


Figure B8. Wahikuli Stream, Maui: 2% of channel length altered. Longitudinal gradient (m/km) = 121.

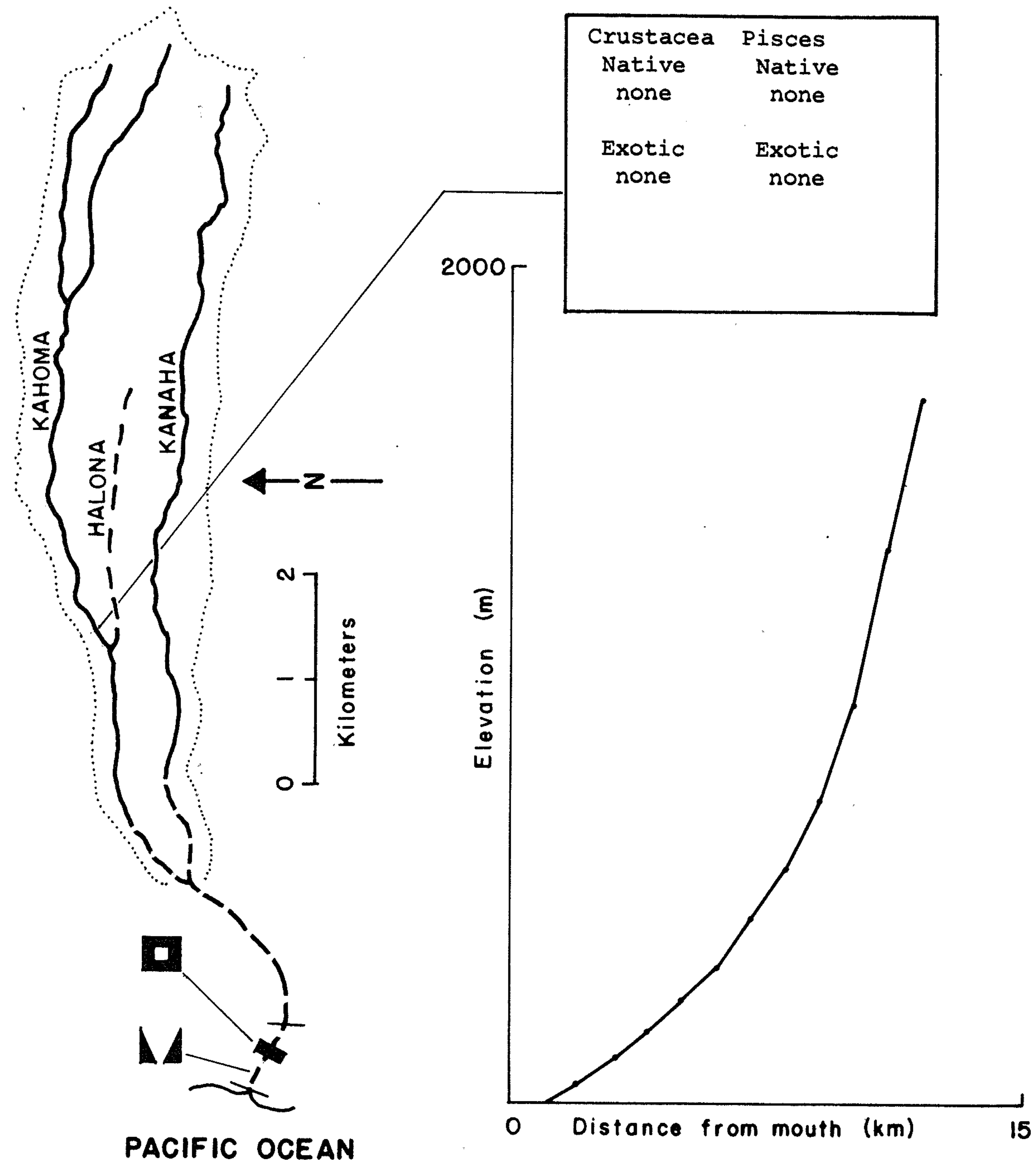


Figure B9. Kahoma Stream, Maui: 4% of channel length altered. Longitudinal gradient (m/km) = 140.

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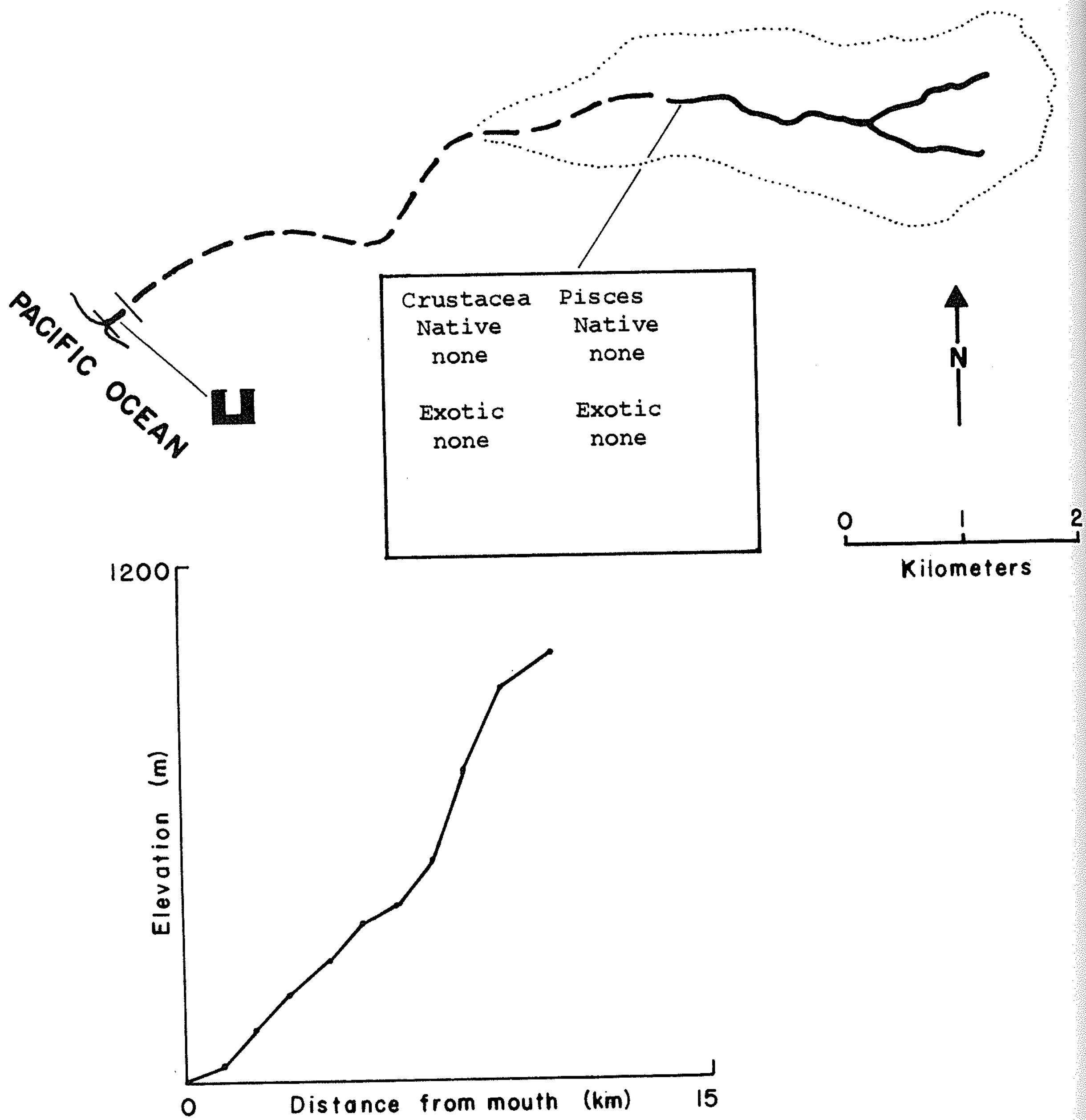

Figure B10. Kauaula Stream, Maui: 3% of channel length altered. Longitudinal gradient (m/km) = 108.

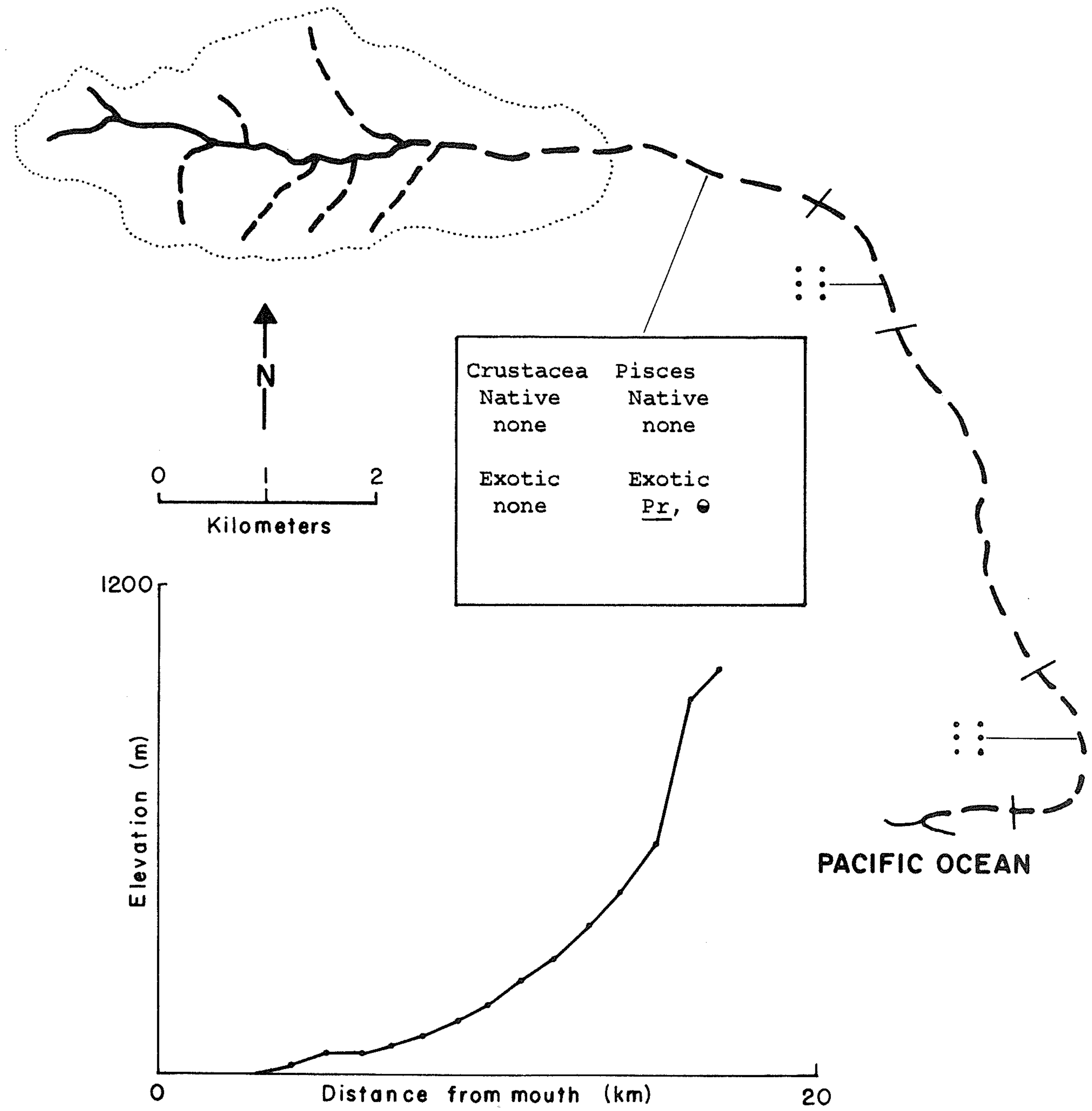

Figure B11. Waikapu Stream, Maui: 11% of channel length altered. Longitudinal gradient (m/km) = 63.

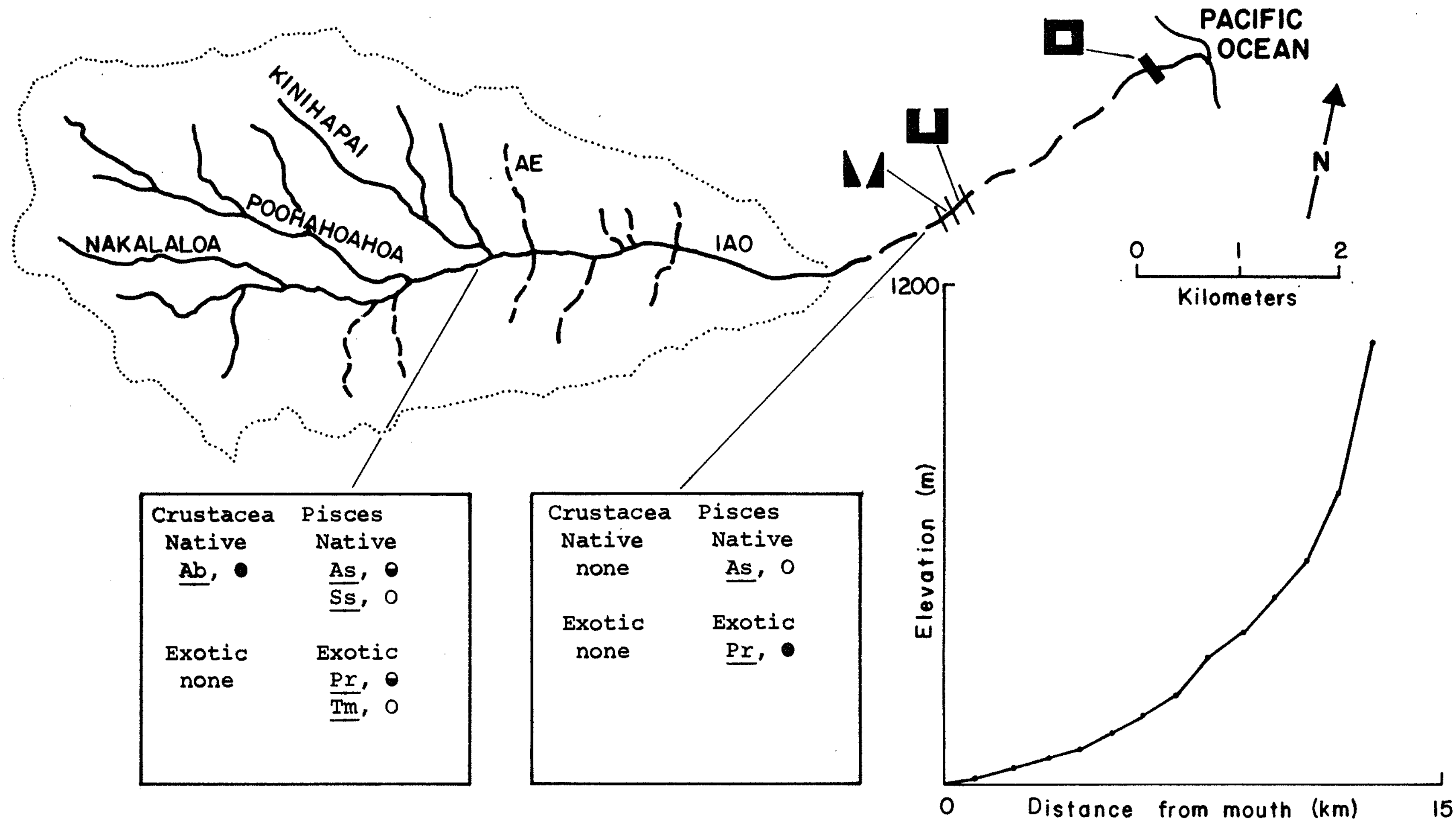

Figure B12. Iao Stream, Maui: 1% of channel length altered. Longitudinal gradient (m/km) = 80.

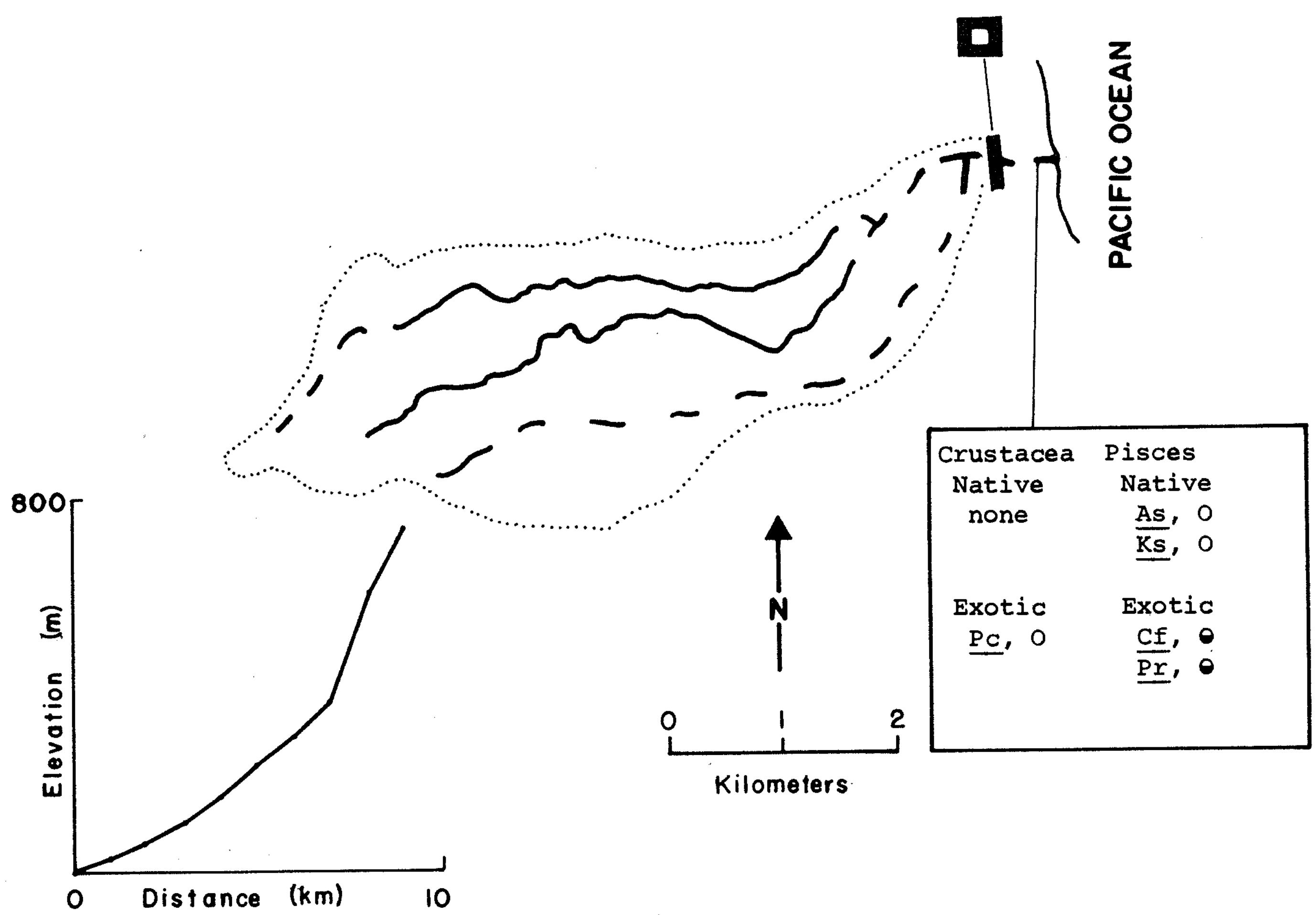

Figure B13. Waiehu Stream, Maui: <1% of channel length altered. Longitudinal gradient (m/km) = 91.

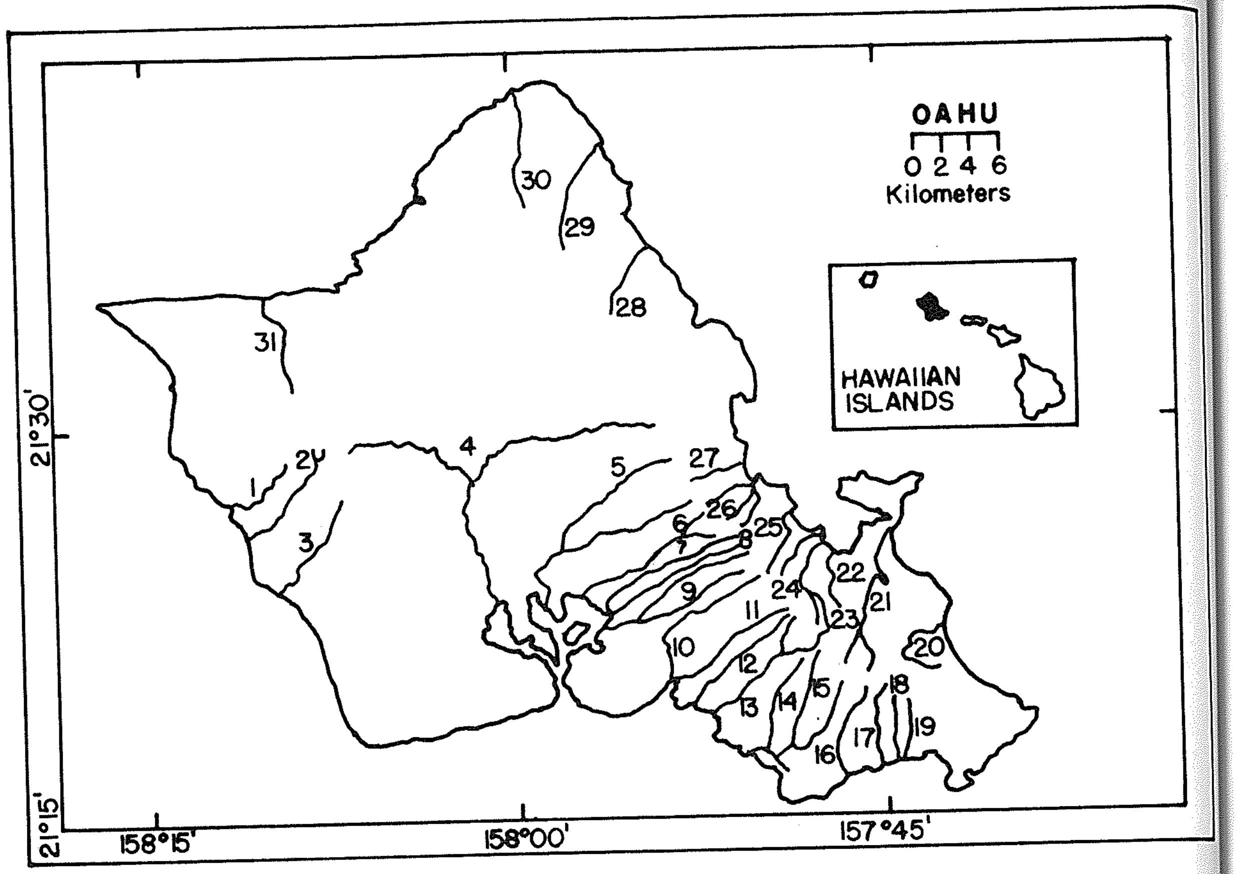

Figure B14. Locator map for the 31 Oahu Streams having modified channels.

Legend:

1. Kaupuni Stream
2. Mailiili Stream
3. Ulehawa Stream
4. Waikele Stream
5. Waiawa Stream
6. Waimalu Stream
7. Kalauao Stream
8. Aiea Stream
9. Halawa Stream
10. Moanalua Stream
11. Kalihi Stream
12. Kapalama Stream
13. Nuuanu Stream
14. Makiki Stream
15. Manoa Stream
16. Waialaenui Stream
17. Wailupe Stream
18. Pia Stream
19. Kuliouou Stream
20. Waimanalo Stream
21. Maunawili Stream
22. Kawa Stream
23. Kaneohe Stream
24. Keaahala Stream
25. Heeia Stream
26. Kahaluu Stream
27. Kaalaea Stream
28. Kaipapau Stream
29. Malaekahana Stream
30. Oio Stream
31. Makaleha Stream

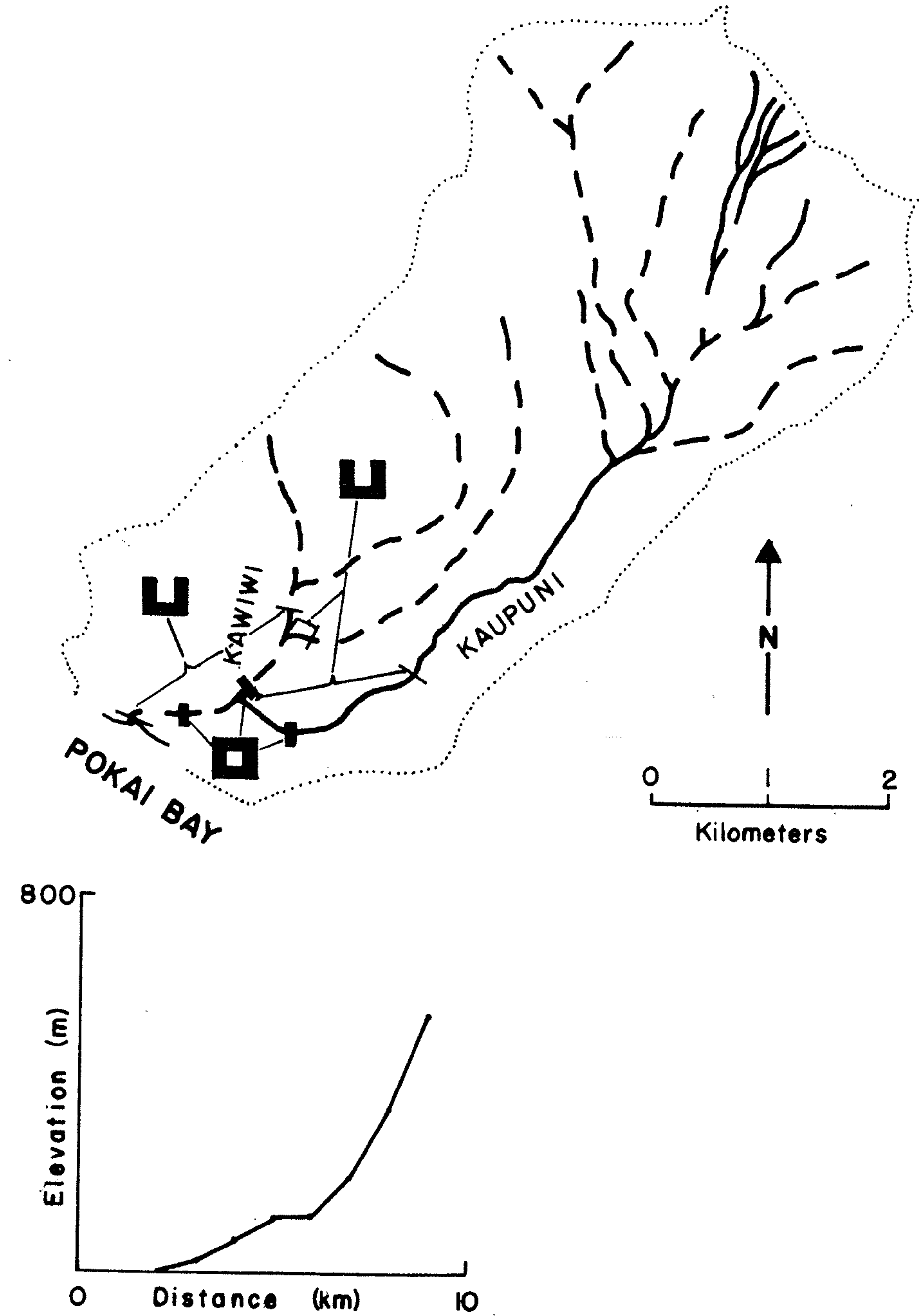

Figure B15. Kaupuni Stream, Oahu: 10% of channel length altered. Longitudinal gradient (m/km) = 61.

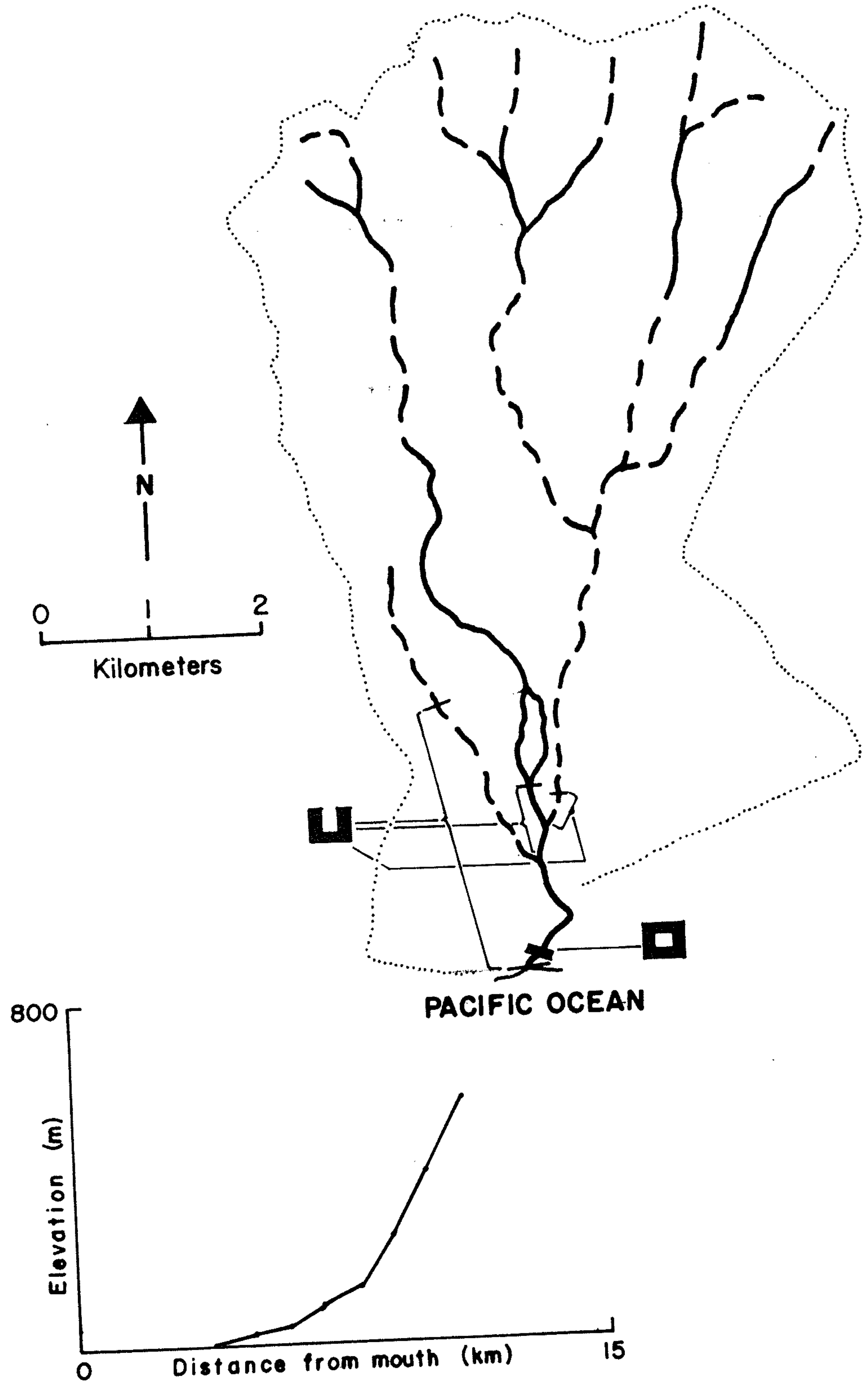

Figure B16. Mailiili Stream, Oahu: 13% of channel length altered. Longitudinal gradient (m/km) = 51.

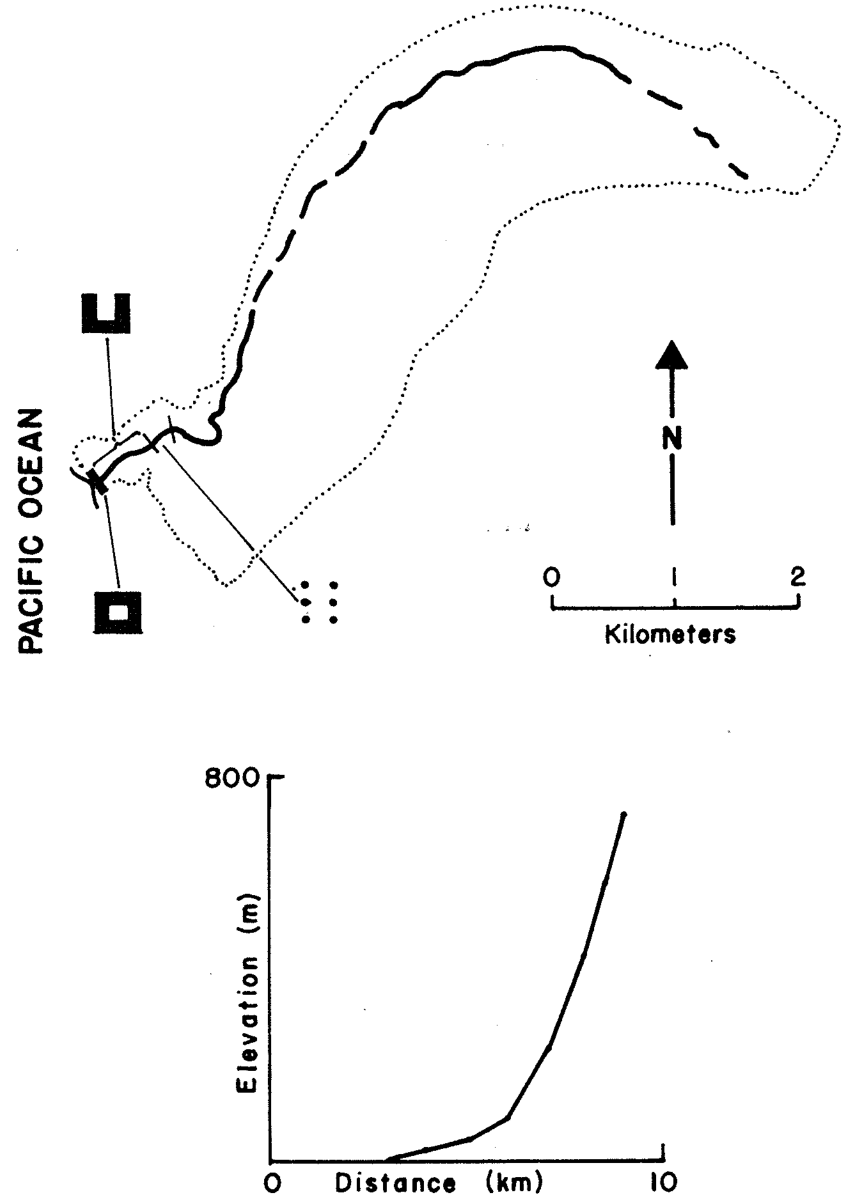

Figure B17. Ulehawa Stream, Oahu: 14% of channel length altered. Longitudinal gradient (m/km) = 86.

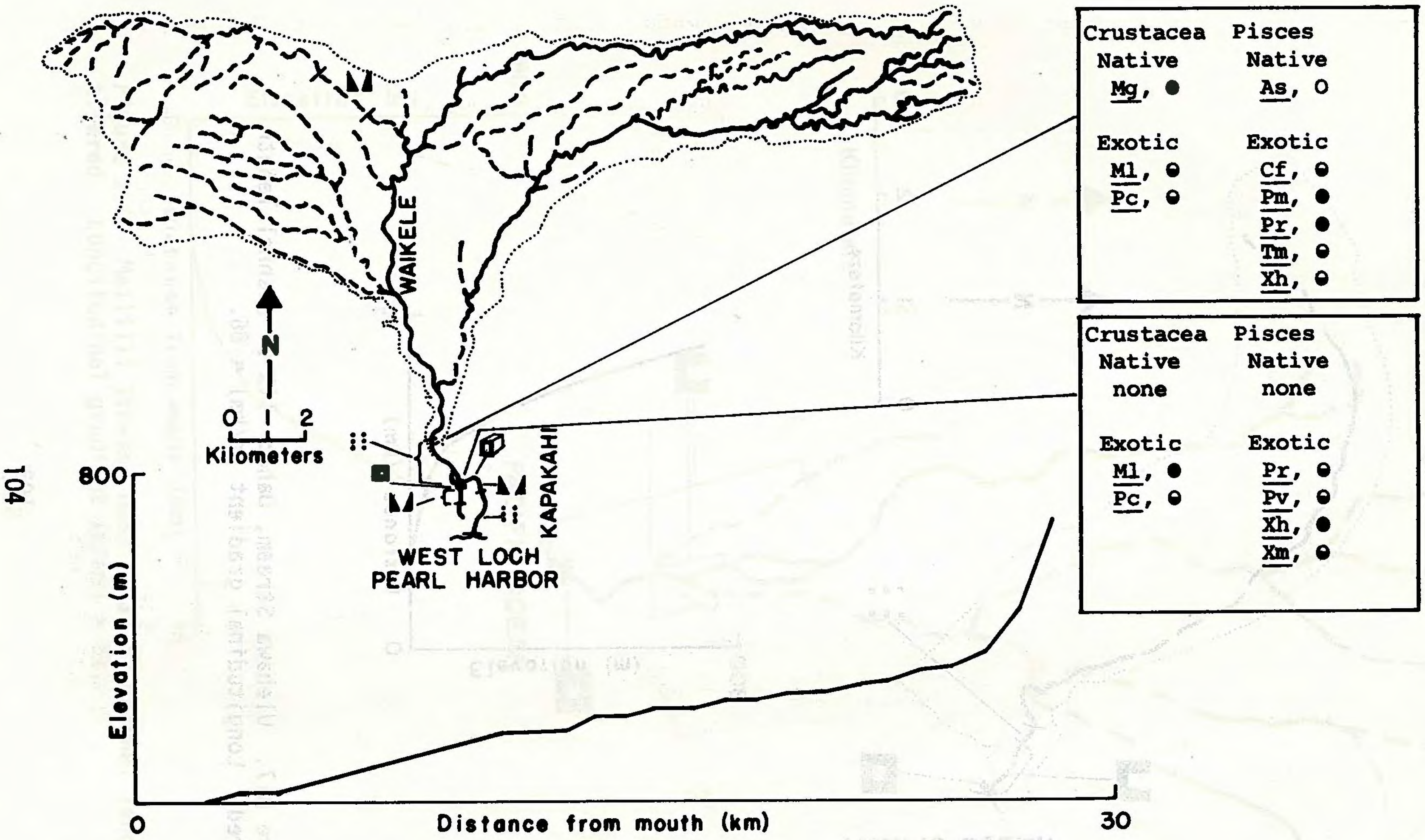

Figure B18. Waikele Stream, Oahu: 3% of channel length altered. Longitudinal gradient (m/km) = 24.

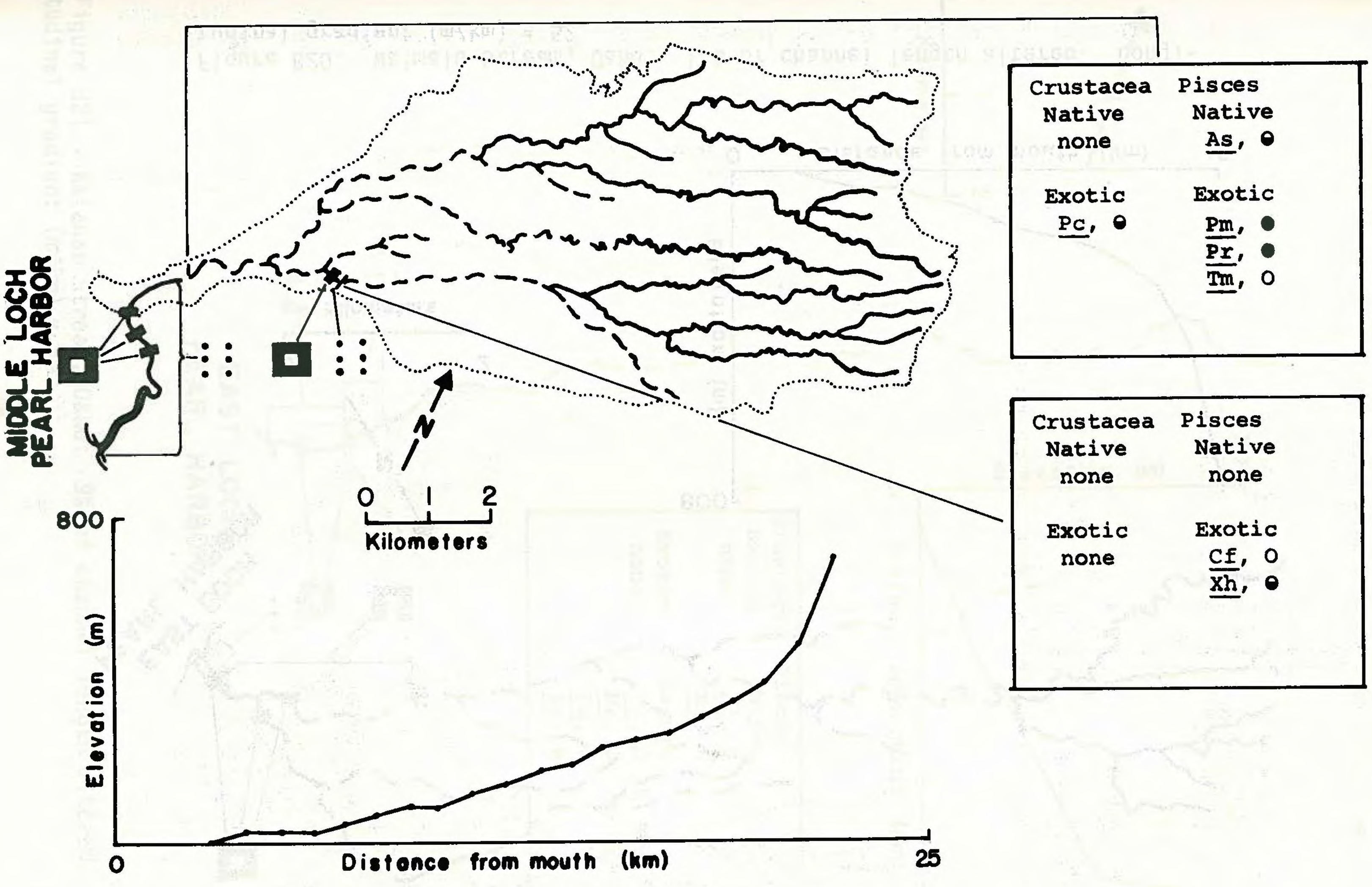

Figure B19. Waiawa Stream, Oahu: 5% of channel length altered. Longitudinal gradient (m/km) = 30.

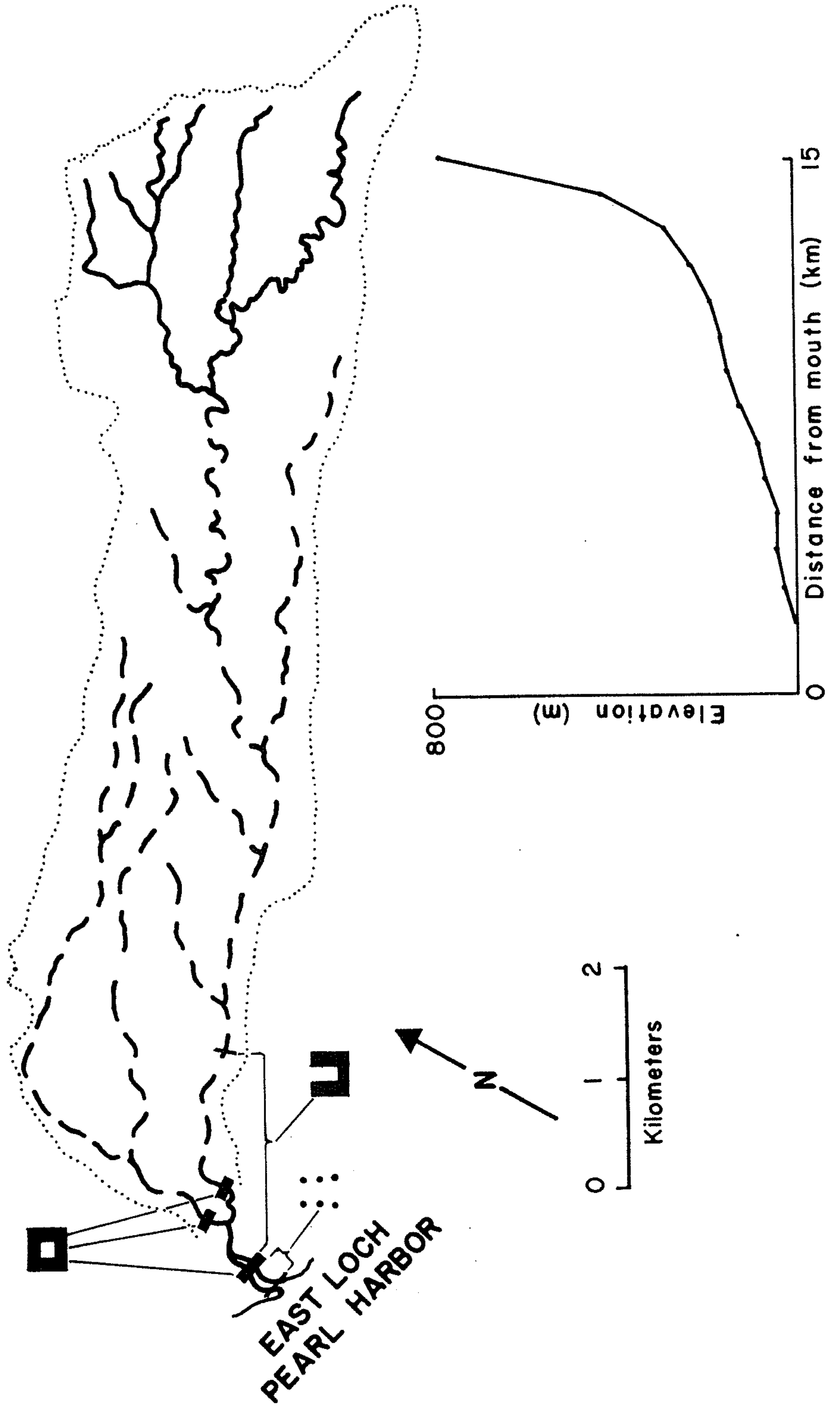

Figure B20. Waimalu Stream, Oahu: 11% of channel length altered. Longitudinal gradient (m/km) = 52.

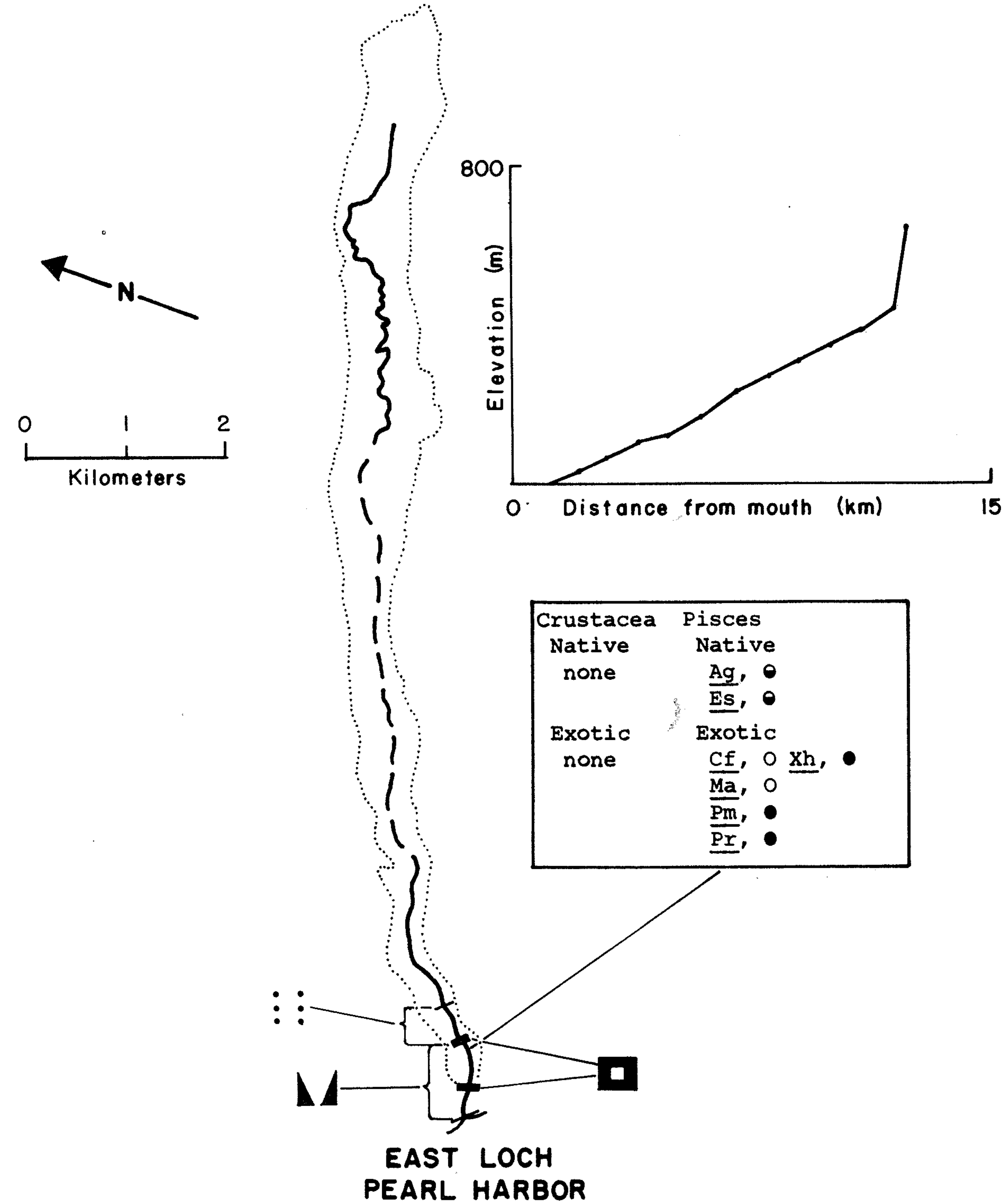

Figure B21. Kalauao Stream, Oahu: 9% of channel length altered. Longitudinal gradient (m/km) = 50.

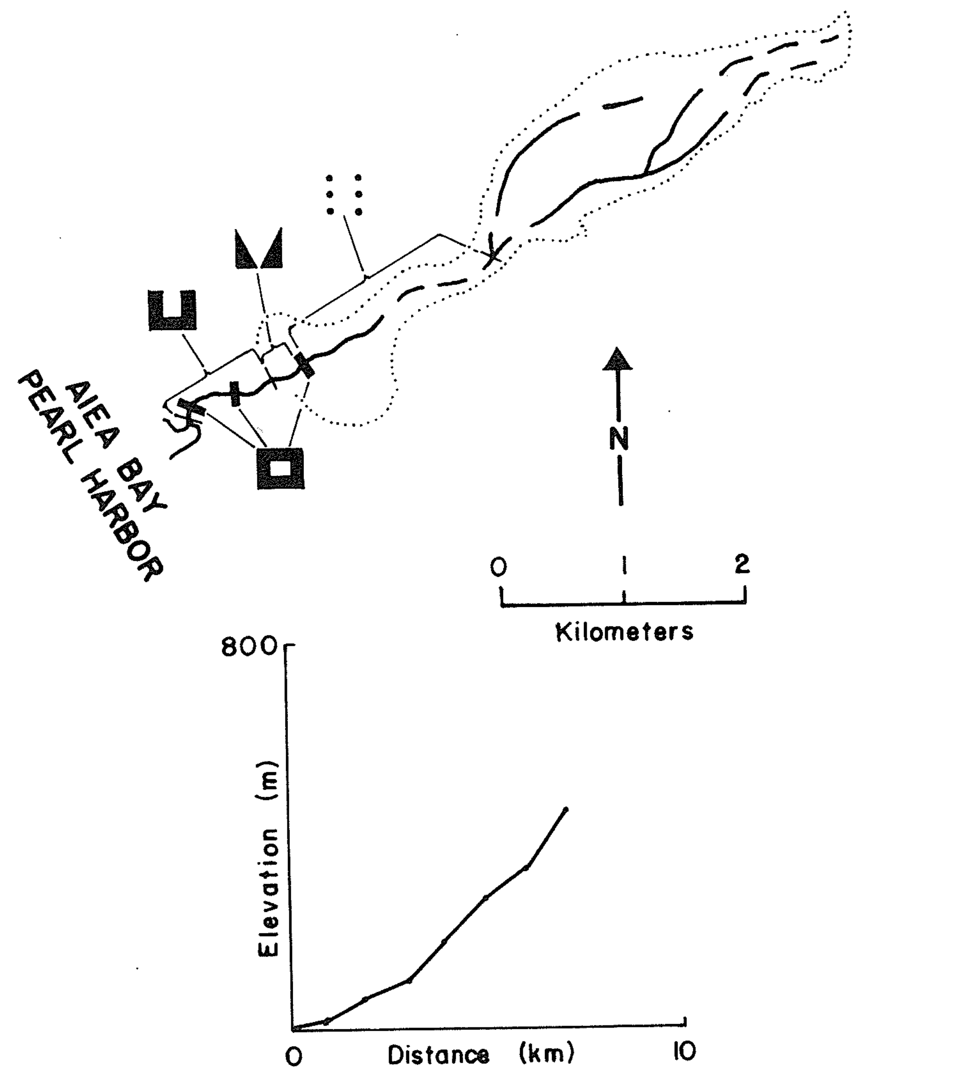

Figure B22. Aiea Stream, Oahu: 25% of channel length altered. Longitudinal gradient (m/km) = 63.

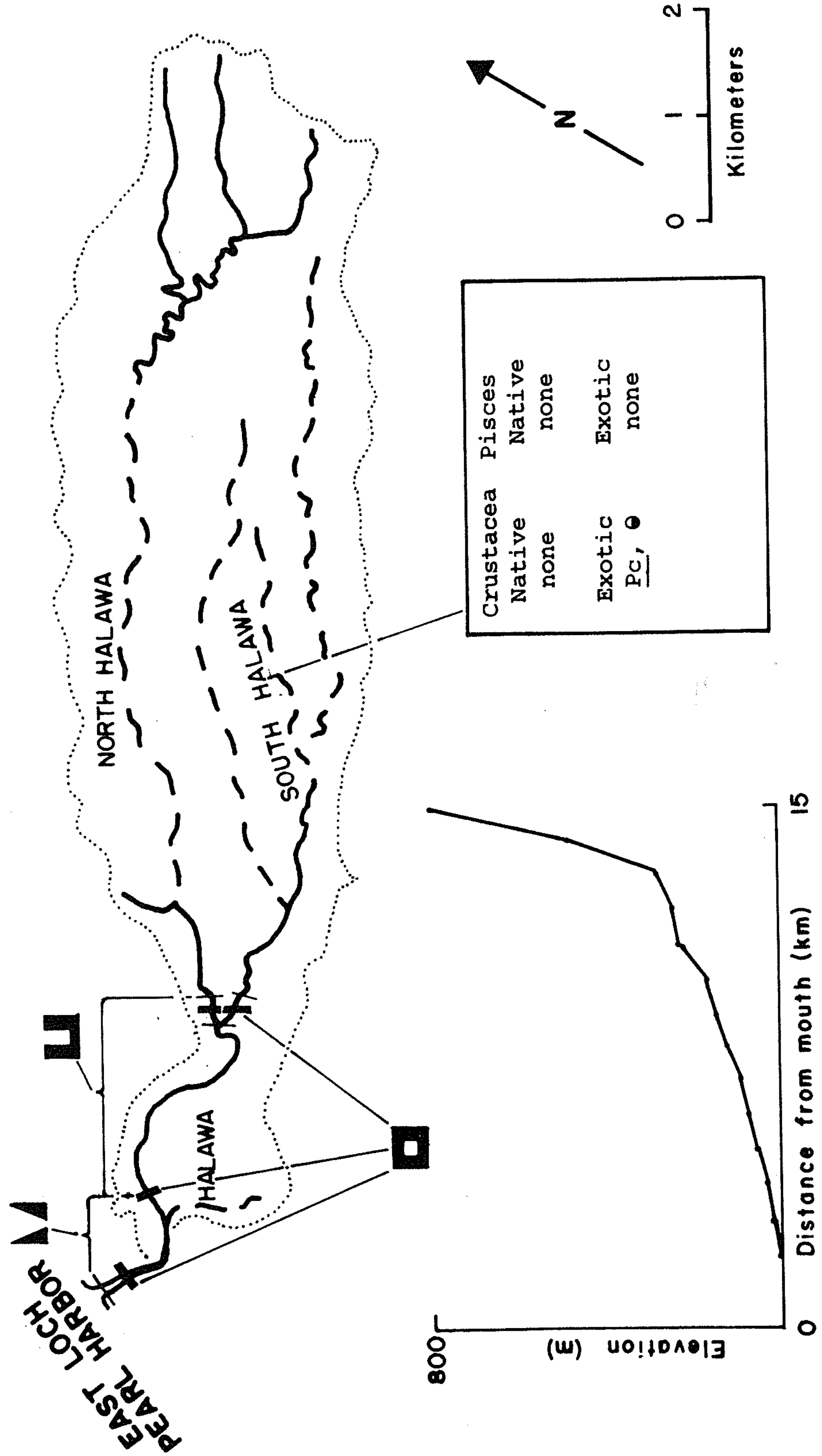

Figure B23. Halawa Stream, Oahu: 10% of channel length altered. Longitudinal gradient (m/km) = 53.

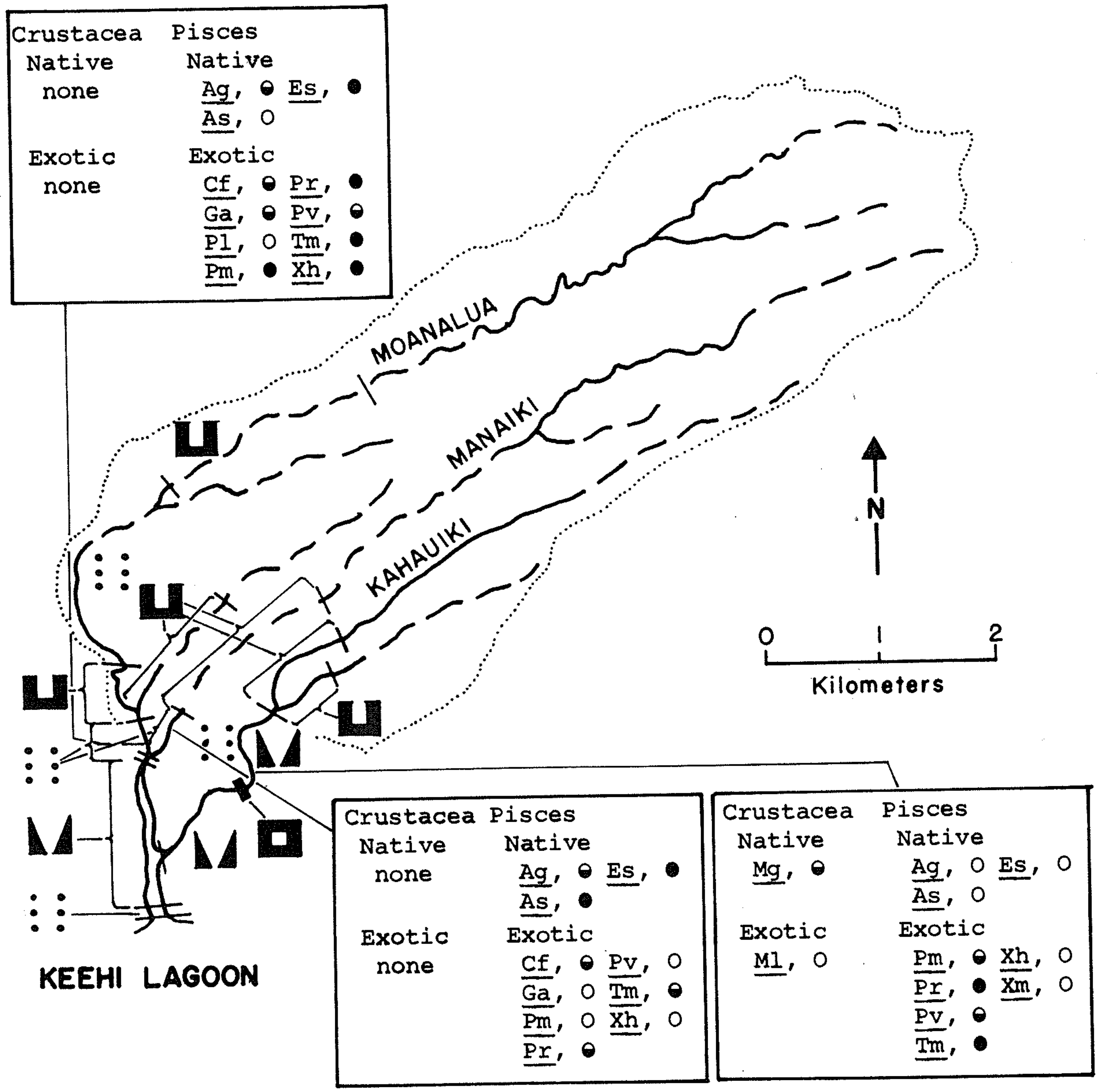

Figure B24. Moanalua Stream, Oahu: 34% of channel length altered.

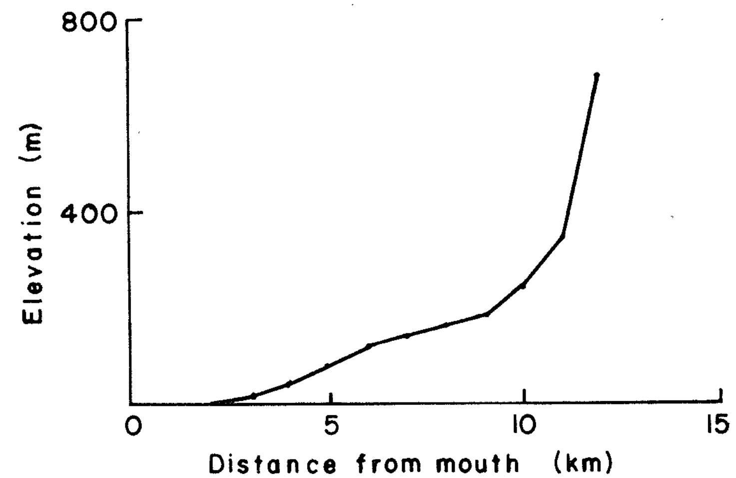

Figure B25. Profile of Moanalua Stream, Oahu. Longitudinal gradient (m/km) = 56.

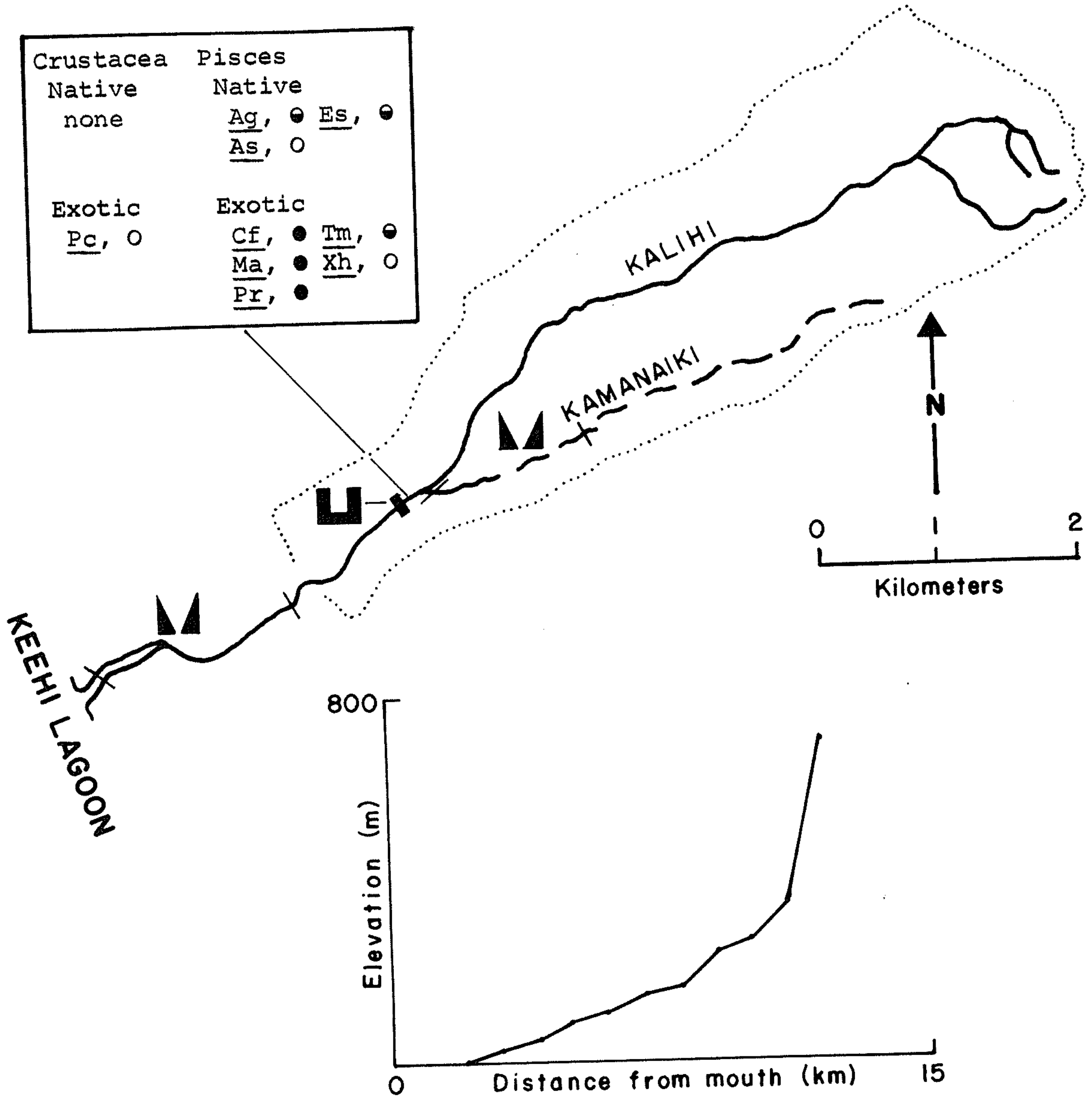

Figure B26. Kalihi Stream, Oahu: 27% of channel length altered. Longitudinal gradient (m/km) = 57.

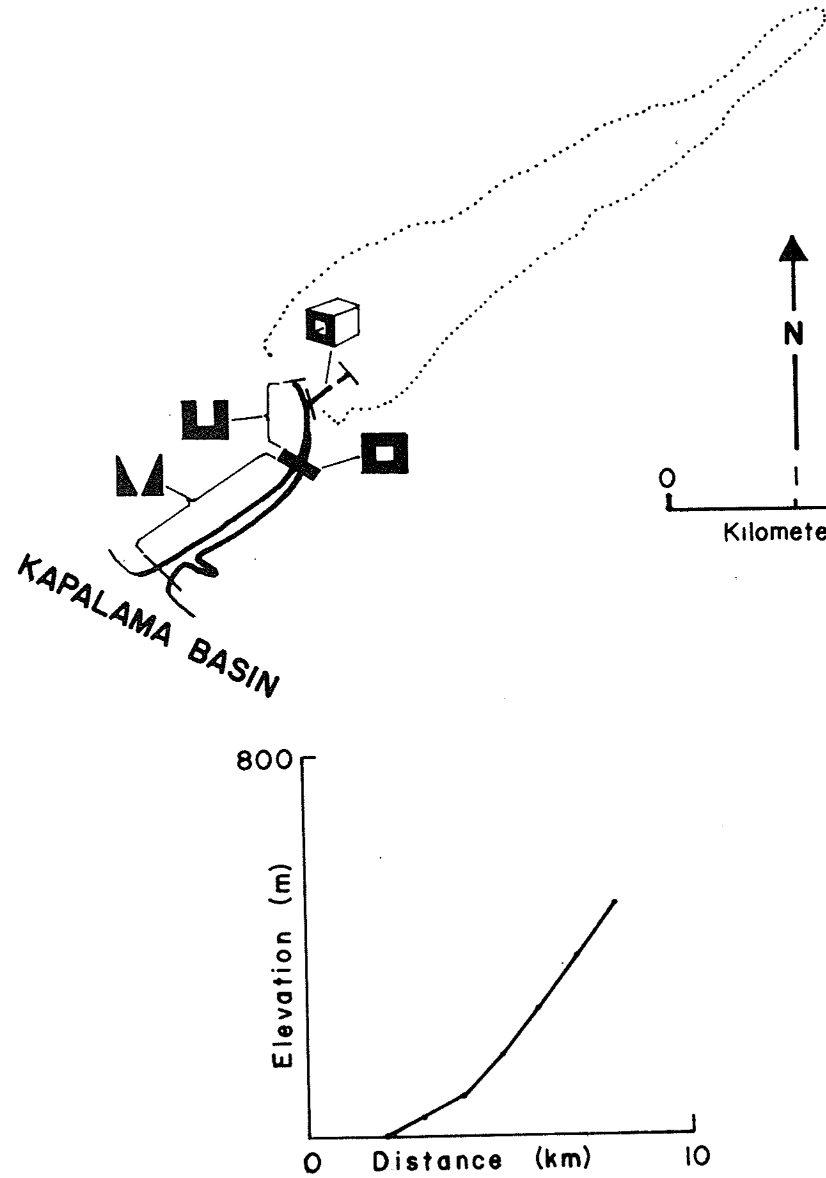

Figure B27. Kapalama Stream, Oahu: 100% of channel length altered. Longitudinal gradient (m/km) = 59.

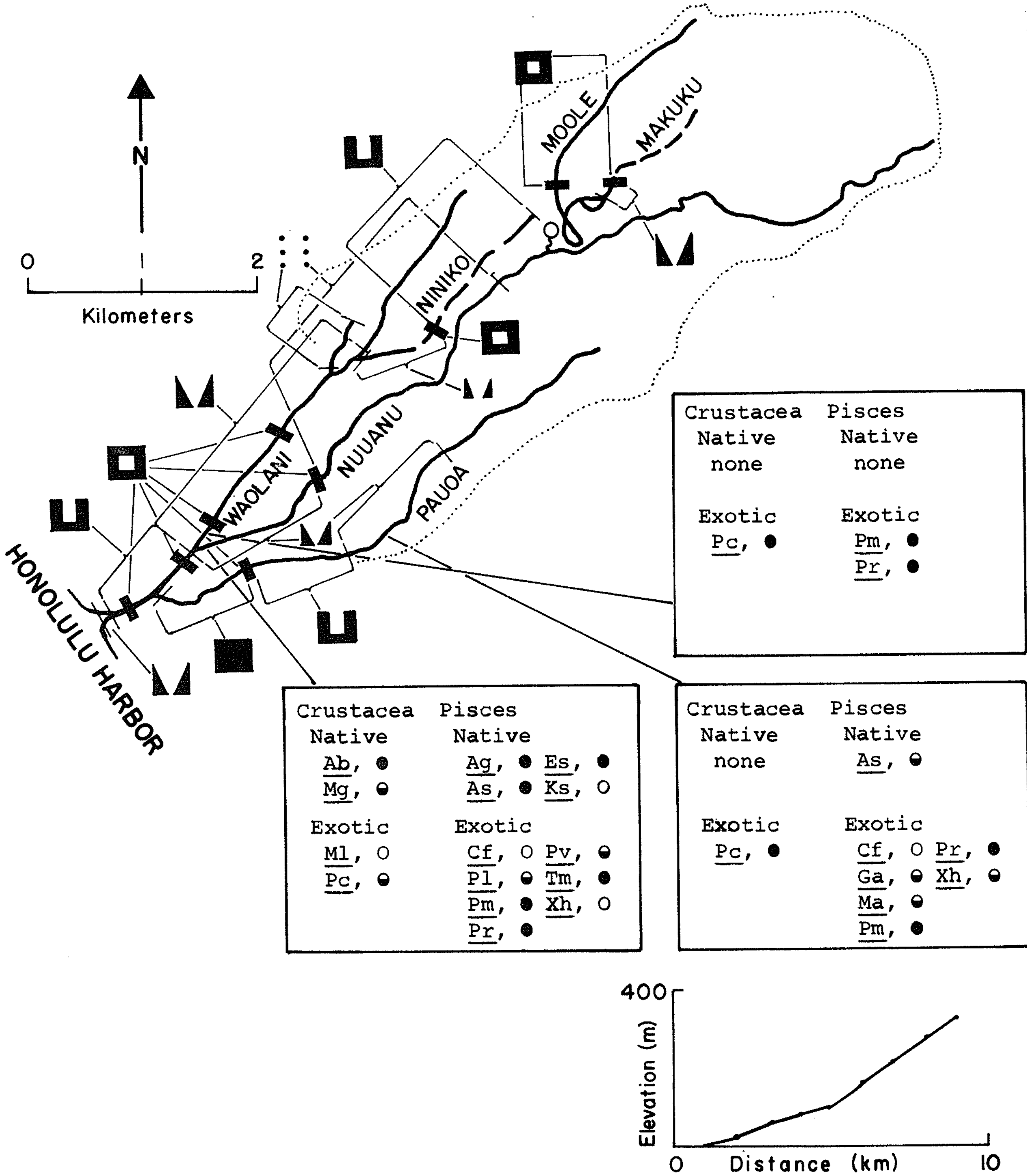

Figure B28. Nuuanu Stream, Oahu: 60% of channel length altered. Longitudinal gradient (m/km) = 35.

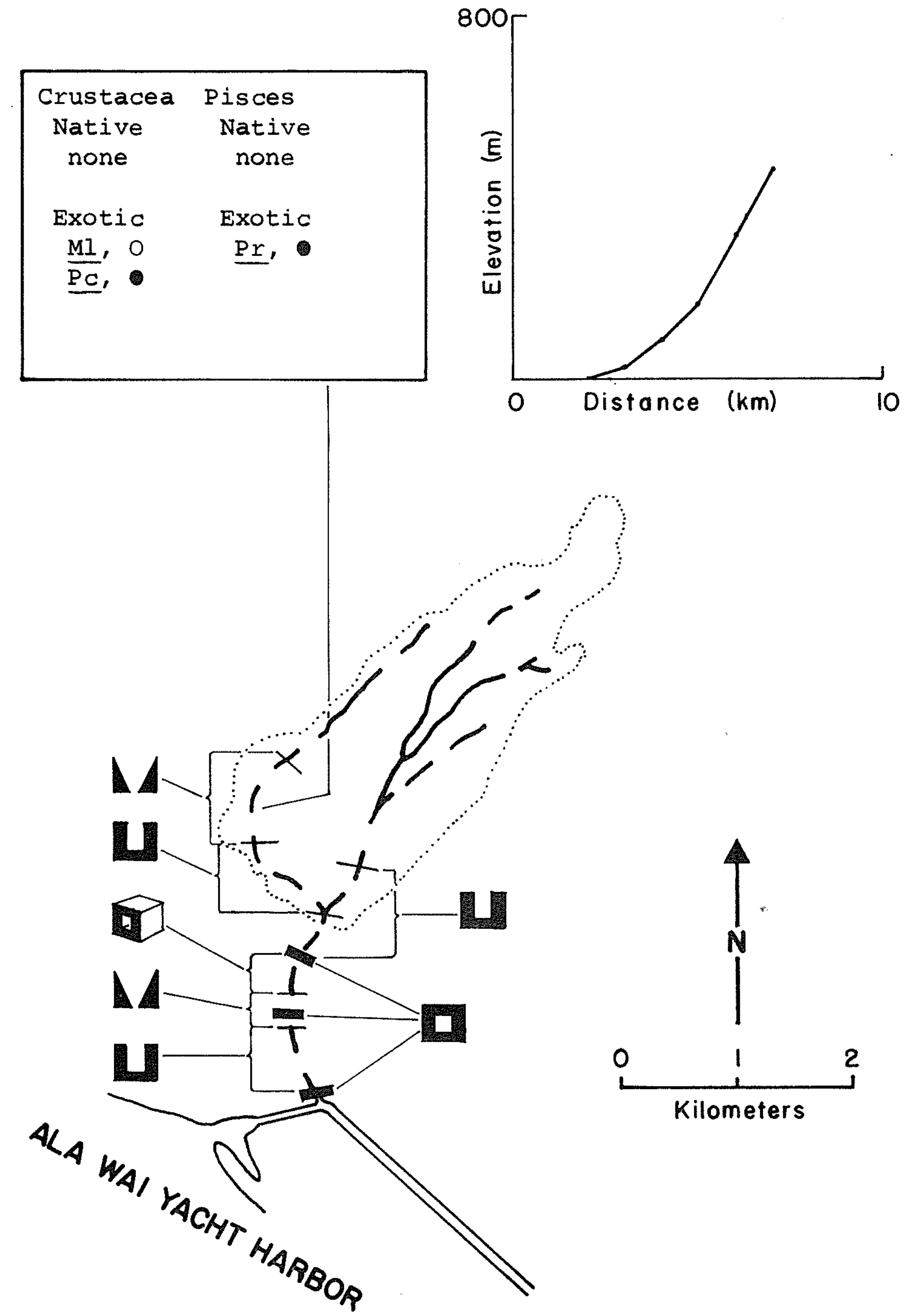

Figure B29. Makiki Stream, Oahu: 32% of channel length altered. Longitudinal gradient (m/km) = 65.

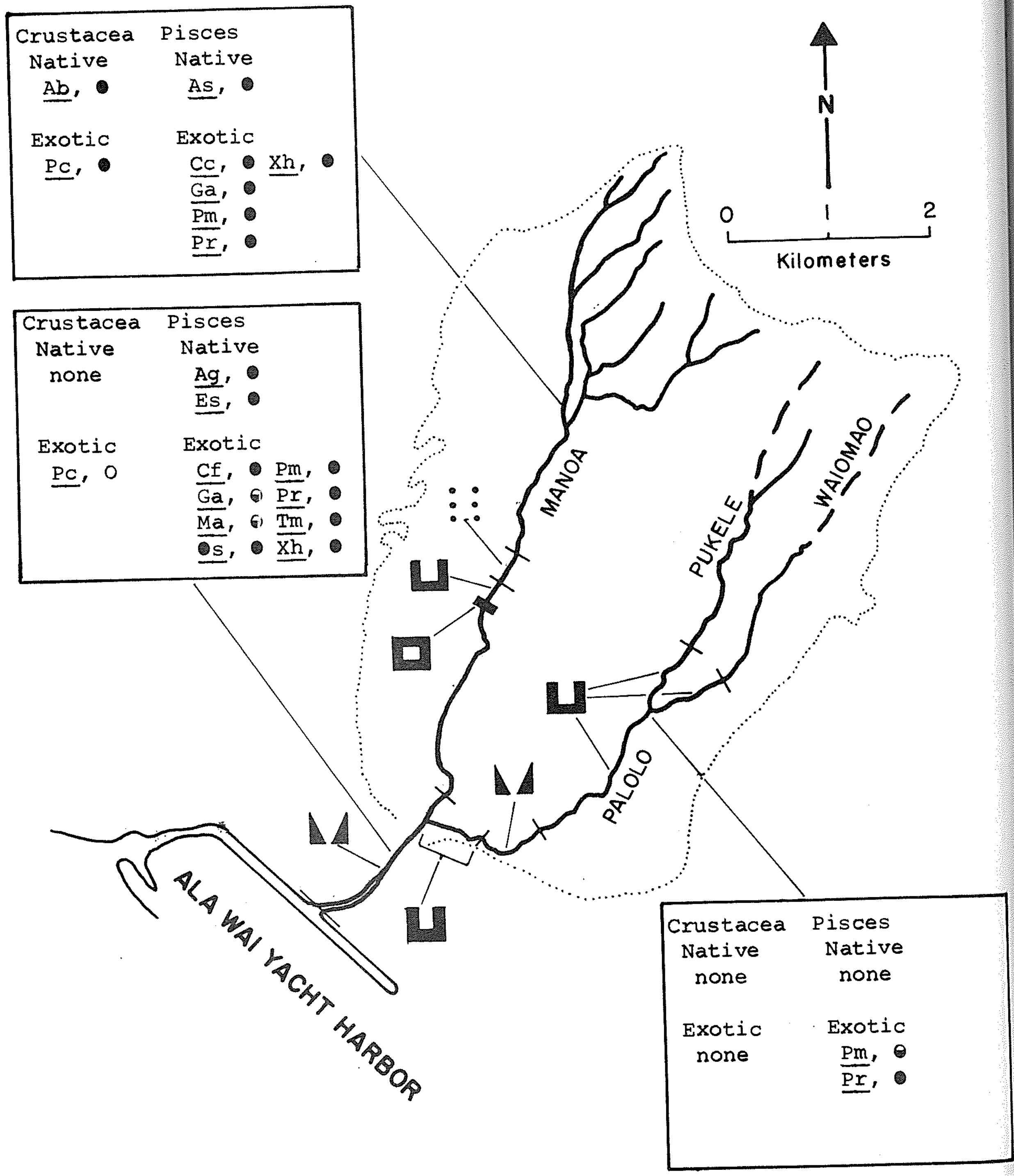

Figure B30. Manoa Stream, Oahu: 24% of channel length altered. Longitudinal gradient (m/km) = 64.

COPY

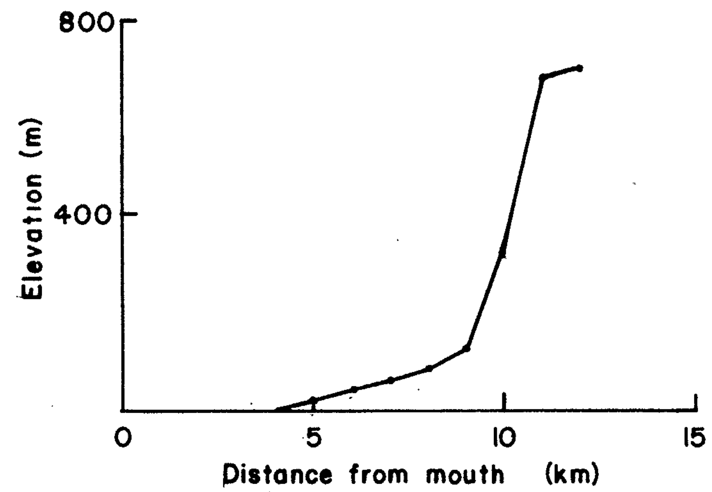

Figure B31. Profile of Manoa Stream, Oahu. Longitudinal gradient (m/km) = 64.

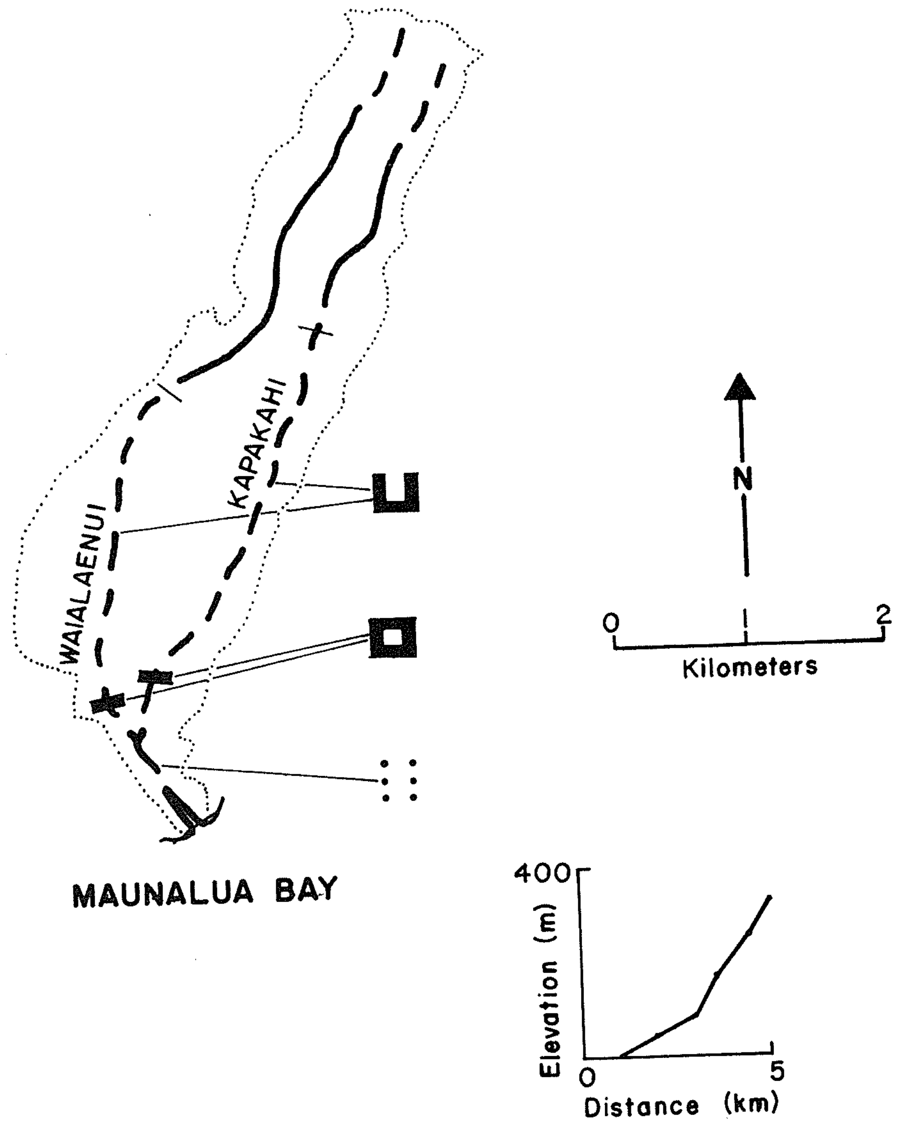

Figure B32. Waialaenui Stream, Oahu: 54% of channel length altered. Longitudinal gradient (m/km) = 64.

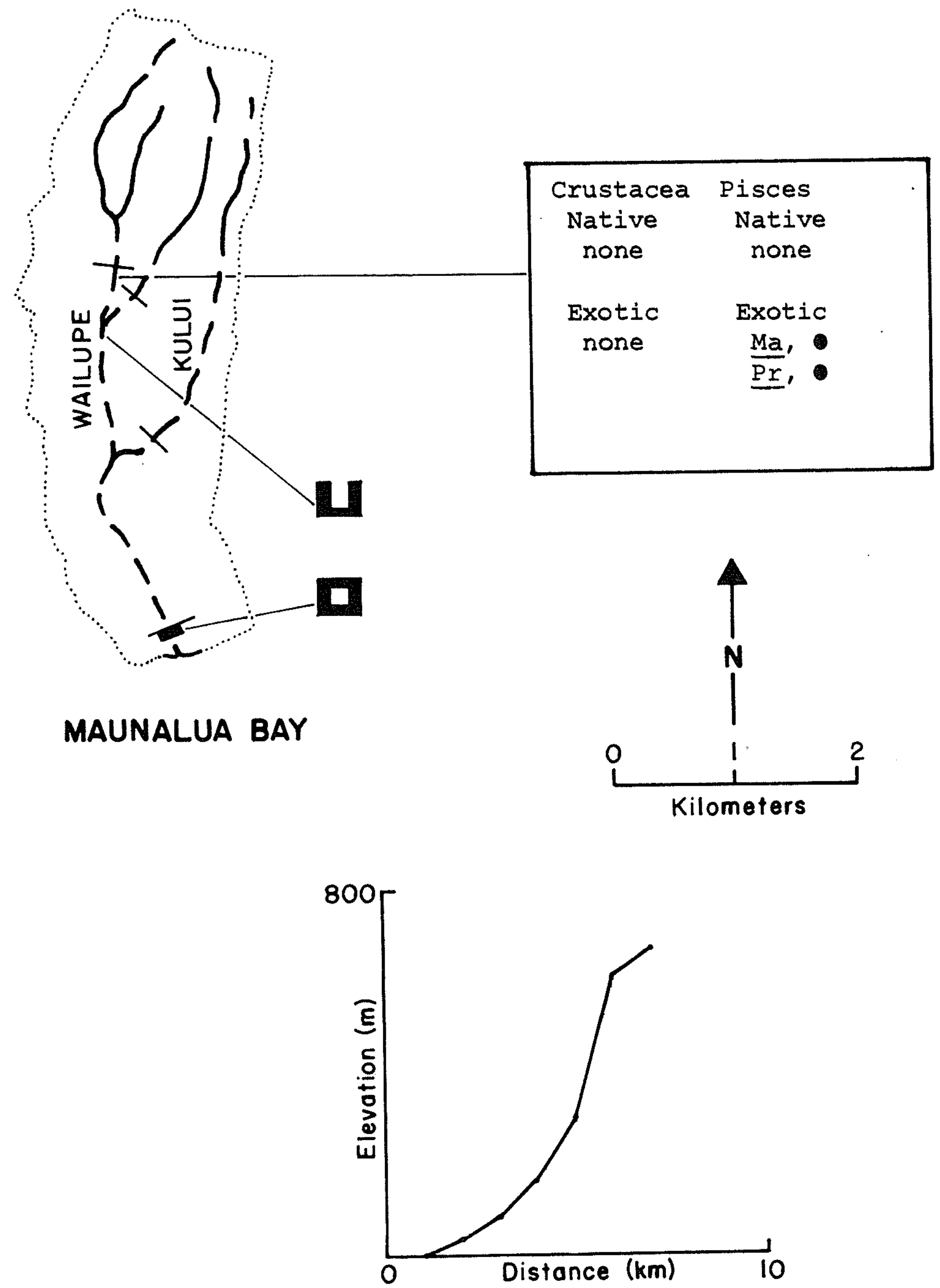

Figure B33. Wailupe Stream, Oahu: 29% of channel length altered. Longitudinal gradient (m/km) = 93.

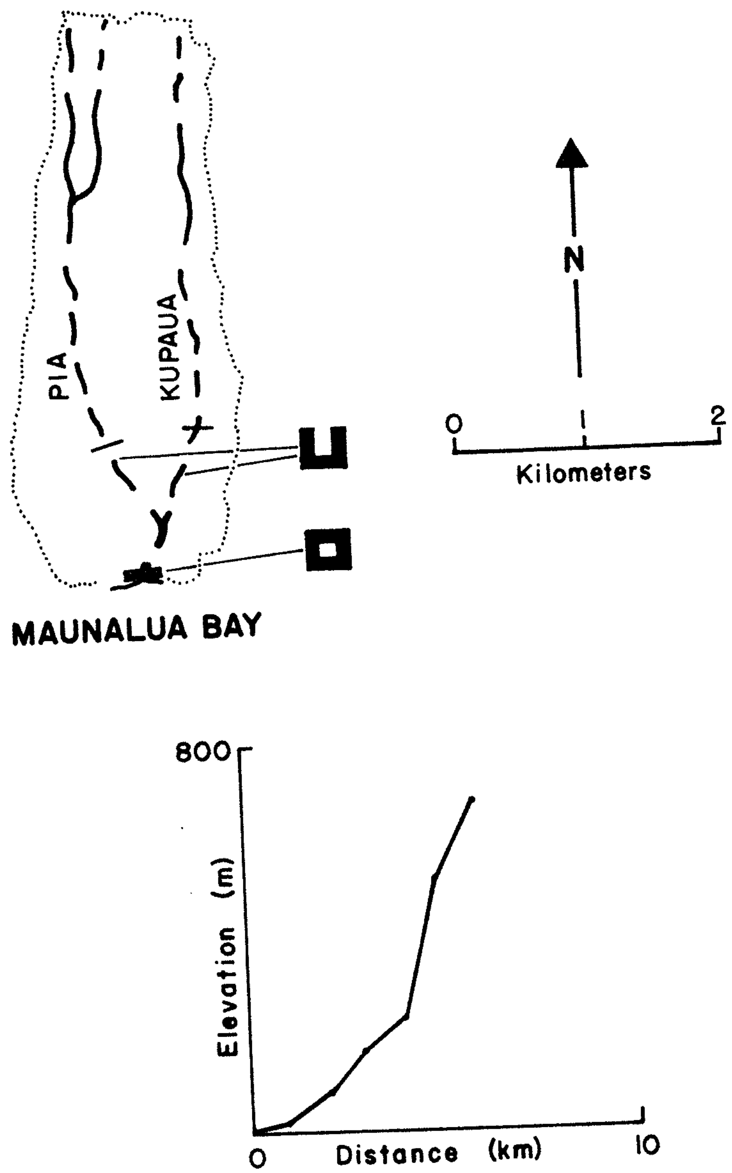

Figure B34. Pia Stream, Oahu: 21% of channel length altered. Longitudinal gradient (m/km) = 134.

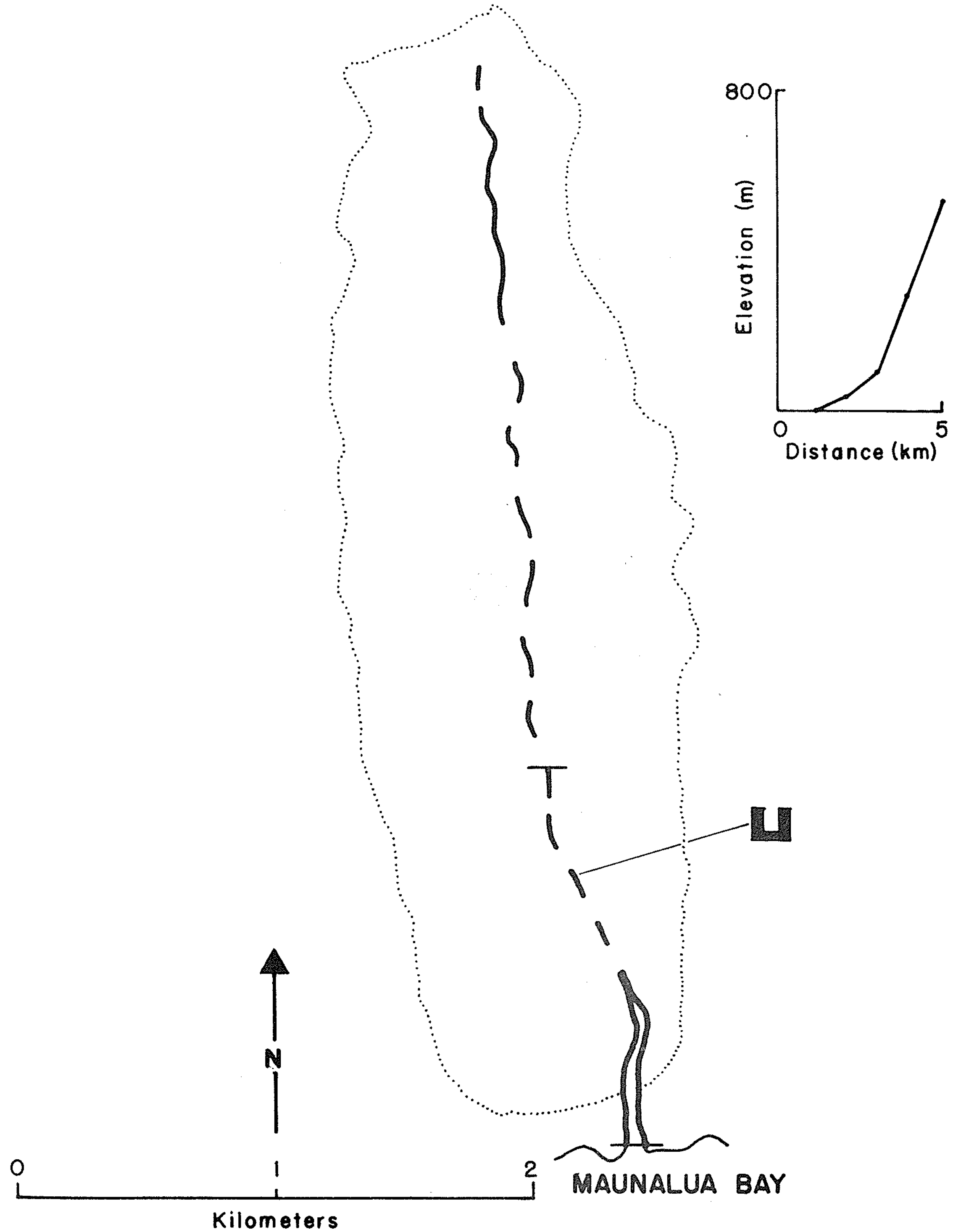

Figure B35. Kuliouou Stream, Oahu: 40% of channel length altered. Longitudinal gradient (m/km) = 121.

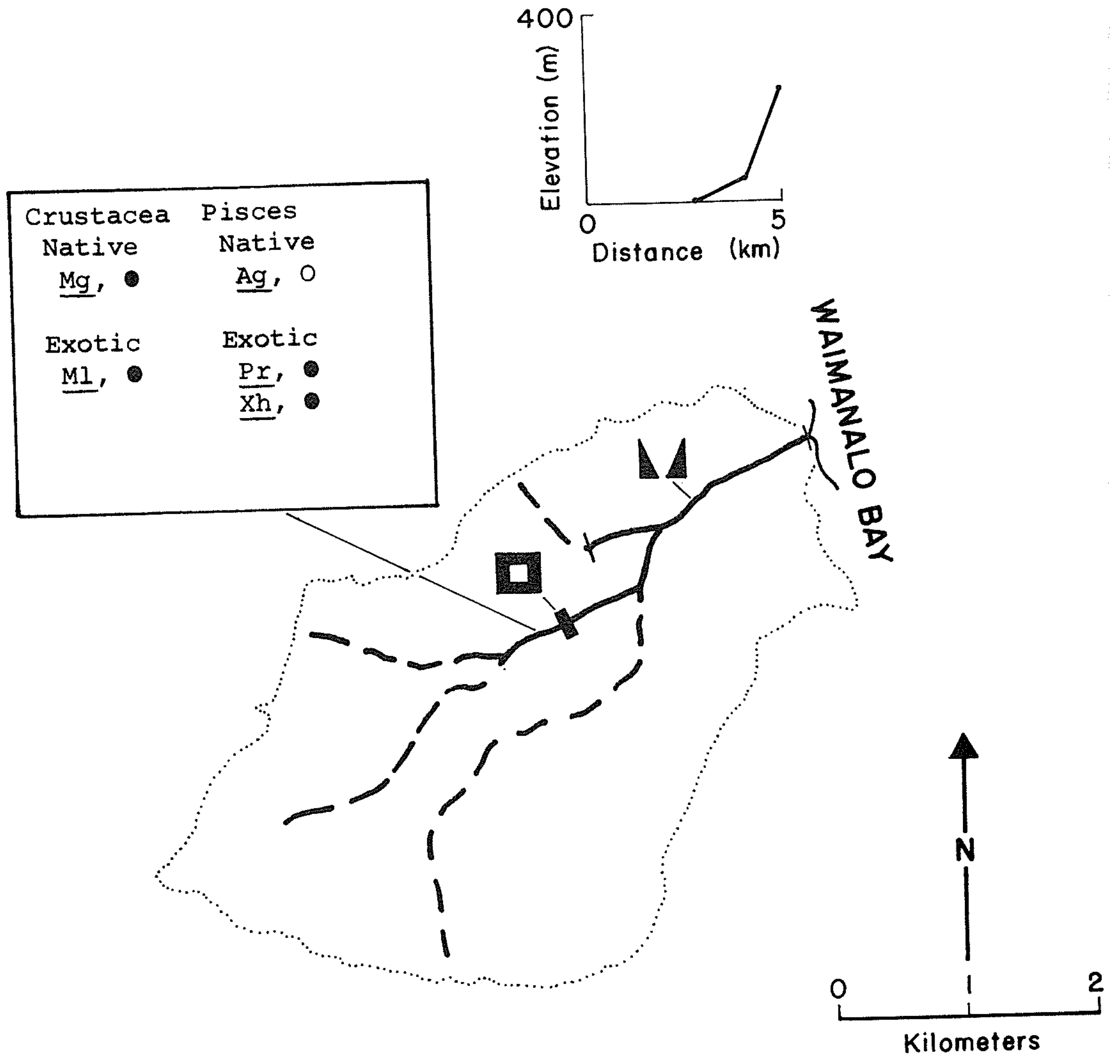

Figure B36. Waimanalo Stream, Oahu: 23% of channel length altered. Longitudinal gradient (m/km) = 44.

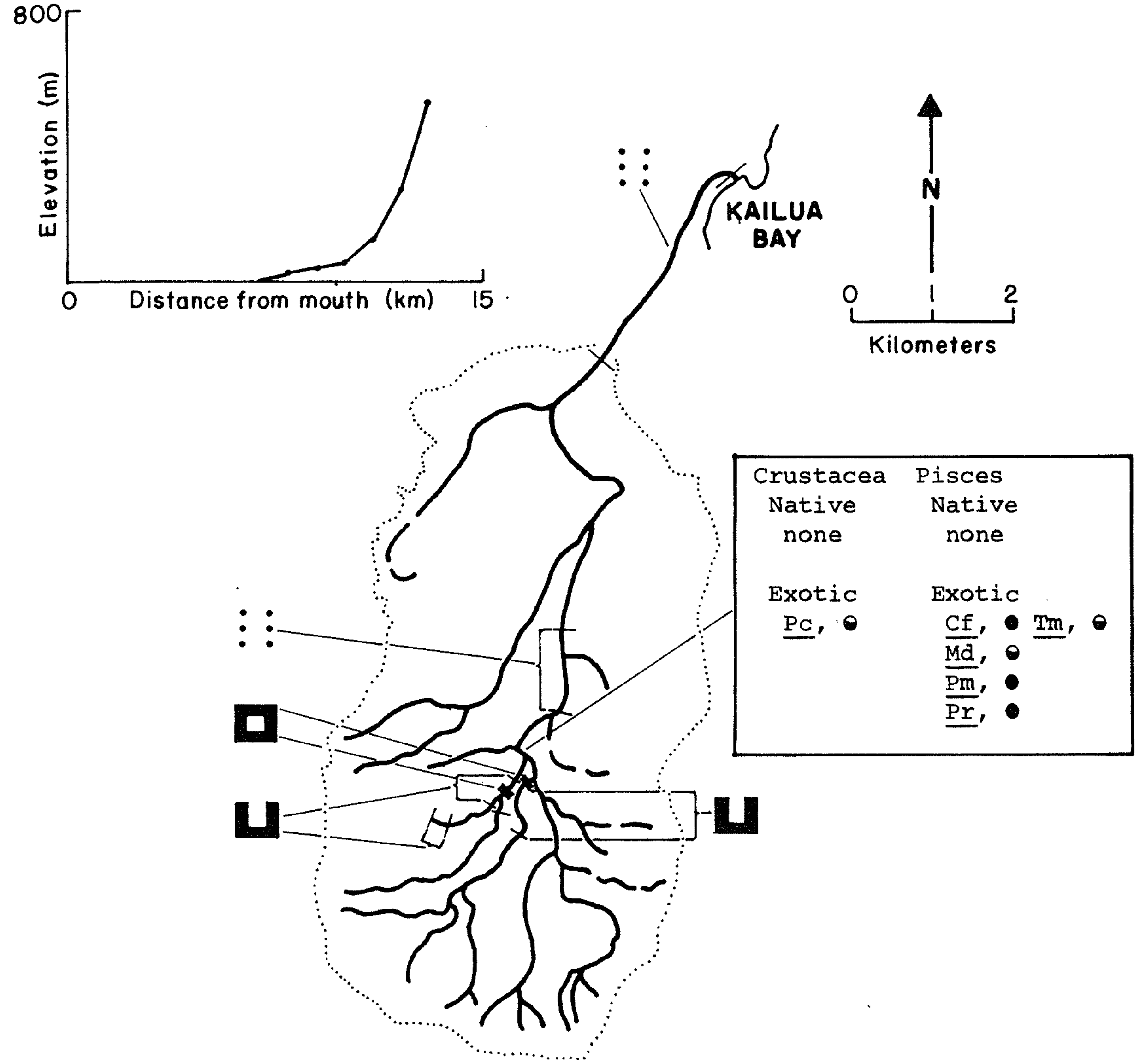

Figure B37. Maunawili Stream, Oahu: 4% of channel length altered. Longitudinal gradient (m/km) = 43.

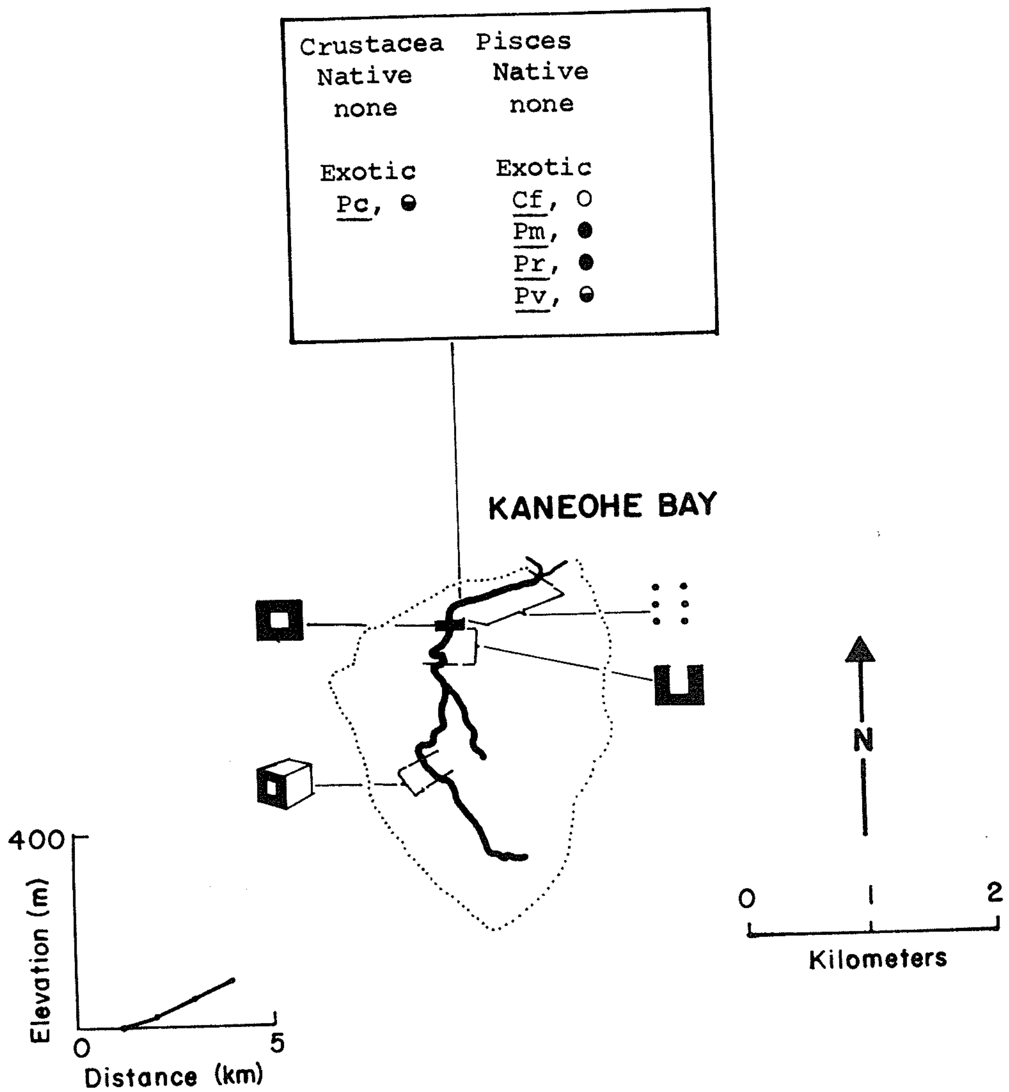

Figure B38. Kawa Stream, Oahu: 36% of channel length altered. Longitudinal gradient (m/km) = 24.

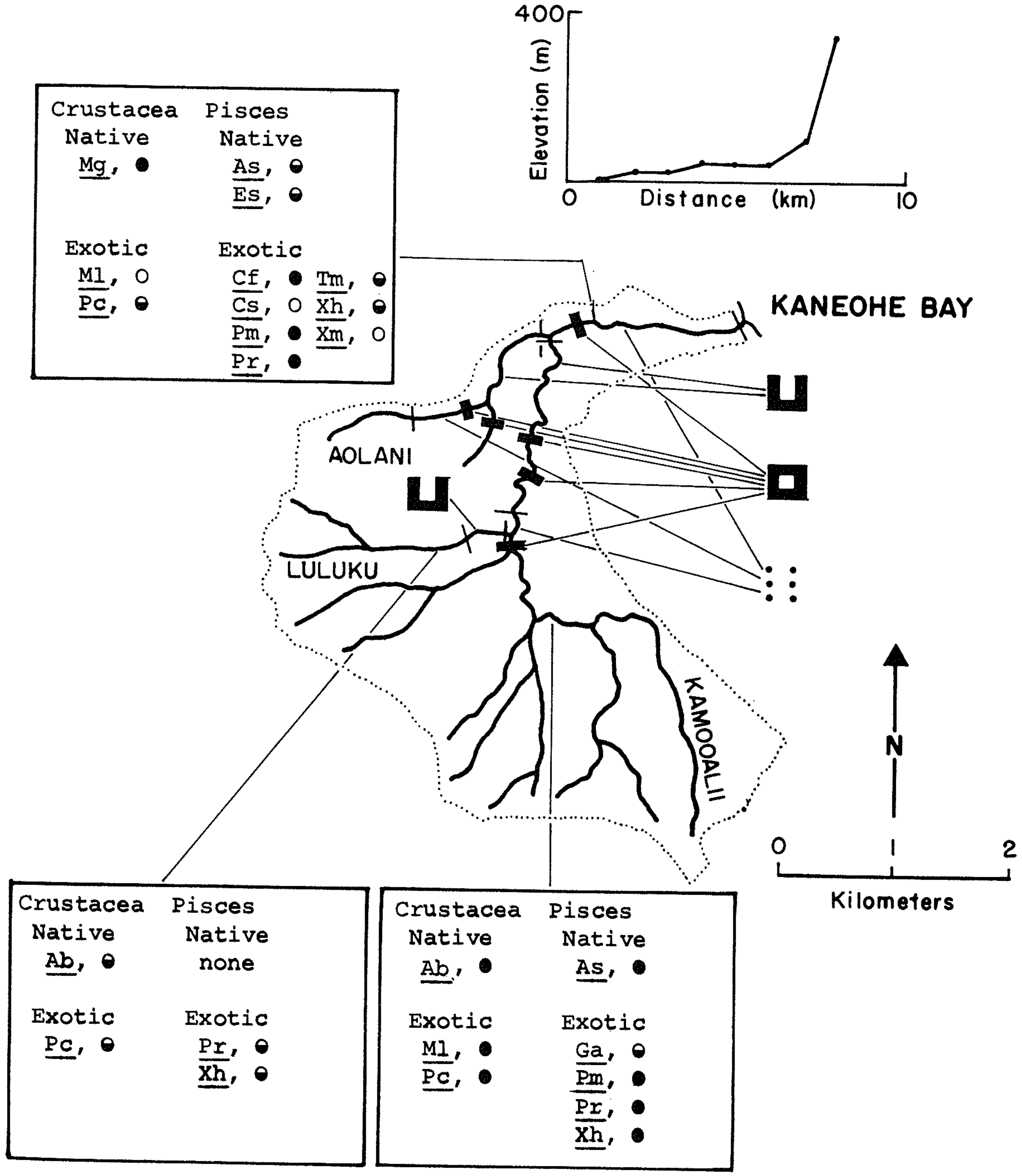

Figure B39. Kaneohe Stream, Oahu: 25% of channel length altered. Longitudinal gradient (m/km) = 67.

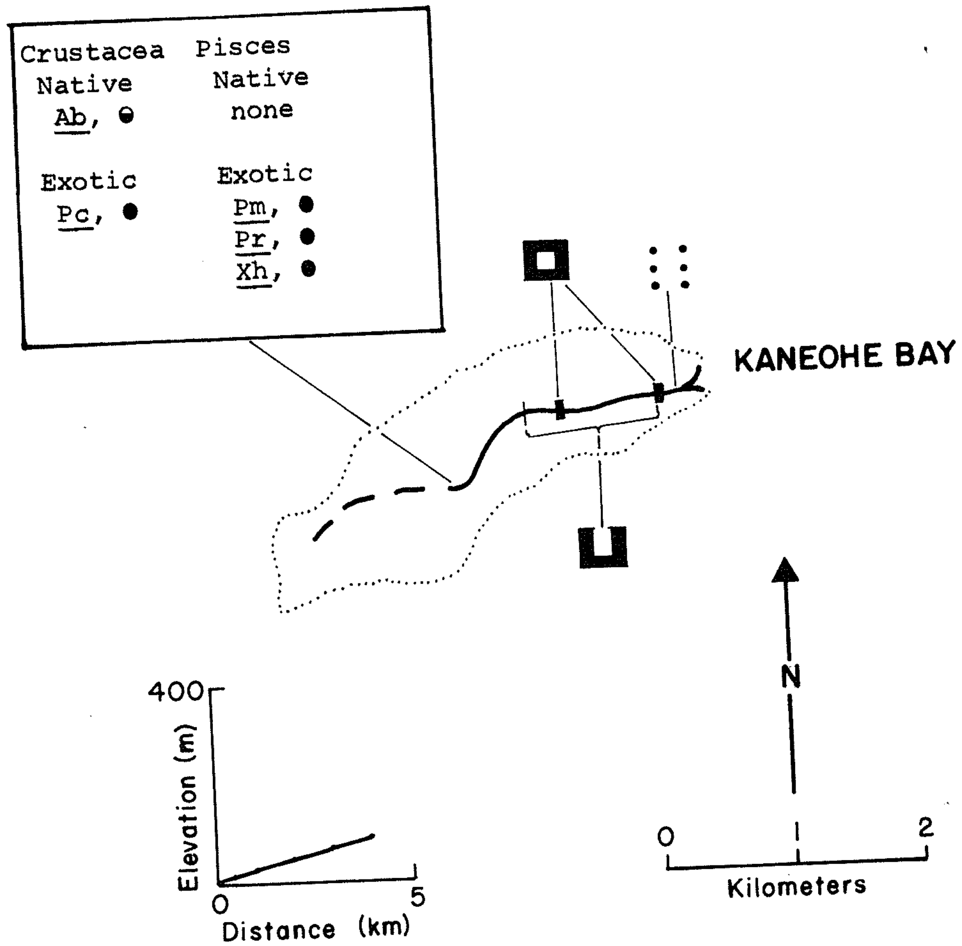

Figure B40. Keaahala Stream, Oahu: 38% of channel length altered. Longitudinal gradient (m/km) = 23.

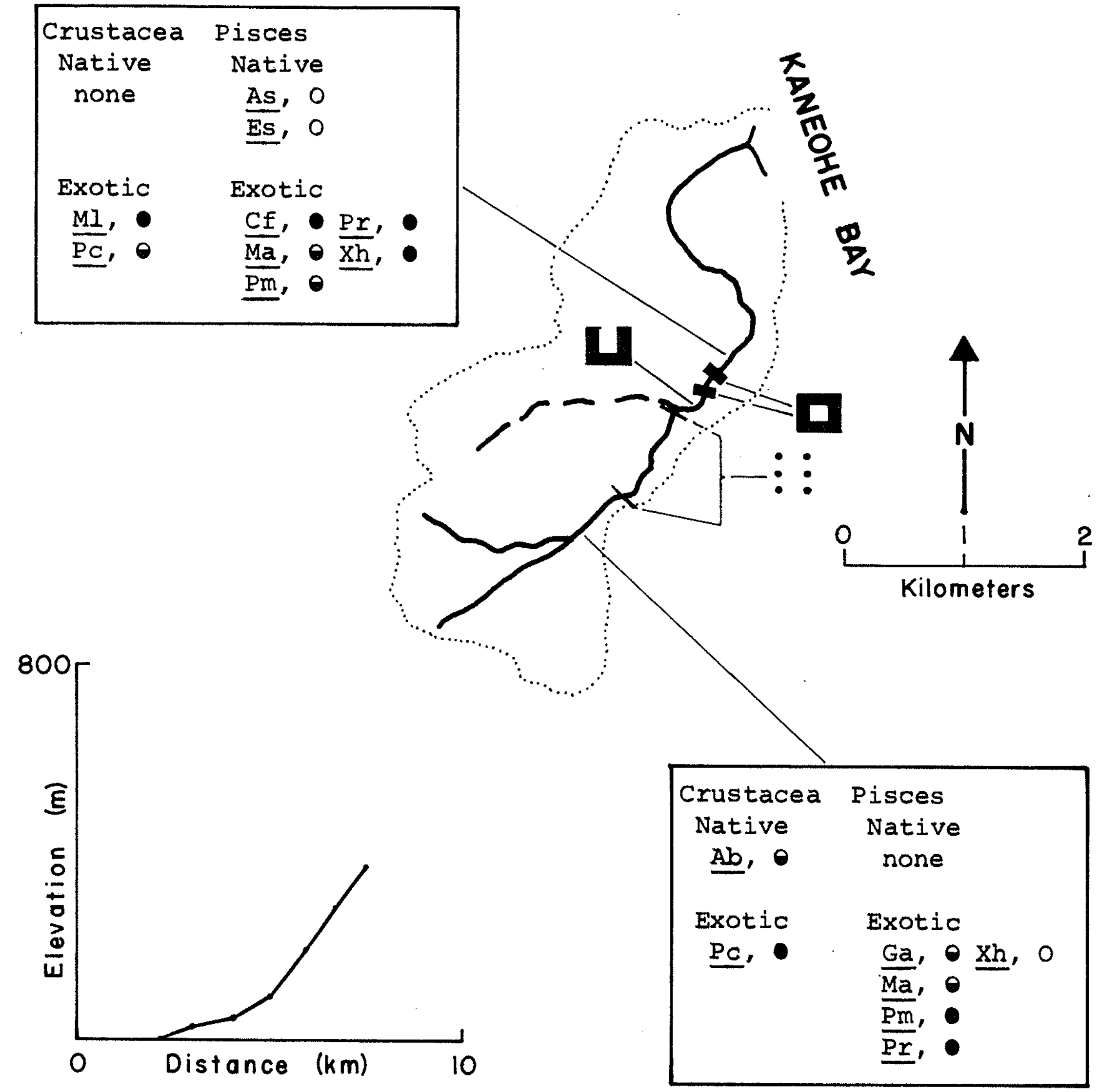

Figure B41. Heeia Stream, Oahu: 14% of channel length altered. Longitudinal gradient (m/km) = 48.

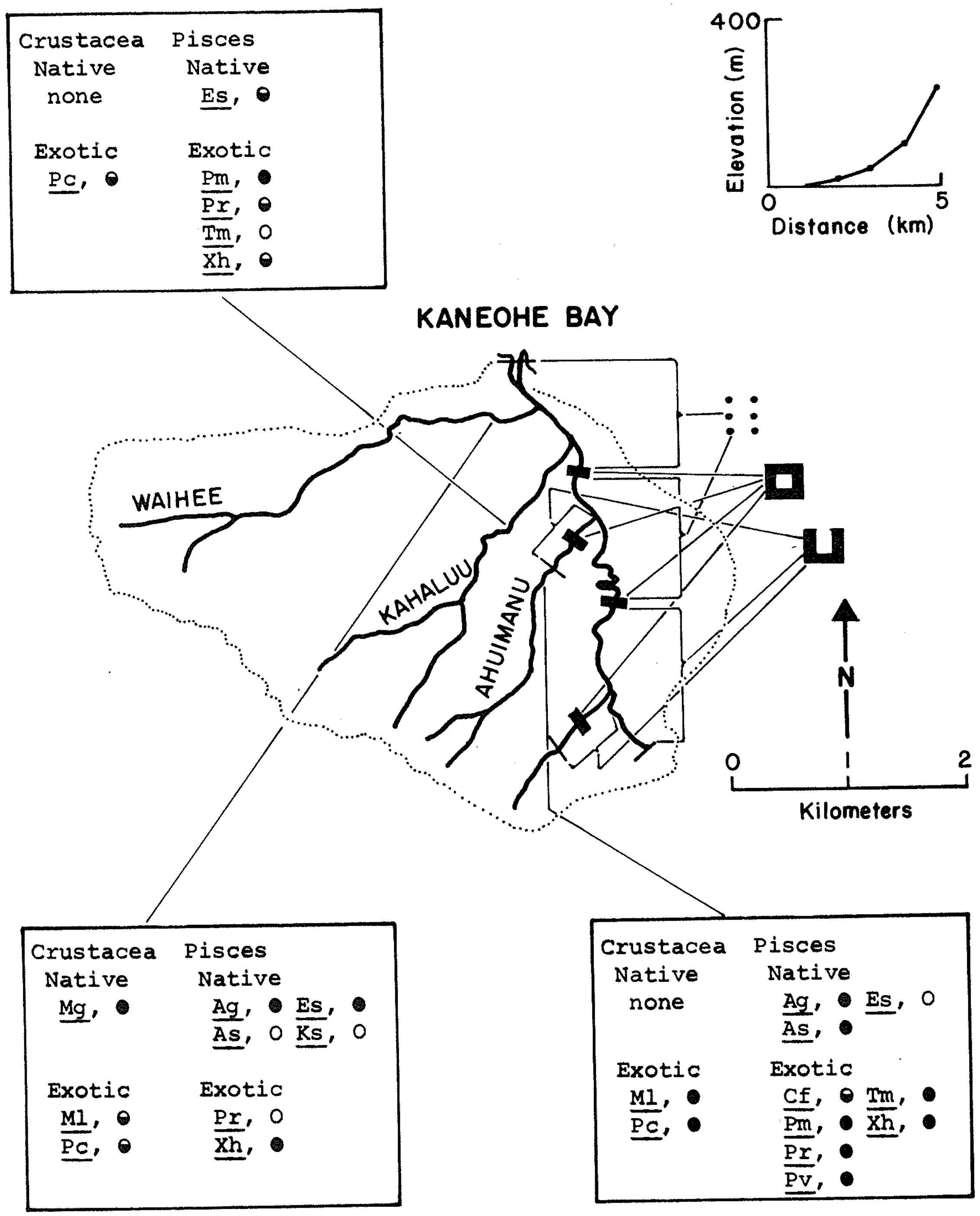

Figure B42. Kahaluu Stream, Oahu: 14% of channel length altered. Longitudinal gradient (m/km) = 52.

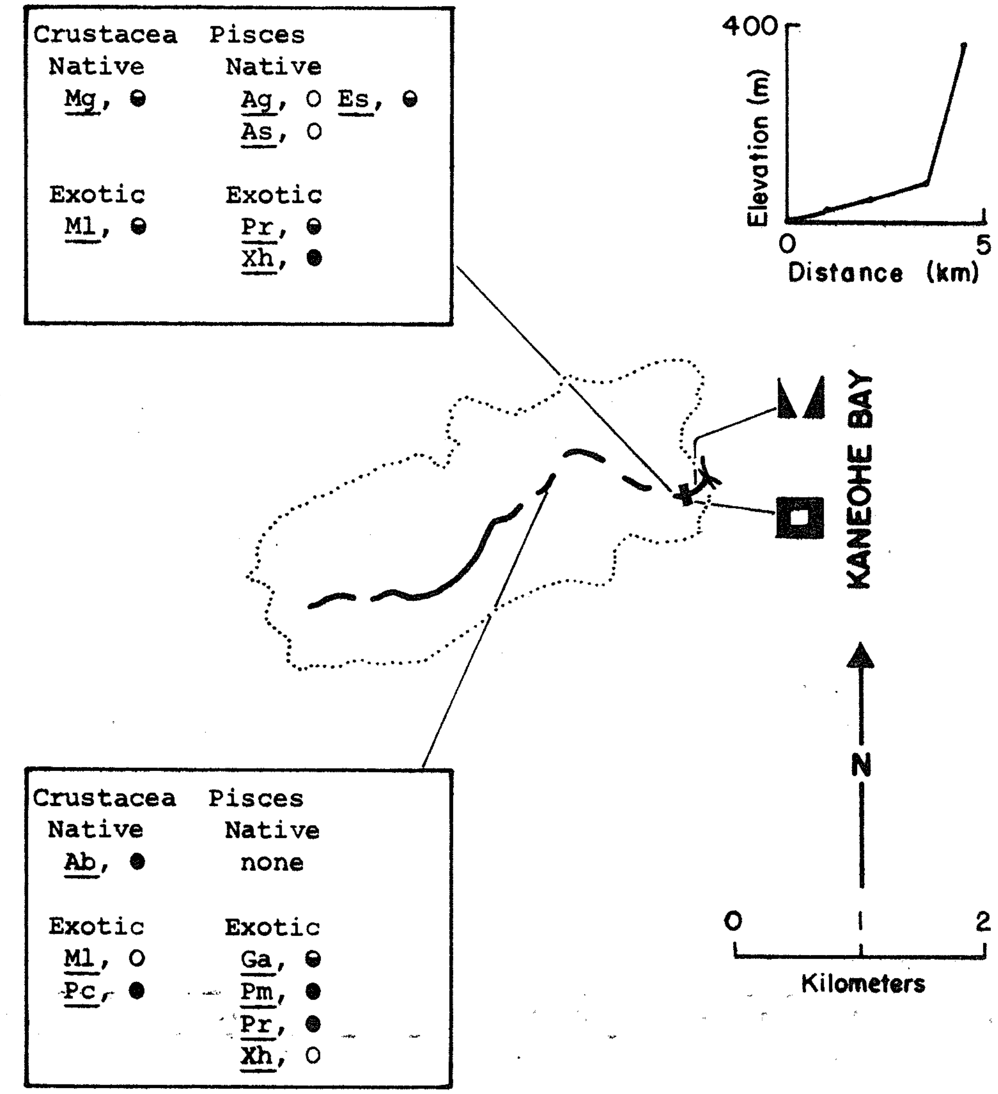

Figure B43. Kaalaea Stream, Oahu: 3% of channel length altered. Longitudinal gradient (m/km) = 88.

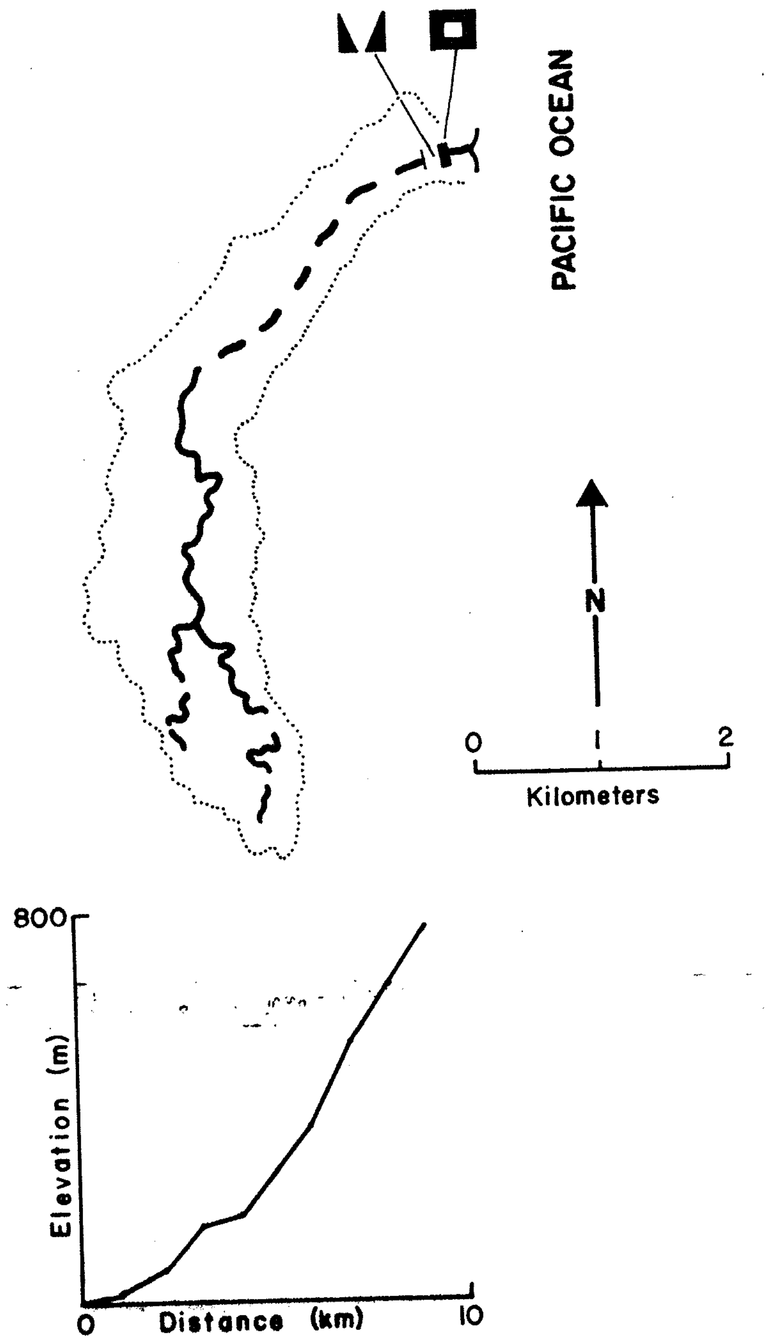

Figure B44. Kaipapau Stream, Oahu: 2% of channel length altered. Longitudinal gradient (m/km) = 86.

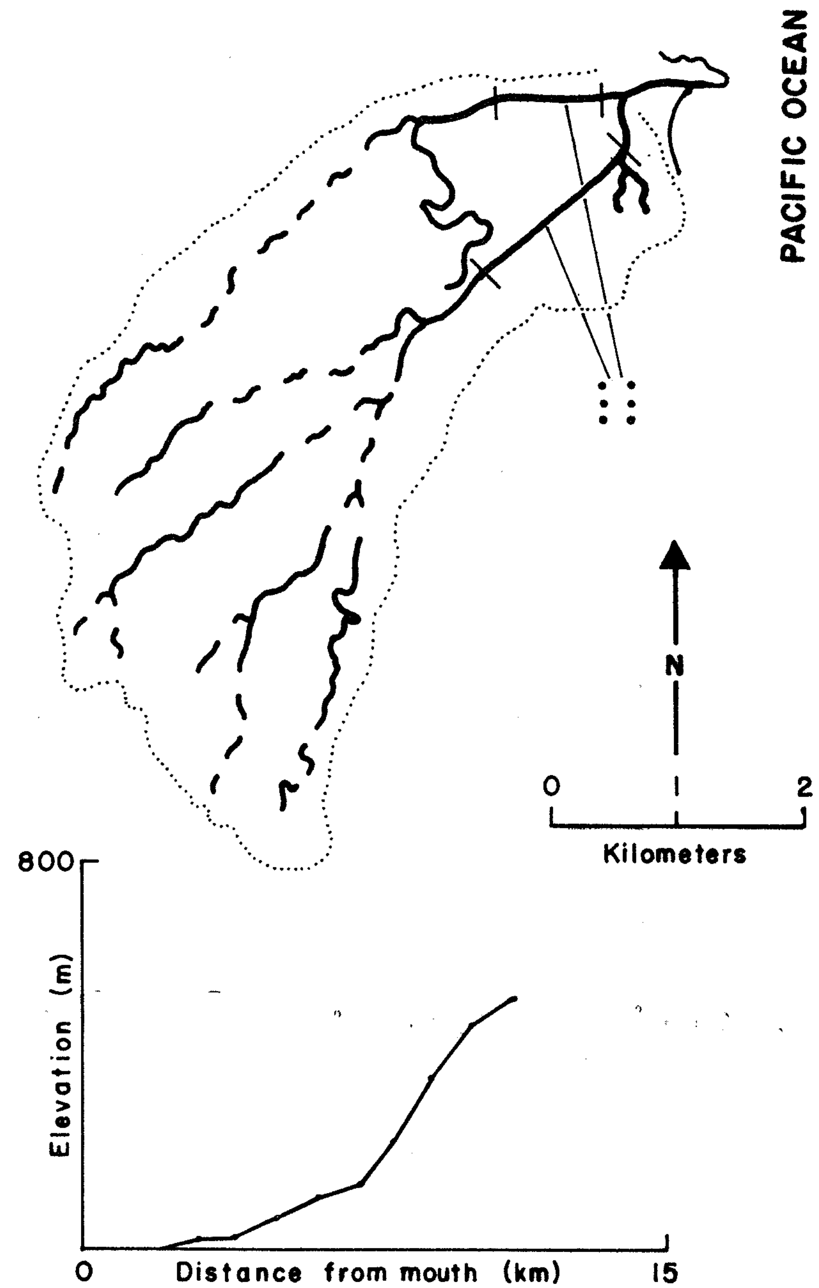

Figure B45. Malaekahana Stream, Oahu: 8% of channel length altered. Longitudinal gradient (m/km) = 50.

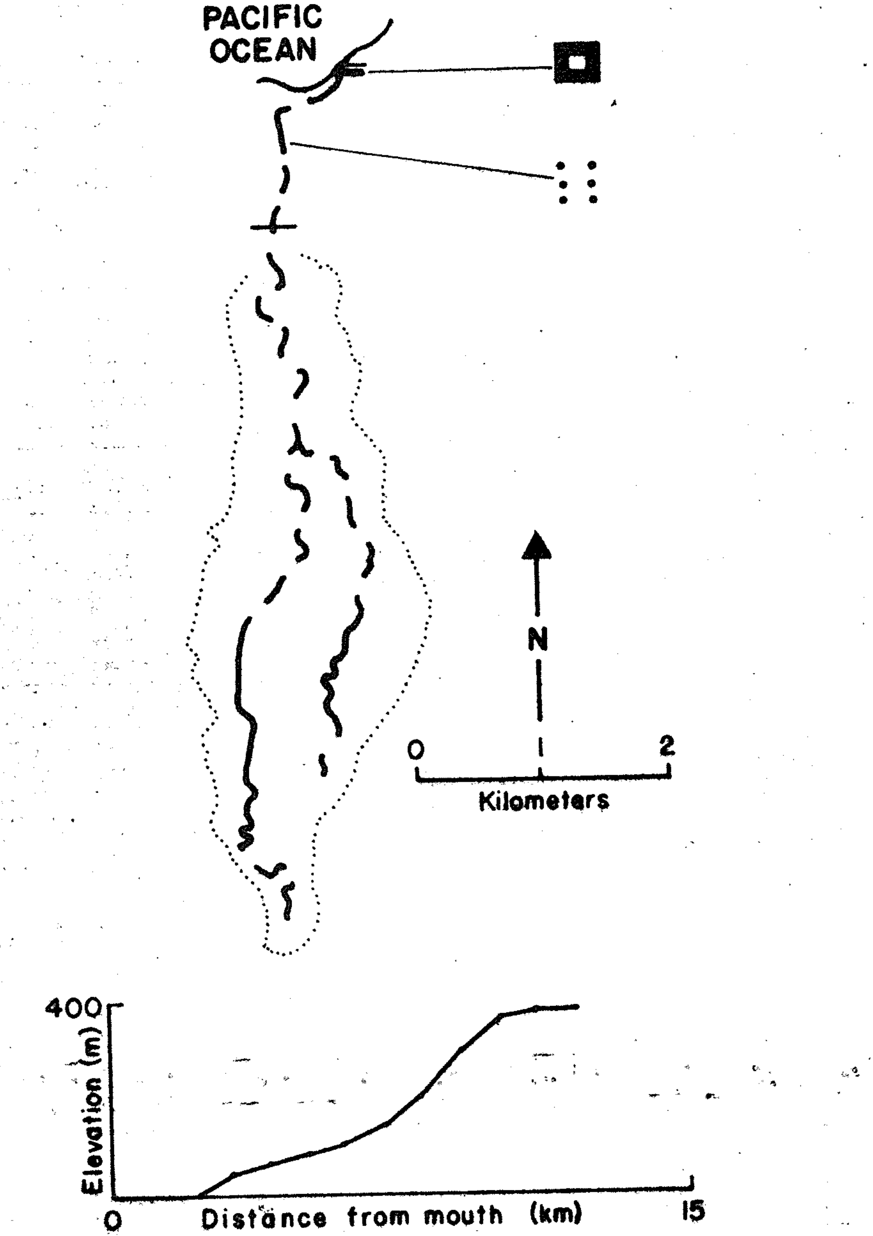

Figure B46. Oio Stream, Oahu: 20% of channel length altered. Longitudinal gradient (m/km) = 37.

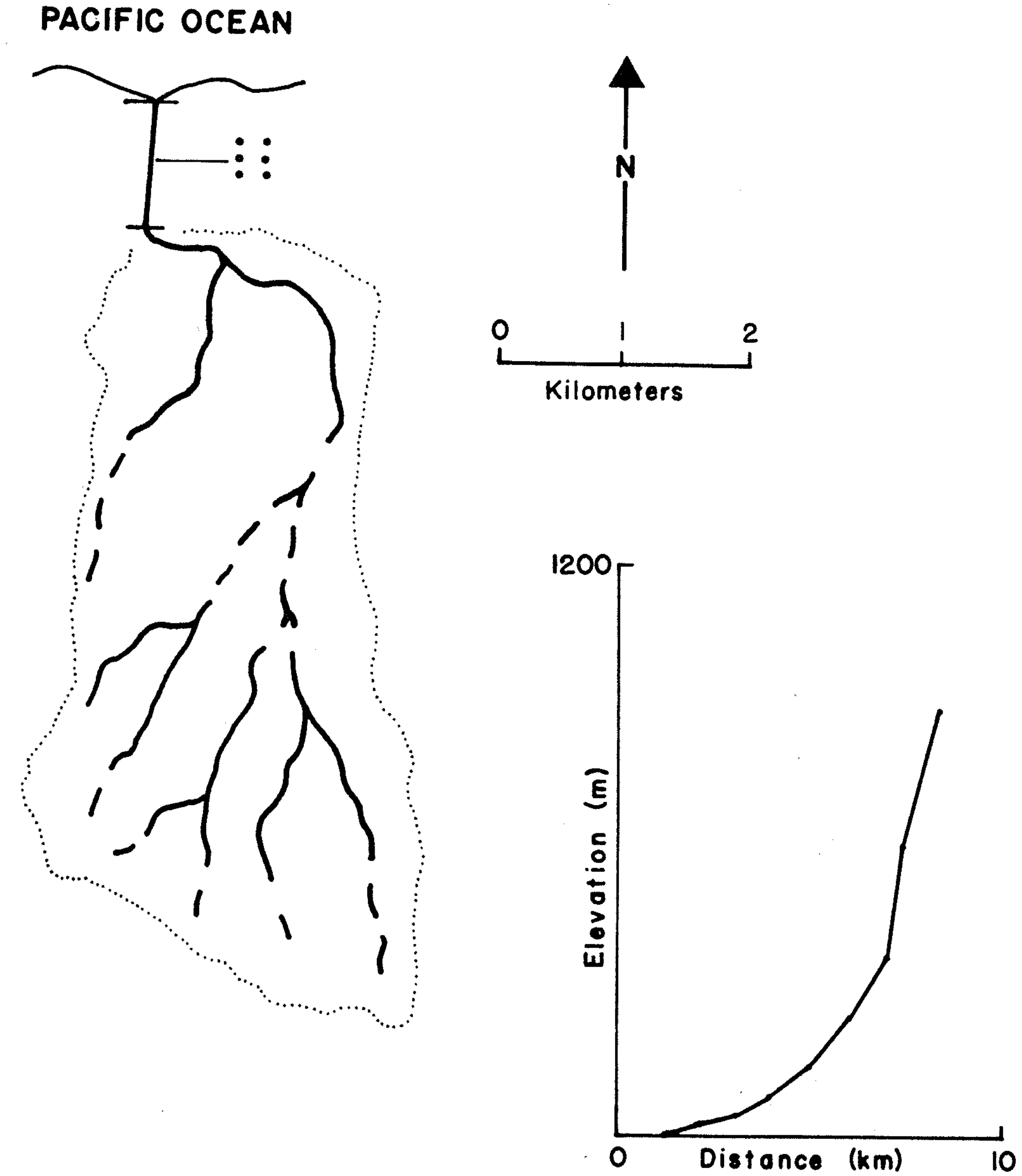

Figure B47. Makaleha Stream, Oahu: 6% of channel length altered. Longitudinal gradient (m/km) = 105.

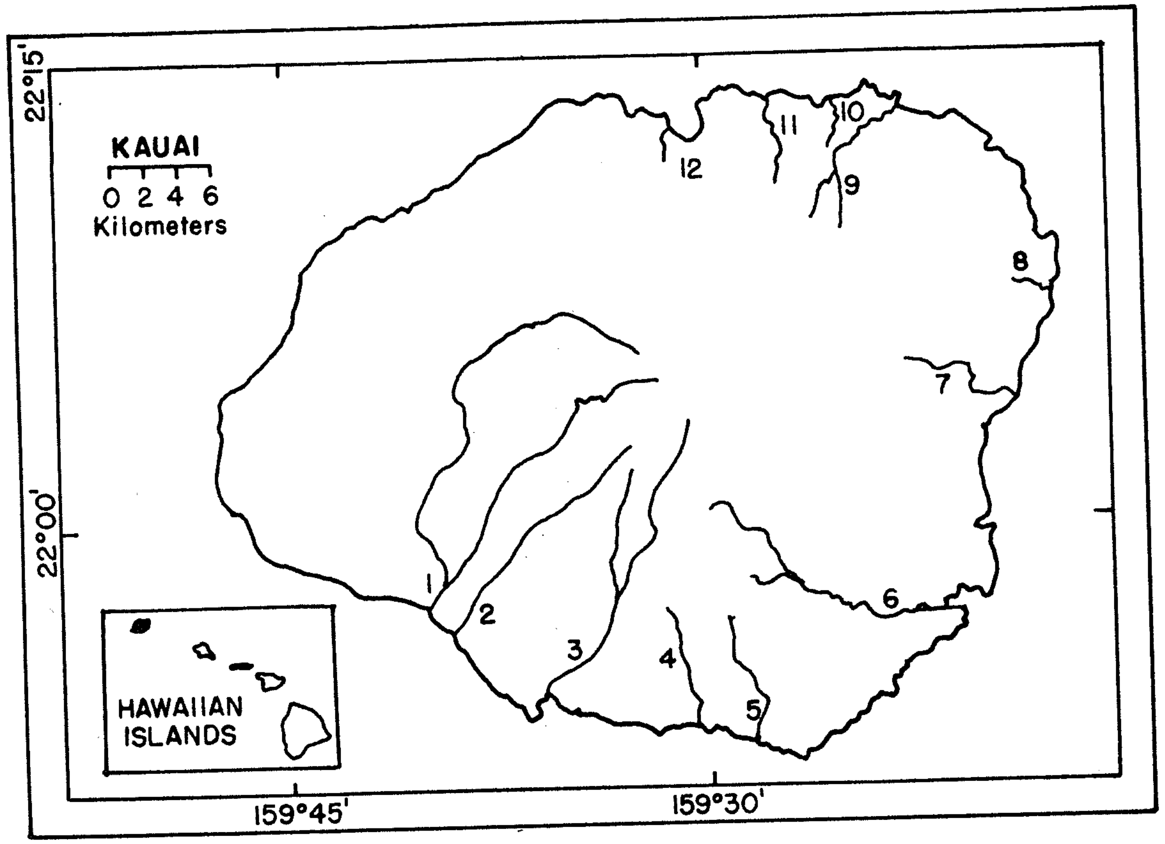

Figure B48. Locator map for the 12 Kauai streams having modified channels.

Legend:

1. Waimea River
2. Waipao Stream
3. Hanapepe Stream
4. Lawai Stream
5. Waikomo Stream
6. Huleia Stream
7. Konohiki Stream
8. Kumukumu Stream
9. Kilauea Stream
10. Puukumu Stream
11. Anini Stream
12. Waikoko Stream

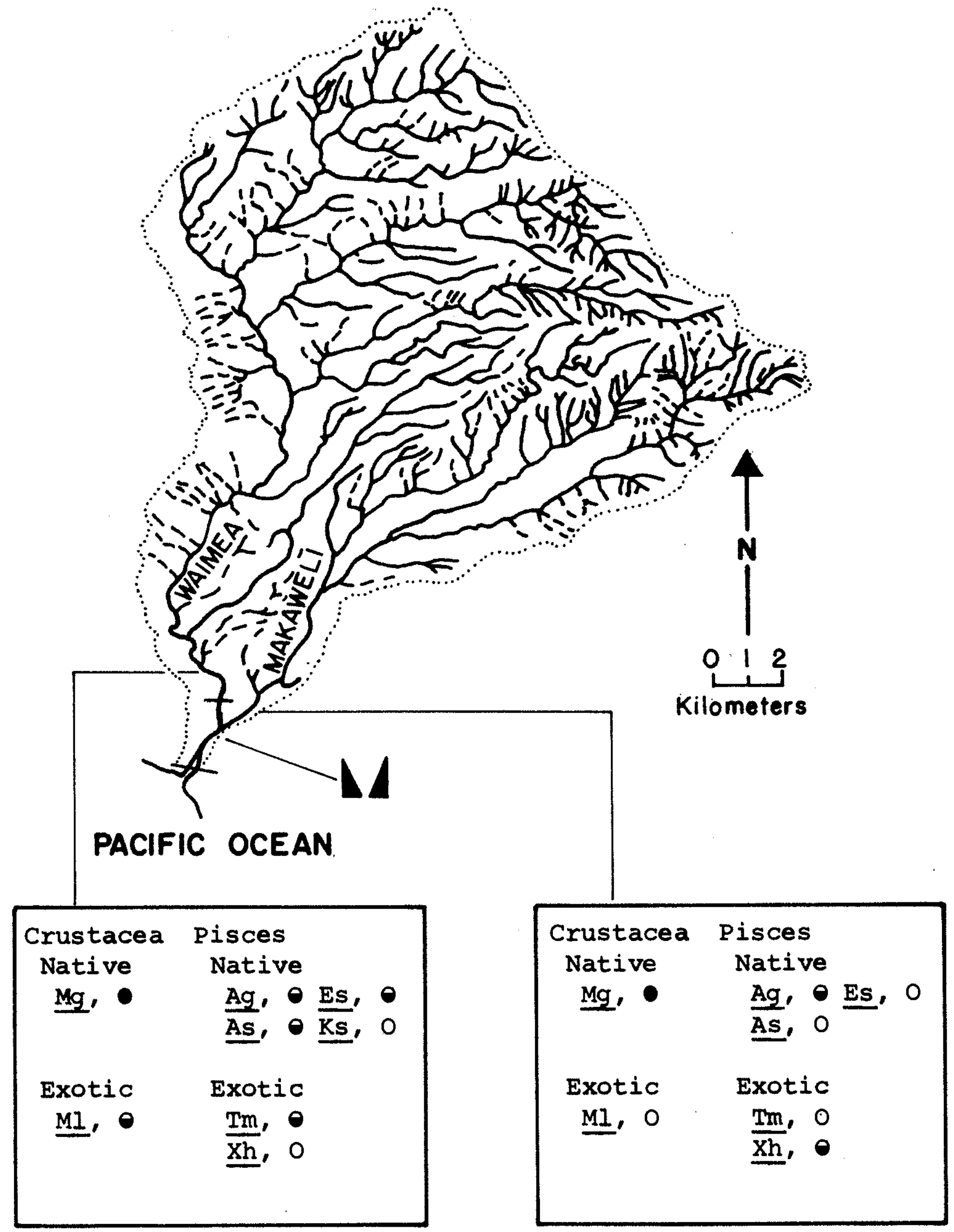

Figure B49. Waimea River, Kauai: <1% of channel length altered.

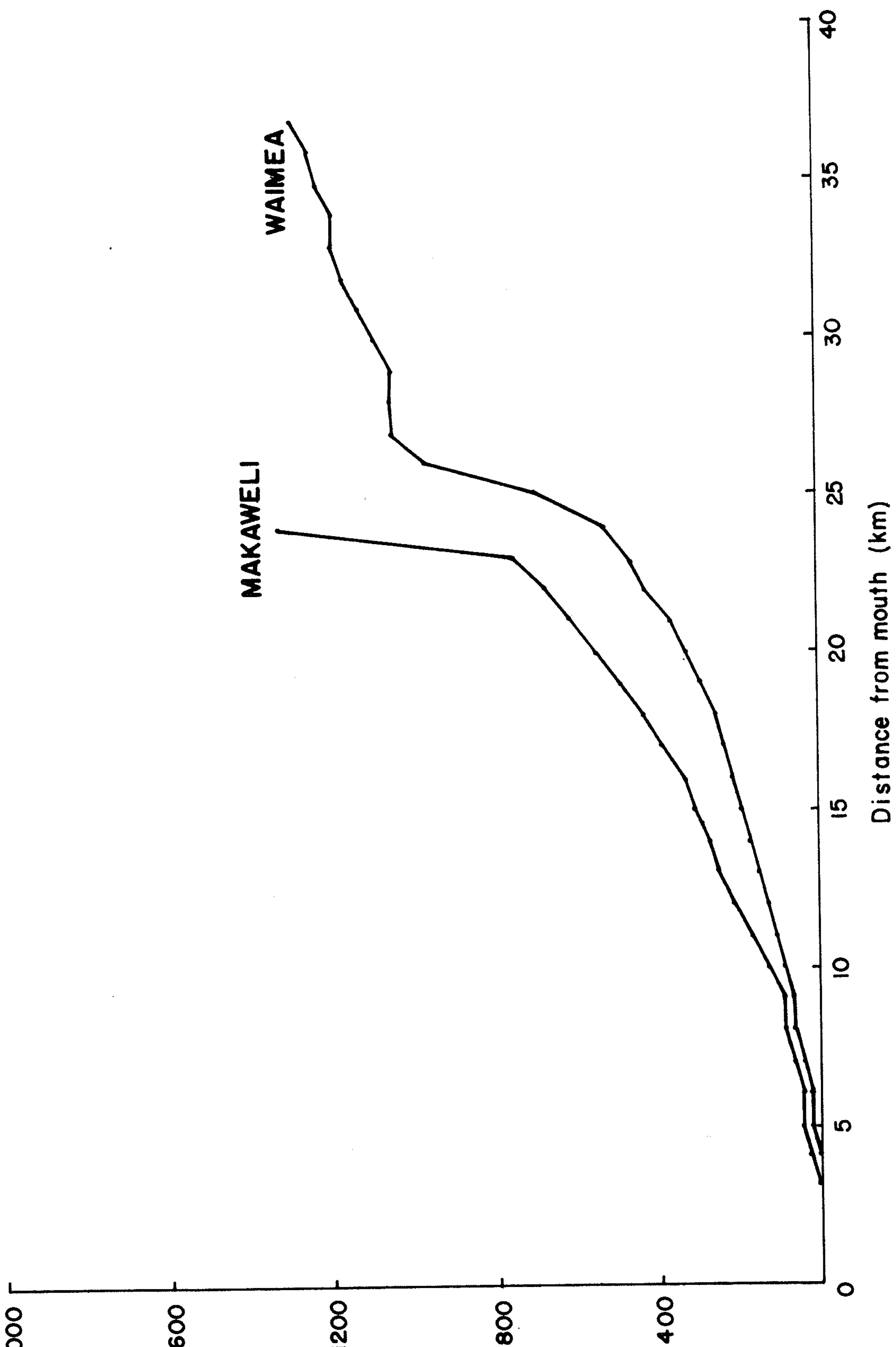

Figure B50. Profile of Waimea River, Kauai. Mainstream longitudinal gradient (m/km) = 34; Makaweli Trib. longitudinal gradient (m/km) = 55.

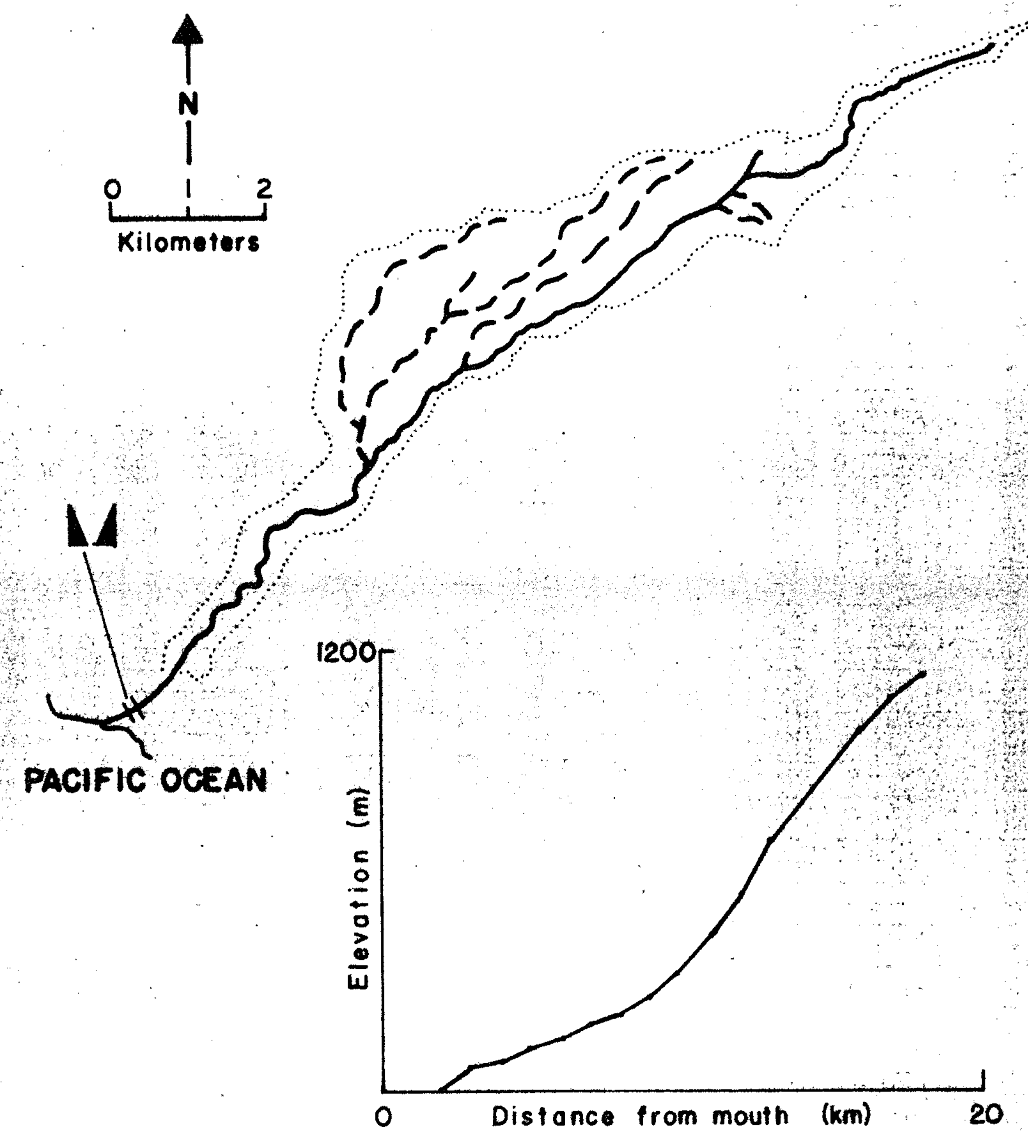

Figure B51. Waipao Stream, Kauai: <1% of channel length altered. Longitudinal gradient (m/km) = 62.

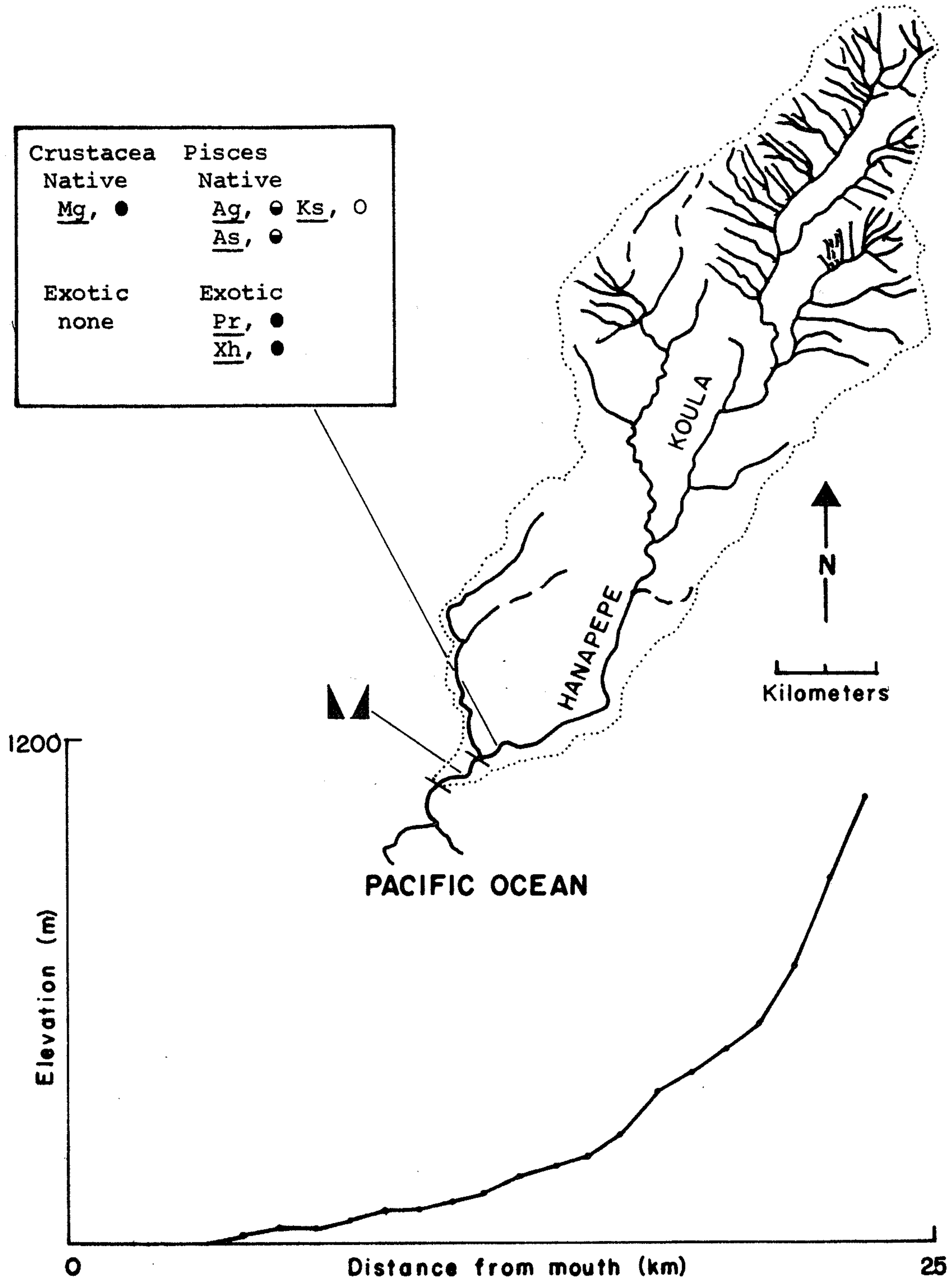

Figure B52. Hanapepe Stream, Kauai: <1% of channel length altered. Longitudinal gradient (m/km) = 46.

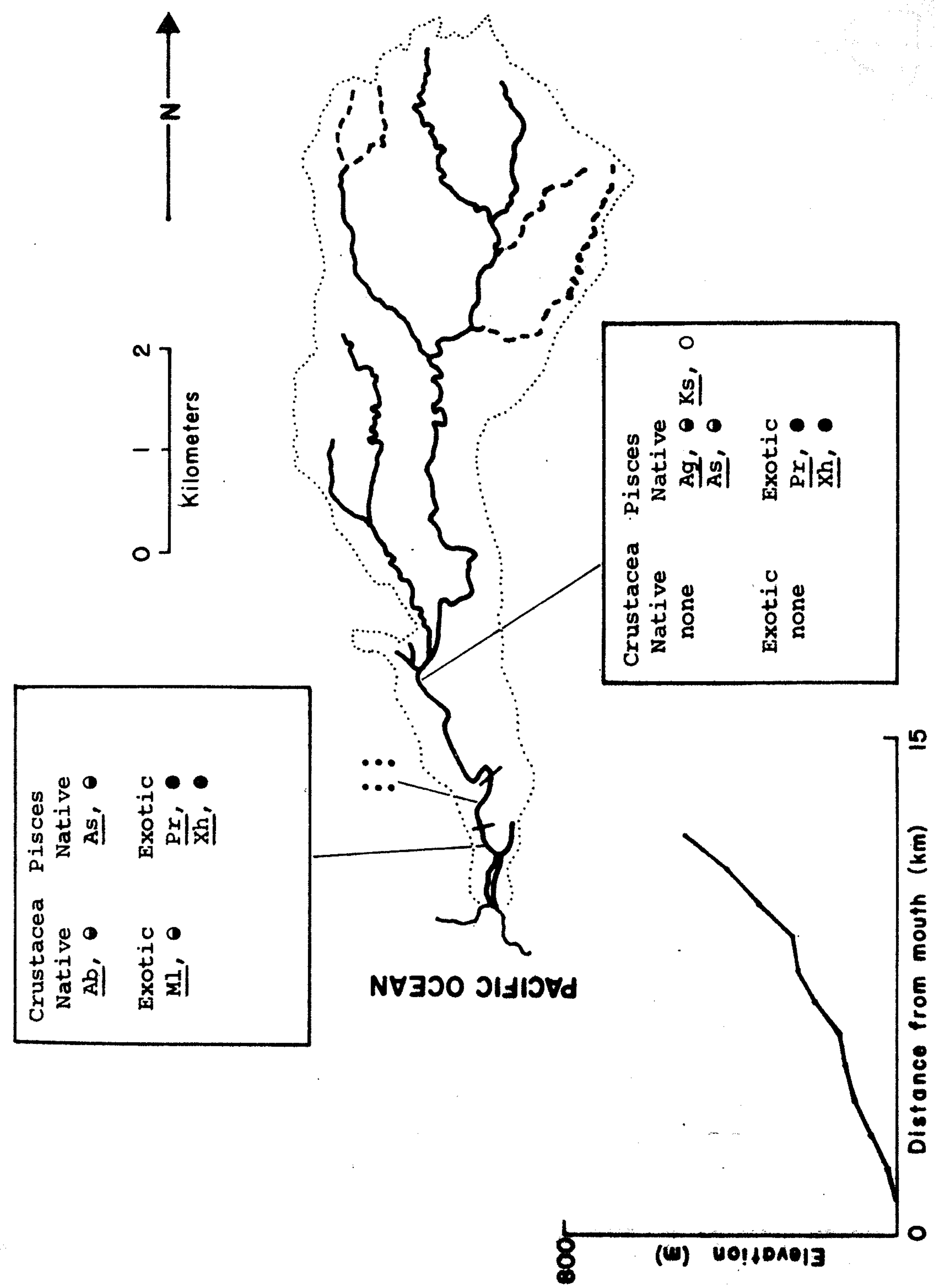

Figure B53. Lawai Stream, Kauai: 2% of channel length altered. Longitudinal gradient (m/km) = 44.

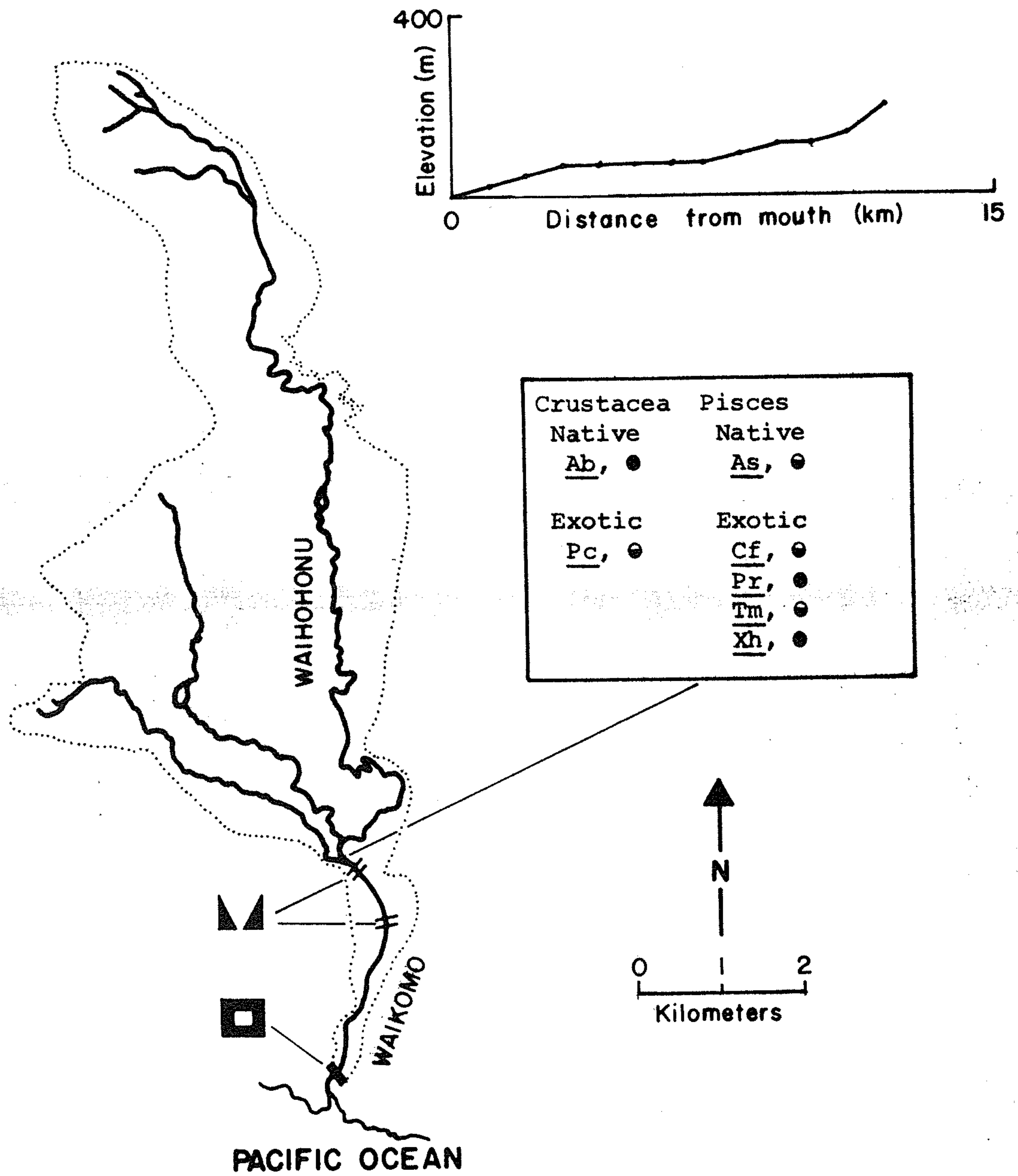

Figure B54. Waikomo Stream, Kauai: <1% of channel length altered. Longitudinal gradient (m/km) = 15.

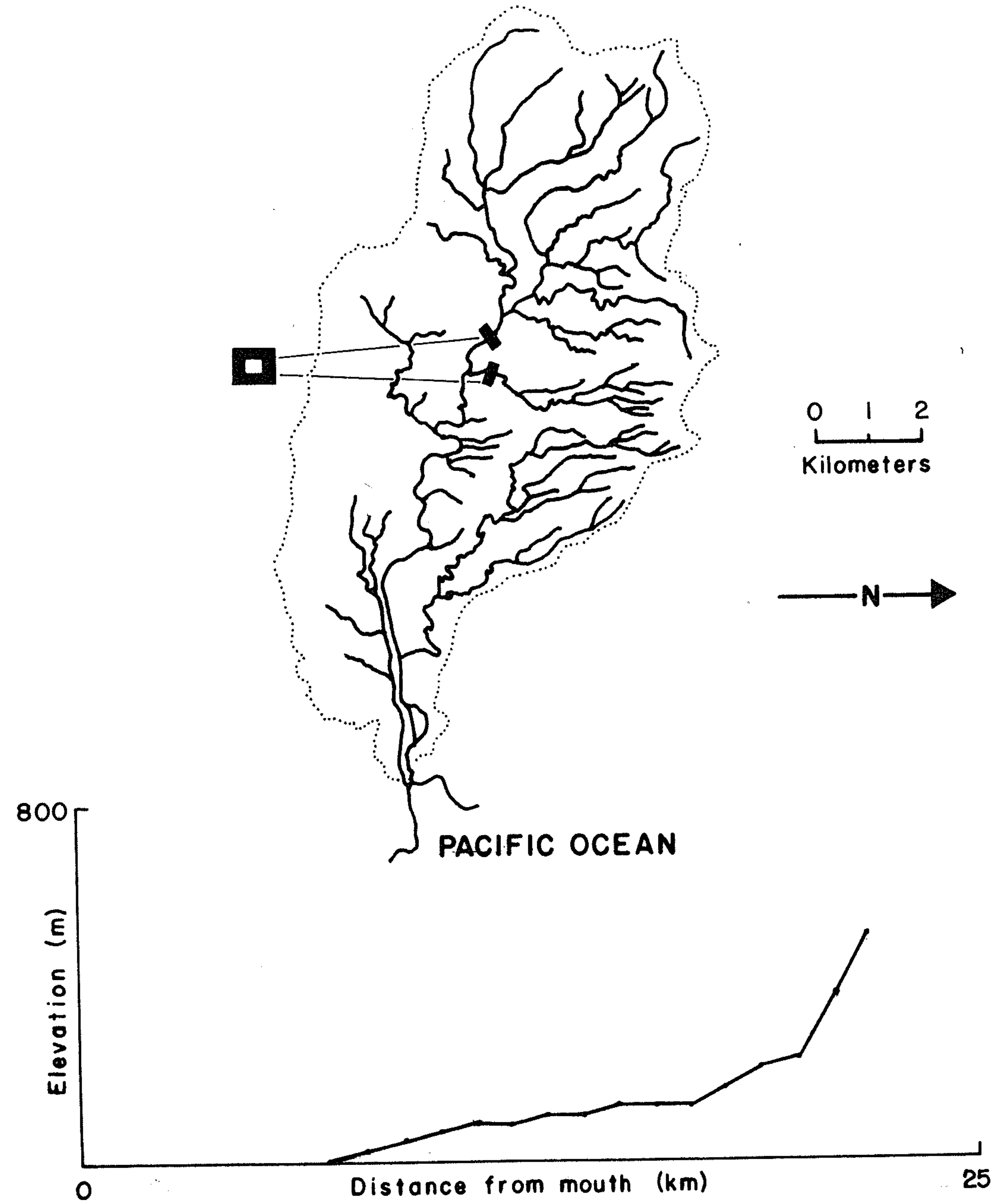

Figure B55. Huleia Stream, Kauai: <1% of channel length altered. Longitudinal gradient (m/km) = 23.

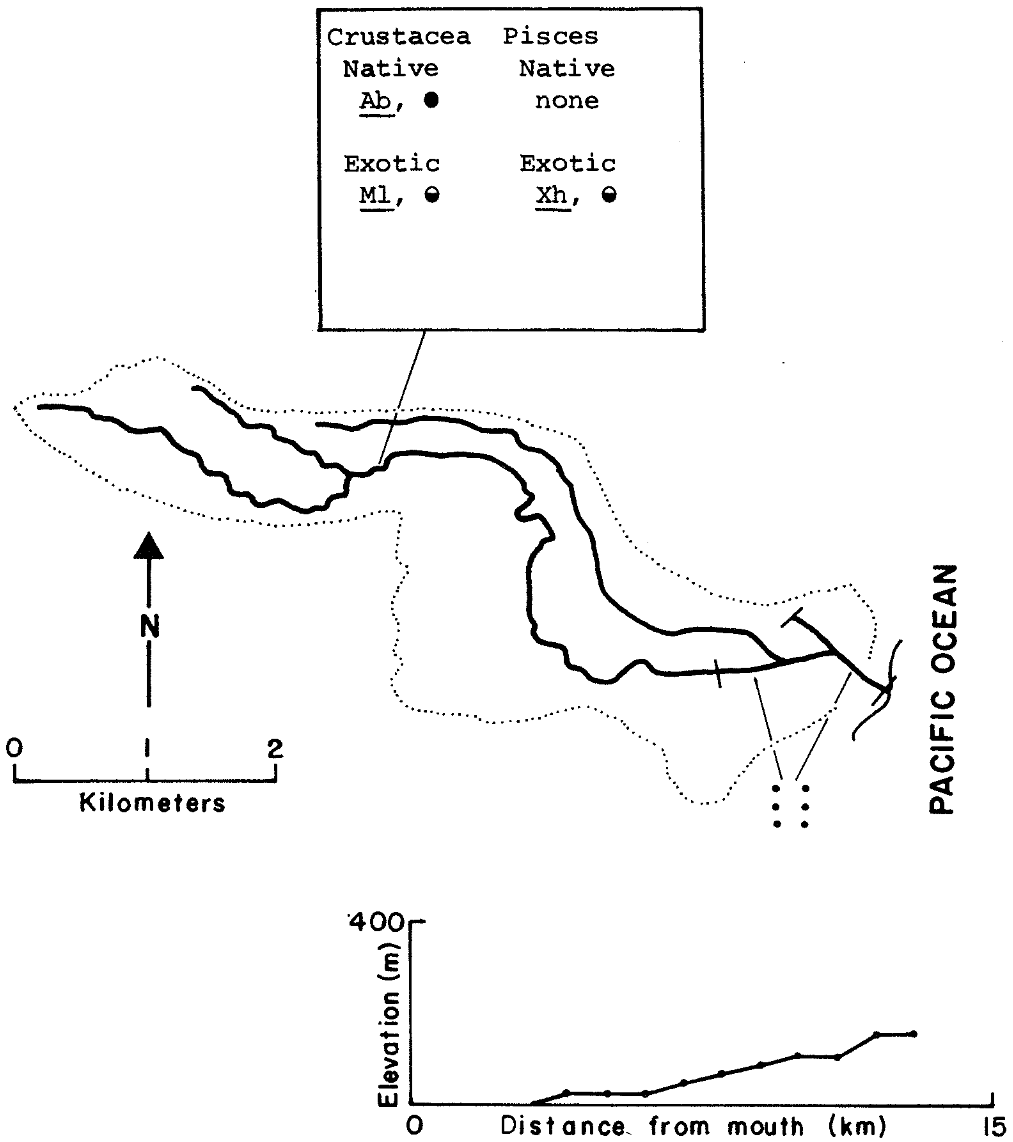

Figure B56. Konohiki Stream, Kauai: 13% of channel length altered. Longitudinal gradient (m/km) = 12.

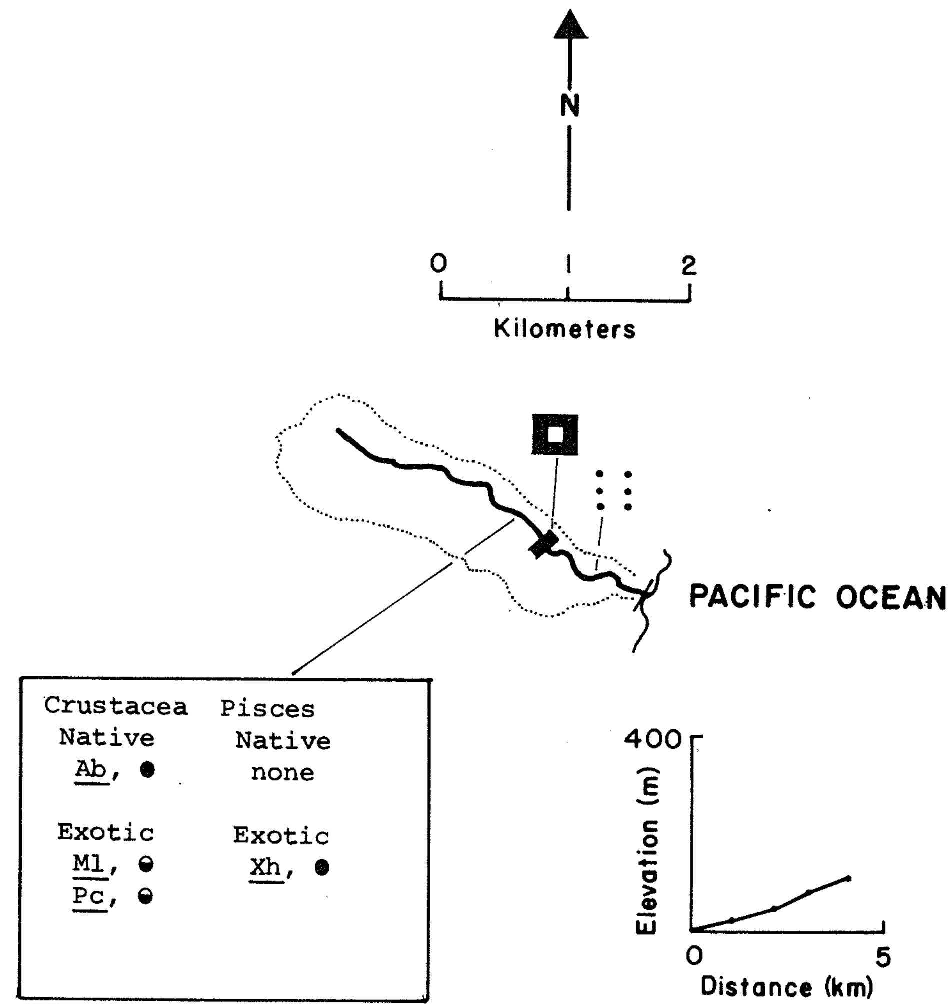

Figure B57. Kumukumu Stream, Kauai: 20% of channel length altered. Longitudinal gradient (m/km) = 27.

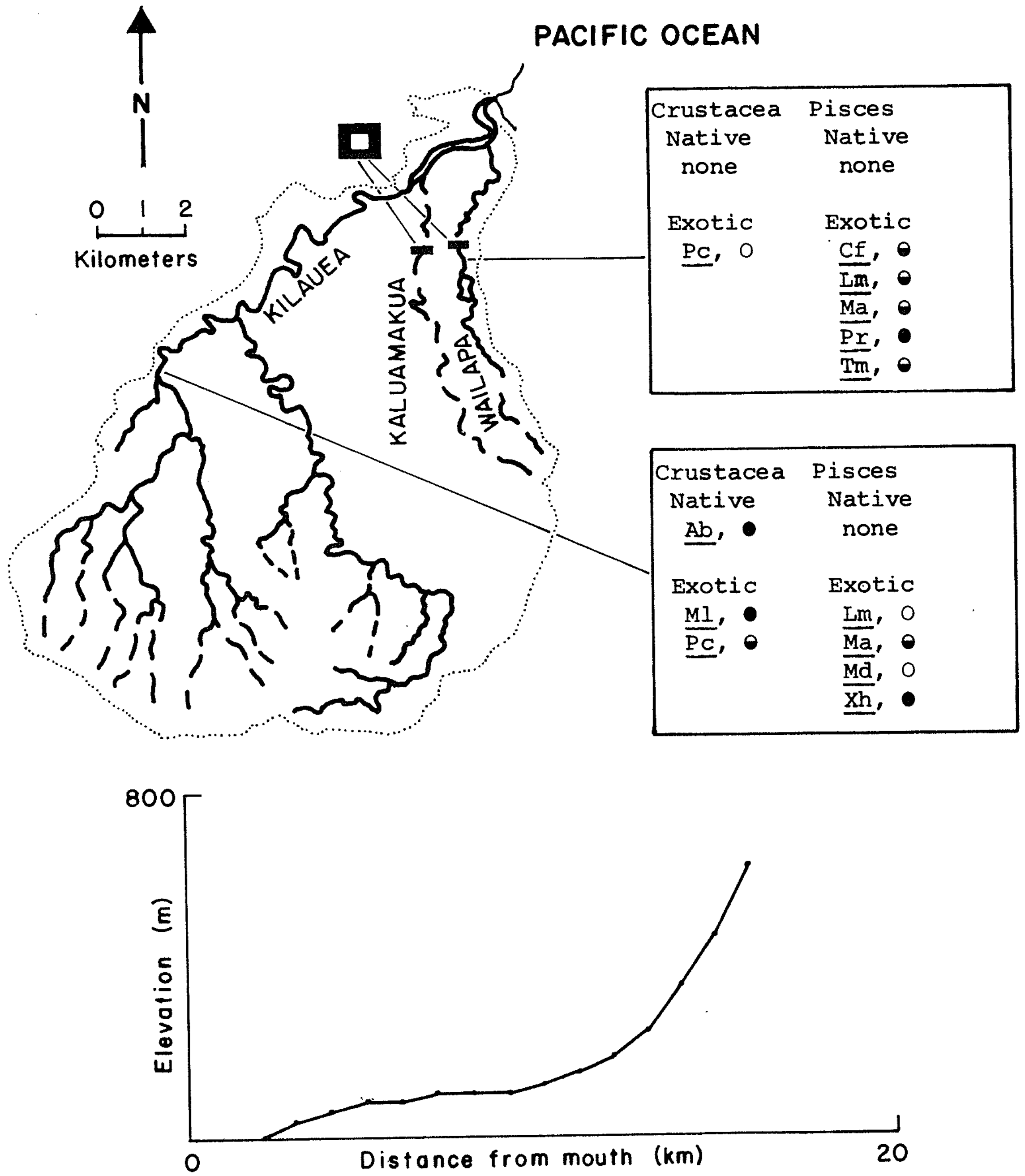

Figure B58. Kilauea Stream, Kauai: <1% of channel length altered. Longitudinal gradient (m/km) = 39.

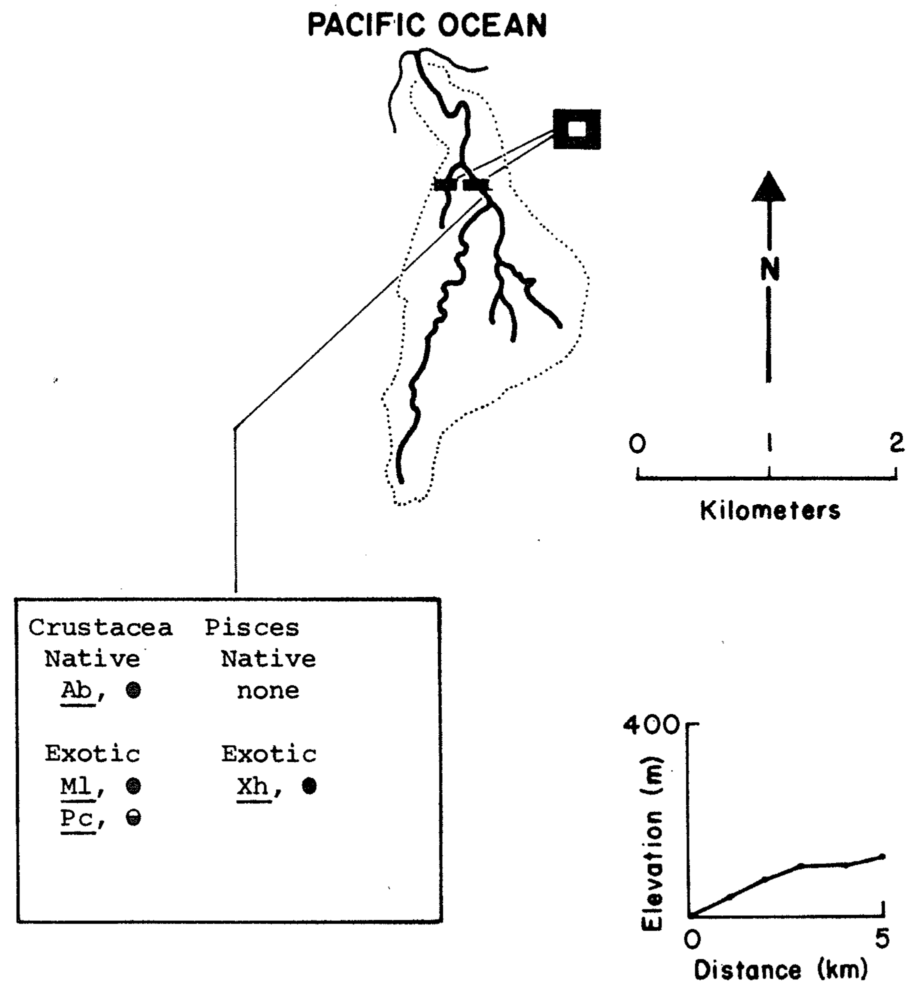

Figure B59. Puukumu Stream, Kauai: <1% of channel length altered. Longitudinal gradient (m/km) = 24.

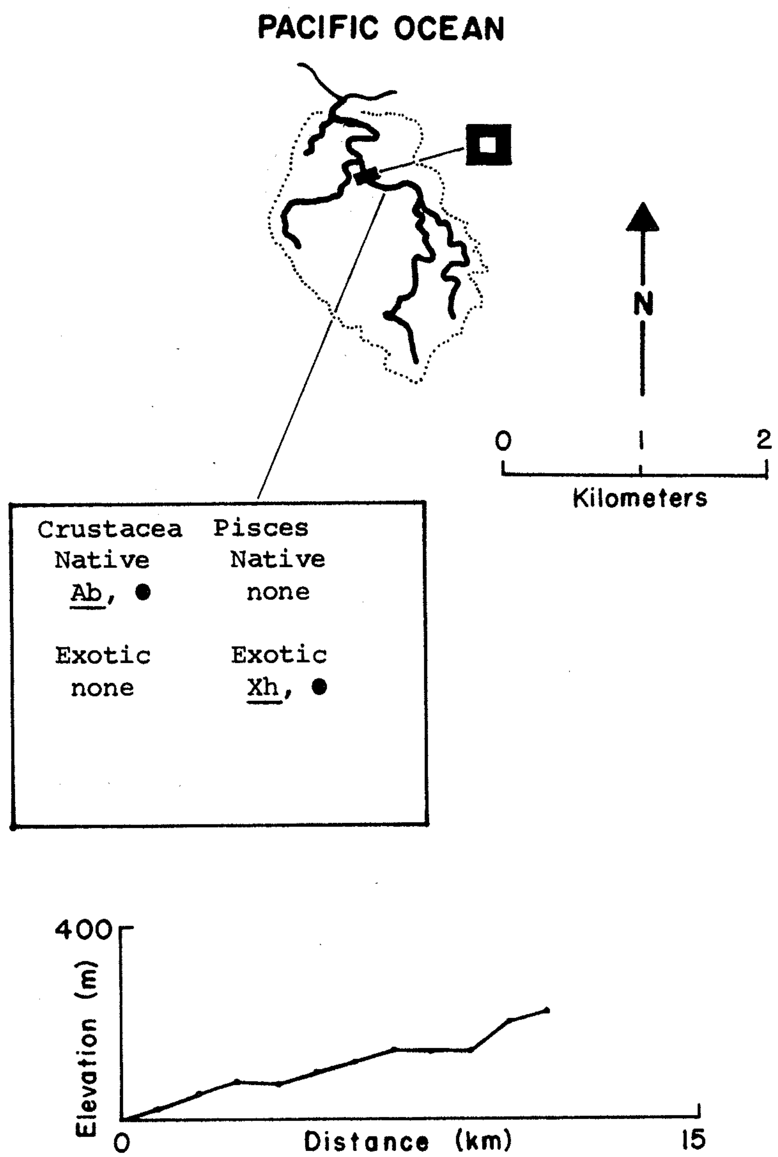

Figure B60. Anini Stream, Kauai: <1% of channel length altered. Longitudinal gradient (m/km) = 21.

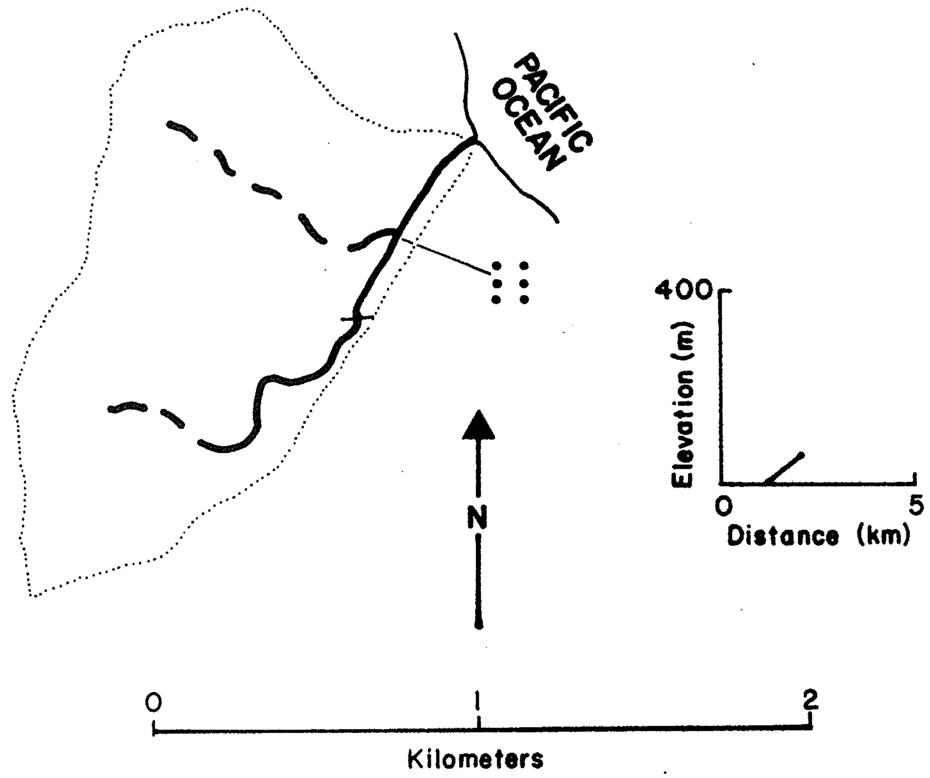

Figure B61. Waikoko Stream, Kauai: **30% of channel length altered. Longitudinal gradient (m/km) = 29.**

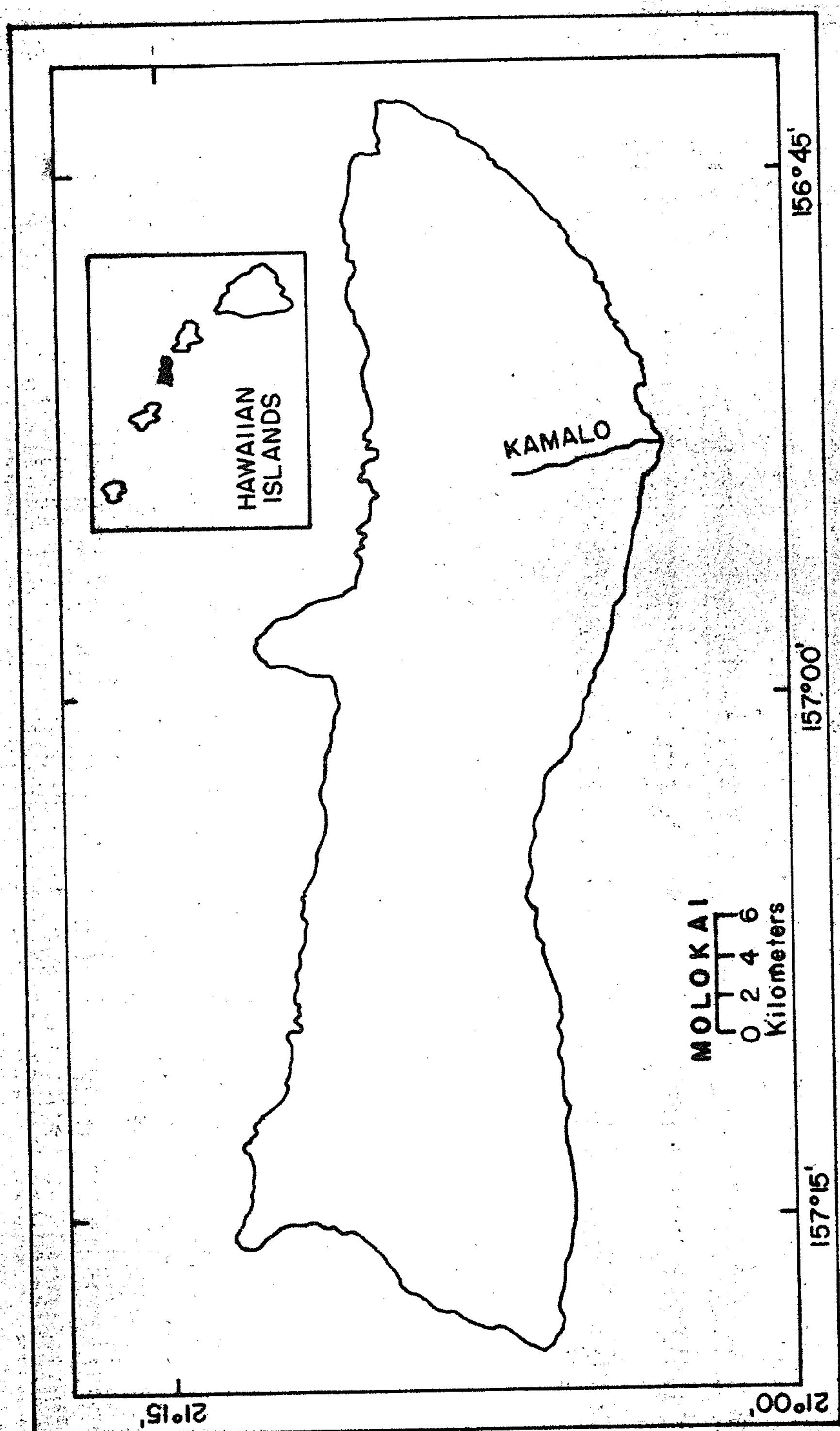

Figure B62. Locator map for Kamalo Stream, the only stream with an altered channel on Molokai.

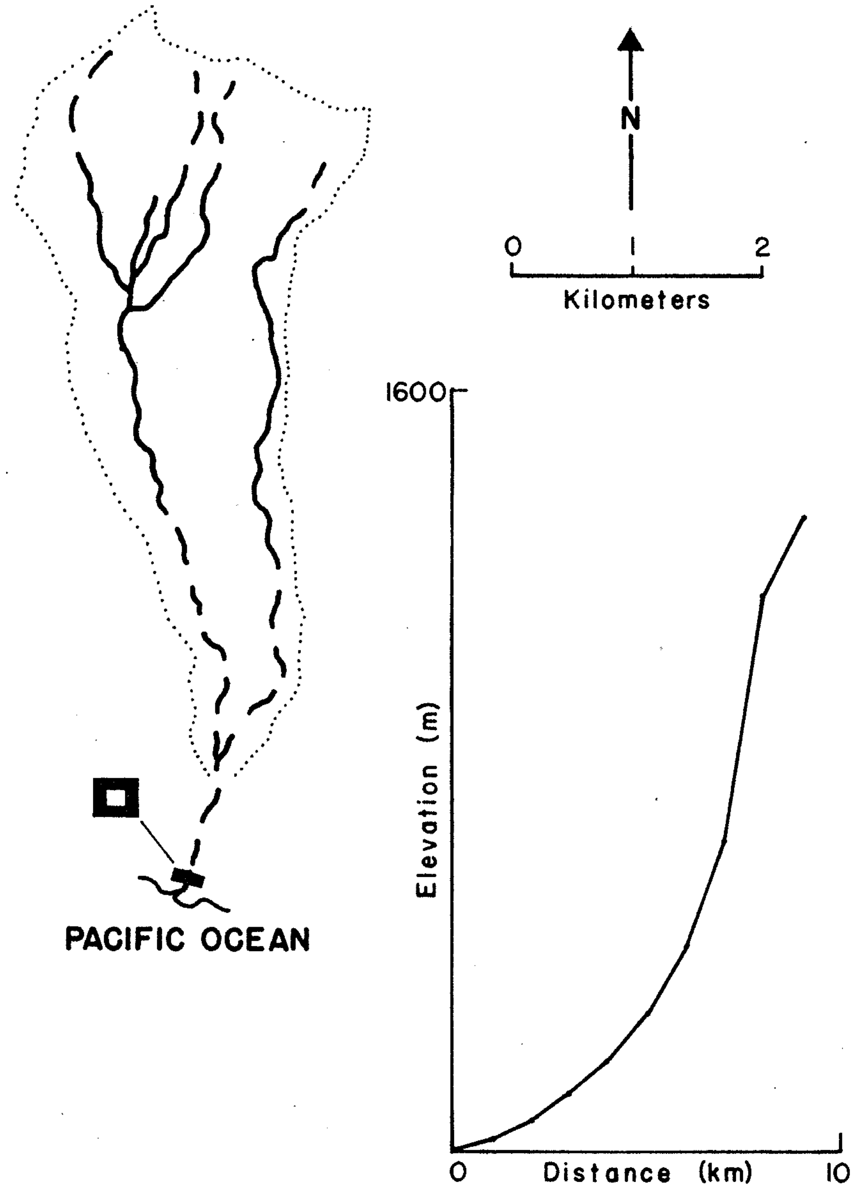

Figure B63. Kamalo Stream, Molokai: <1% of channel length altered. Longitudinal gradient (m/km) = 146.

Appendix C. Discharges of Altered Streams for which Discharge Data are Available (USGS 1977). See Figures C1-C4 for Gaging Station Locations. Legend: D = Diversion(s) Present above Gaging Station; E = Estimated; -- = No Data. Dates Indicated under Comments Column are Dates for Maximum Flow; Elevations when Indicated Refer to Gage Elevations

Island Stream	Discharge (m^3/s) Annual Mean	Instantaneous Maximum	Instantaneous Minimum	USGS Gage No.	Comments
Hawaii					
Wailoa River	0.337	16.0	0	7000	Waiakea Trib. 46-yr av., 589 m elev.
Maui					
Honokowai	--	10.818	--	6302	03/04/76, D
Kahoma	0.106	70.5	0	6385	13-yr av., D, 27 m elev.
Kauaula	--	0.283E	0	6433	03/04/76, D
Waikapu	--	8.581	--	6505	03/04/76, D
Iao	--	67.685	--	6070	03/04/76, D
Oahu					
Kaupuni	--	48.994	--	2118	02/07/76
Mailiili	--	37.949	--	2122	02/07/76

Continued

Appendix C (Continued)

Island Stream	Discharge (m^3/s) Annual Mean	Instantaneous Maximum	Instantaneous Minimum	USGS Gage No.	Comments
Waikele	1.110	385.0	0.001	2130	24-yr av., D, 0.418 m elev.
Waiawa	0.935	663.0	0.048	2160	24-yr av., D, 0.552 m elev.
Waimalu	--	43.046	--	2230	11/26/75
Kalauao	0.083	73.1	0	2245	19-yr av.
Halawa	0.143	188.0	0	2260	North Halawa 26-yr av., 98 m elev.
Moanalua	0.90	130.0	0	2280	50-yr av., 103 m elev.
Kalihi	0.329	201.0	0.005	2293	14-yr av., 21 m elev.
Nuuanu	0.203	198.0	0.003	2320	60-yr av., D, 193 m elev.
Manoa	--	77.880	--	2471	11/26/75, D, 2.2 m elev.
(Waihi)	0.103	92.0	0.002	2385	01/16/21, 58-yr av., 89 m elev.
(Waiakeakua)	0.144	87.5	0.017	2405	01/16/21, 58-yr av., D, 90 m elev.
(Palolo)	0.160	121.0	0.001	2470	12/18/67, 24-yr av., D, 29 m elev.

Continued

Appendix C (Continued)

Island Stream	Discharge (m^3/s) Annual Mean	Instantaneous Maximum	Instantaneous Minimum	USGS Gage No.	Comments
Wailupe	--	10.478E	--	2475	11/26/75
Kuliouou	--	6.117	--	2479	11/26/75
Waimanalo	--	21.240	--	2490	11/26/75
Maunawili	--	33.984	--	2605	11/27/75
Kaneohe	0.442	340.0	0.096	2739	14-yr av., 12 m elev.
Keaahala	--	11.910E	--	2744.99	11/25/75
Heeia	--	33.701	--	2795	11/25/75
Kahaluu	0.055	7.90	0.031	2840	South Fork Waihee Trib., 14-yr av., 188 m elev.
Malaekahana	--	8.496E	--	3105.01	11/25/75
Oio	--	5.947E	--	3110	02/07/76
Kauai					
Waimea (Waimea Mainstr.)	3.795	1,050	ca. 0 Due to upstream diversions	310	35-yr av., D, 6 m elev.

Continued

Appendix C (Concluded)

Island Stream	Discharge (m^3/s) Annual Mean	Instantaneous Maximum	Instantaneous Minimum		Comments
(Makaweli Trib.)	2.552	736	0.089	360	33-yr av., D, 6 m elev.
Hanapepe	2.481	1,100	0.14	490	52-yr av., D, 68 m elev.
Lawai	--	11.328E	--	525	04/03/77
Huleia	--	39.984E	--	550	03/19/77
Konohiki	--	1.274	--	735	11/26/77
Kilauea	0.320	58.6	0.051	975	Halaulani Trib. 18-yr av., 119 m elev.
Puukumu	--	2.917	--	979	07/20/76

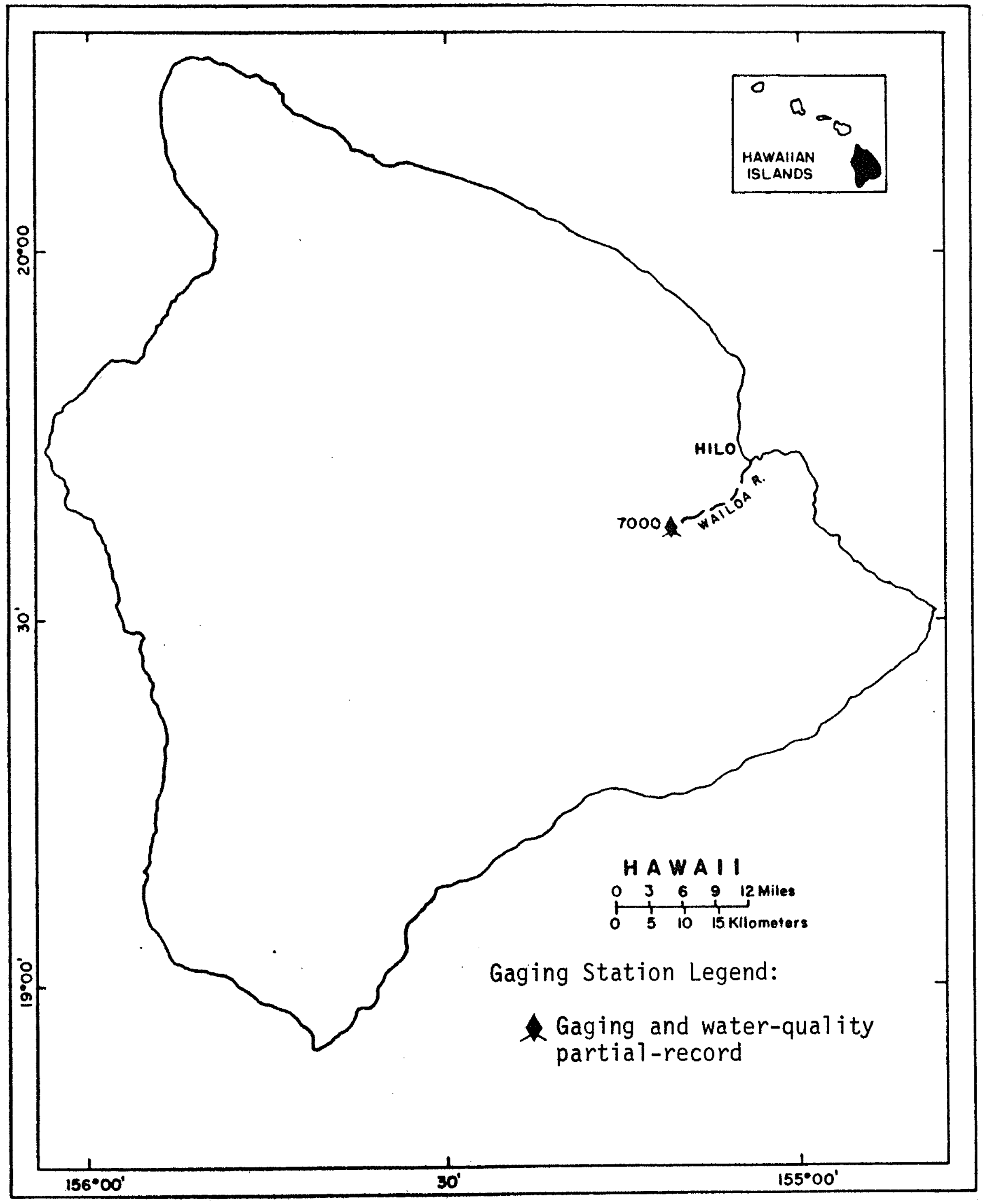

Figure C1. **Location of gaging station** on Wailoa River. From USGS (1977).

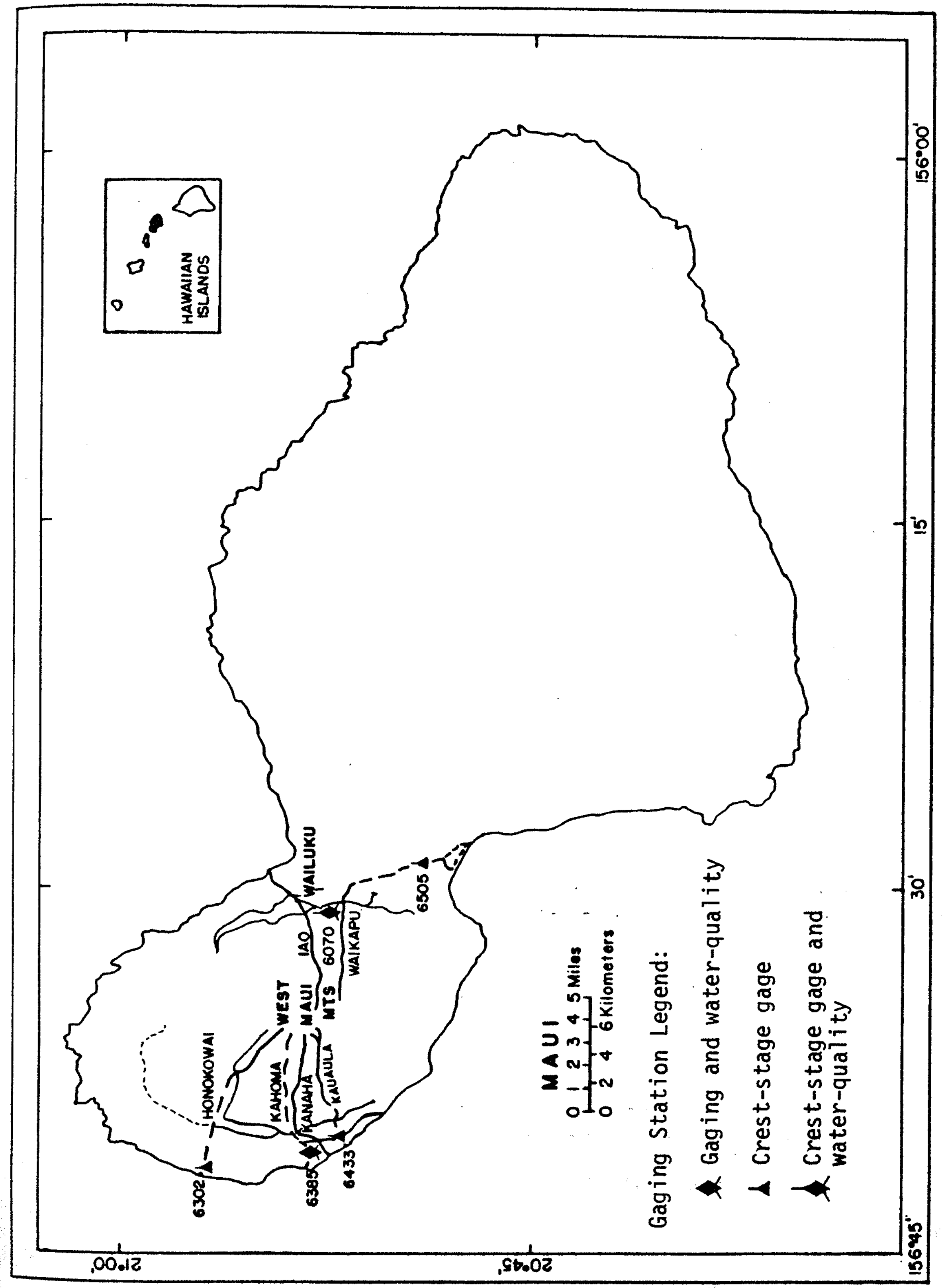

Figure C2. Locations of gaging stations in five of seven altered streams on Maui. From USGS (1977).

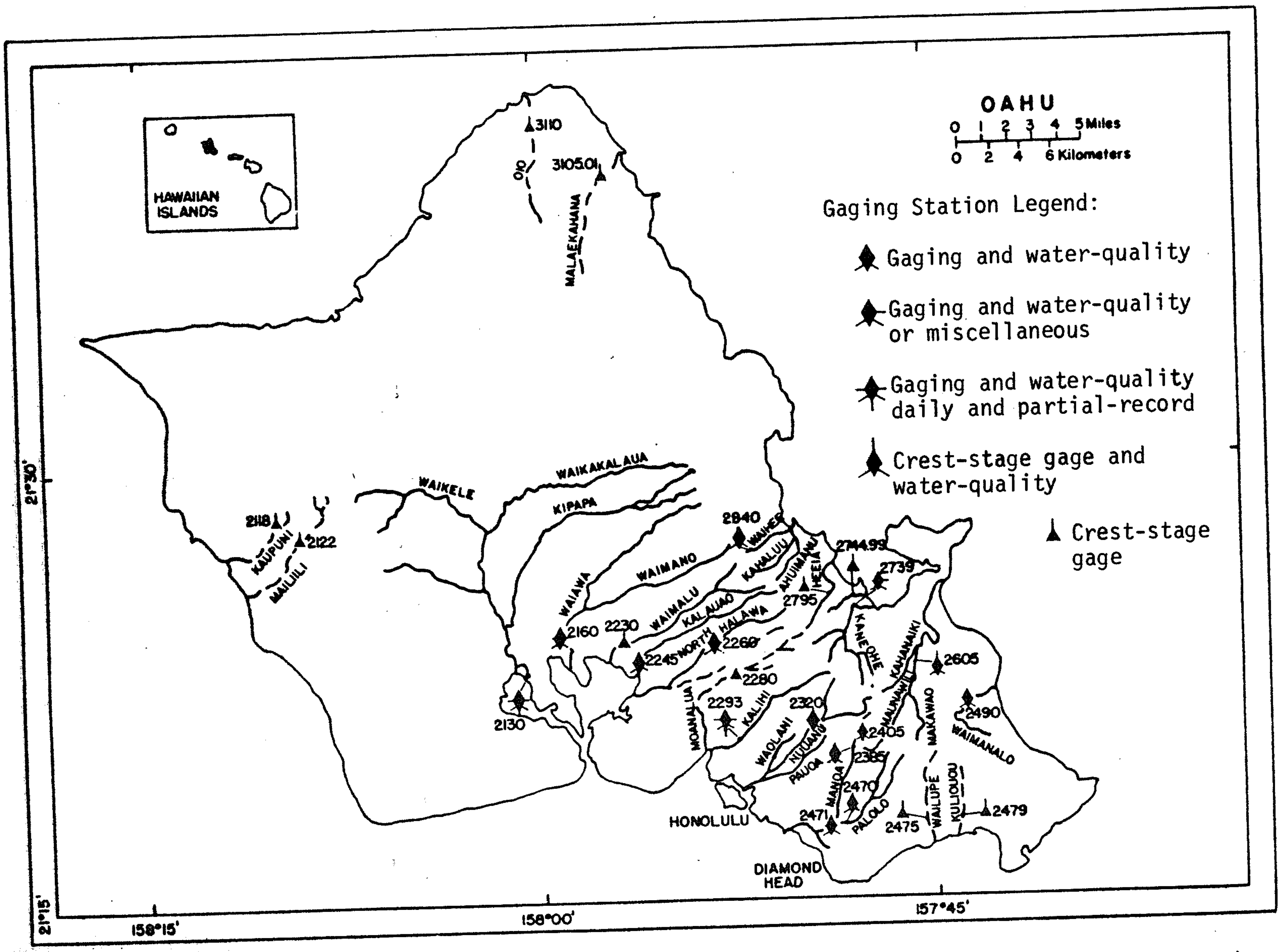

Figure C3. Locations of gaging stations in 21 of 31 altered streams on Oahu. From USGS (1977).

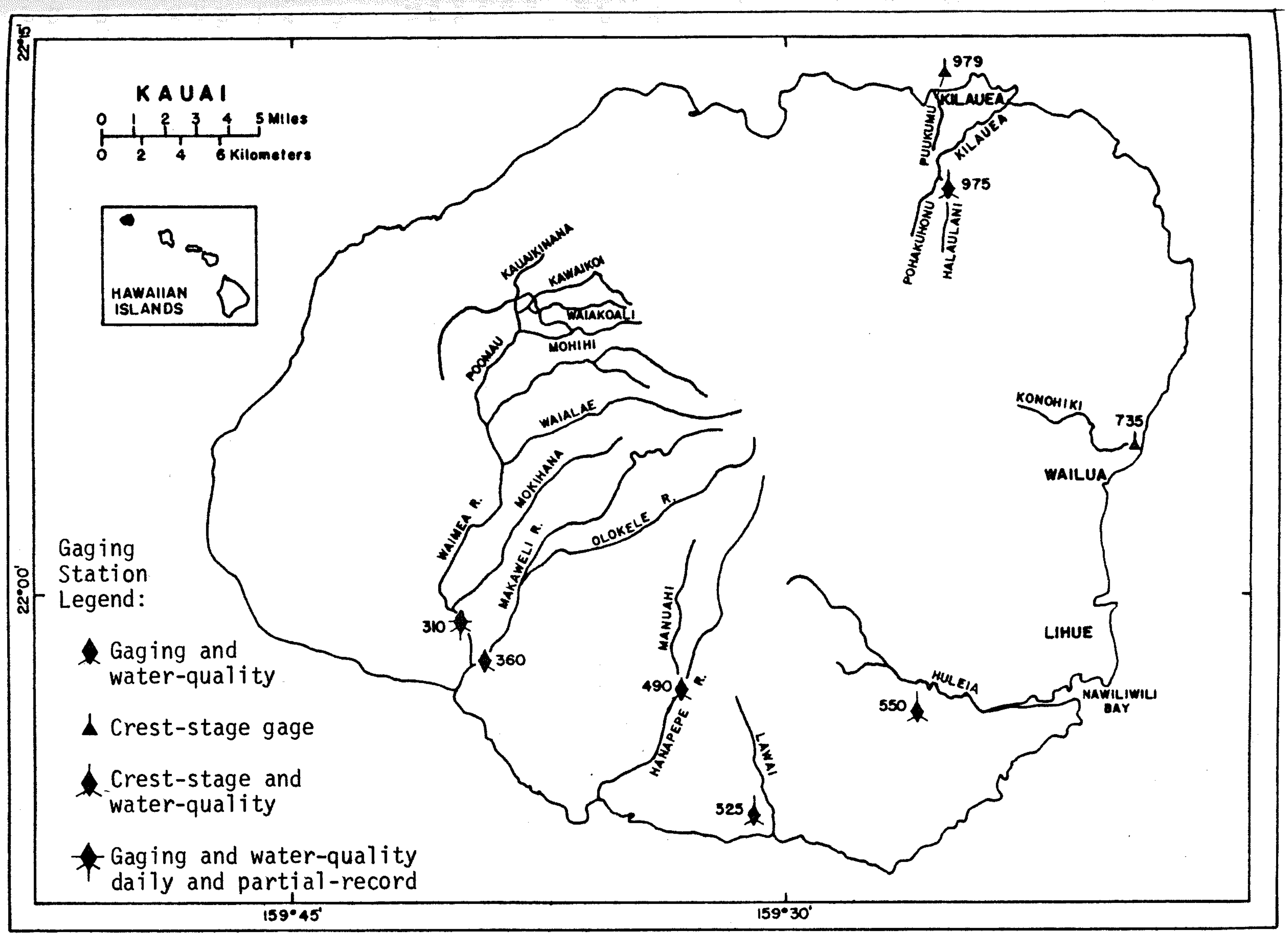

Figure C4. Locations of gaging stations in seven of 12 altered streams on Kauai. From USGS (1977).

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16. Abstract (Limit: 200 words)
A state wide, exhaustive inventory of perennial streams with channel modifications, including a general survey of habitat factors and macrofauna, showed that there are at least 366 perennial streams in the five largest islands of Hawaii. Fifteen percent of these streams have been altered. Six types of channel alteration have been identified: lined channel, channel realignment and riparian clearing, elevated culvert, revetment, filled-in channel, and extended culvert. A total length of 151 km of these modifications has been identified. The comparative "abundances" of these are: lined channel, 40%; realigned/cleared, 28%; revetment, 24%; filled-in channel, 5%; elevated culvert, 3%; and extended culvert, 1%. Eighty-nine percent of the total length of lined channel is located on Oahu. On the basis of other human disturbances, only 14% of Hawaiian streams may be physically pristine, and none of these physically pristine streams is on Oahu, the most populous island in the State. There are apparently no longer any biologically pristine streams, since at least one exotic species was found in all streams sampled. Only 27% are of high ecological quality (pristine-preservation use), and none of these high ecological quality streams is on Oahu. Water is exported from 53% of all perennial Hawaiian Streams. Twenty-five species of fish and decapod crustaceans were collected statewide. Only eight of the species are native to the State. Both in numbers and biomass, native species are dominant in most unaltered streams whereas exotic species are dominant in altered streams.

17. Document Analysis a. Descriptors
Streams, Profile, Attitude, Aquatic Animals, Biomass, Channeling, Channel improvement, Distribution, Diversion, Ecology, Surveys, Crustaceans, Habitats, Hawaii, Perennial streams, Geomorphology, Retaining walls, Riparian land, Riparian plants, Land clearing, Consumptive use, Degradation (stream), Water quality, Water temperature.

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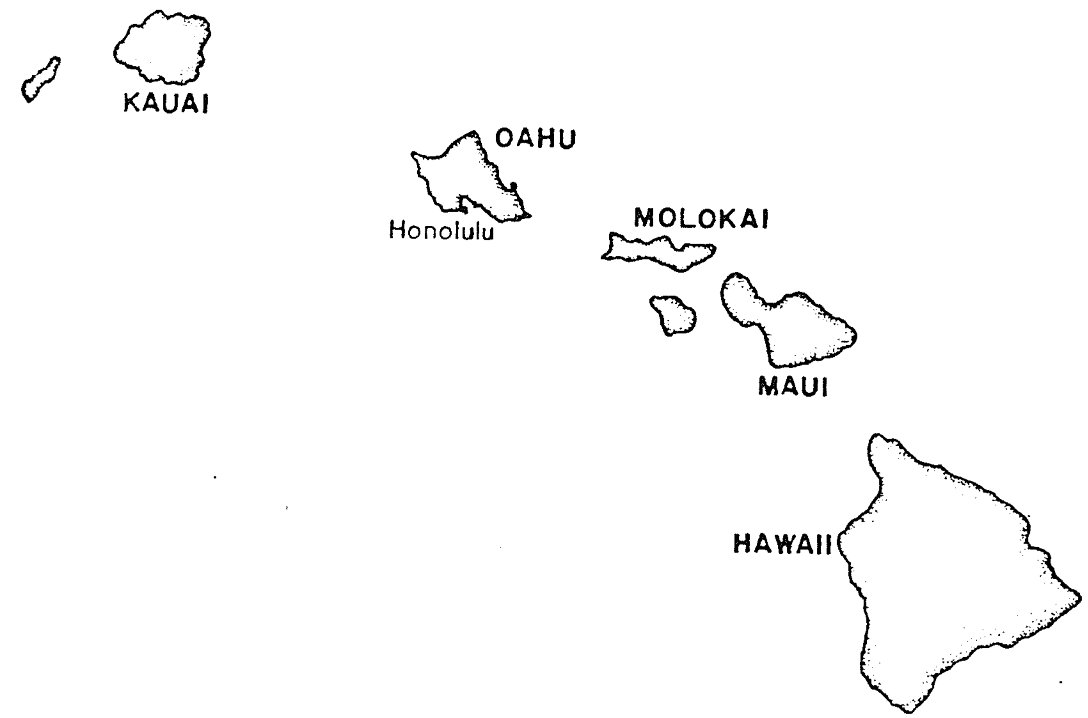
Part B: Effect of Channelization on the Distribution and Abundance of Fauna in Selected Streams



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To gather, analyze, and present information that will aid decision-makers in the identification and resolution of problems associated with major changes in land and water use.

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STREAM CHANNEL MODIFICATION IN HAWAII
PART B: EFFECT OF CHANNELIZATION ON THE DISTRIBUTION AND ABUNDANCE OF FAUNA IN SELECTED STREAMS

by

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Project Officer

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Performed for:
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PREFACE

This is the second of a four-part report on Stream Channel Modification (Channelization) in Hawaii and Its Environmental Effects on Native Fauna. This part deals with the effects of channelization on the distribution and abundance of fauna in Oahu streams. It is published by the National Stream Alteration Team to provide the much-needed baselines for evaluating future stream alteration proposals as well as ecological information applicable to the protection and preservation of native Hawaiian stream fauna. This report covers measurement of some environmental factors and evaluation of aquatic community structure on selected altered and unaltered streams. The objective is to provide concise information on the nature and magnitude of channel alteration effects on stream species and communities.

An earlier report (Part A: FWS/OBS-78/16 March 1978) is an inventory of Hawaiian perennial streams and stream macrofauna. Forthcoming is Part C (FWS/OBS-78/18) dealing with tolerance of native stream macrofauna to environmental stress. Part D (FWS/OBS-78/19) summarizes the series.

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EXECUTIVE SUMMARY

In an effort to assess the effects of channelization on the native fauna of Hawaiian streams, macrofaunal communities were analyzed and compared in channelized and unchannelized streams. Kaneohe and Manoa Streams, in which several types of channel alterations are found, were chosen as representative of altered Hawaiian streams. Waiahole Stream, which has no channel alteration, was selected as representative of unaltered Hawaiian streams.

Three physicochemical features were measured to obtain a general idea of habitat factors in altered and unaltered streams. The aquatic community structure was evaluated for each stream, and interstream comparisons were made. Full-scale monitoring was done for 20 months (February 1976 through September 1977).

The altered study streams were found to have higher mean physicochemical values (water temperature, pH, conductivity) coupled with wider ranges than the unaltered study stream. Channel sections with artificial (concrete) bottom exhibited higher values compared with natural bottom channels.

Exotic fishes were predominant in altered streams while both exotic fishes and native crustaceans were predominant in the unaltered stream. Native fishes appeared to be especially reduced in heavily channelized streams. Altered channels with artificial bottom appeared to serve as nurseries for the exotic poeciliids, Poecilia mexicana and P. reticulata. Species diversity was lower in these artificial bottom channels.

The study results suggest that the delicate ecology of the diadromous native fauna is especially vulnerable to stresses resulting from extreme channelization. There are strong indications that channel alterations, particularly artificially lined channels, are favoring the replacement of native species by valueless exotics. These findings suggest that in Hawaii channelization should be avoided where at all possible. Where it is unavoidable, the use of channels with natural bottom appears to be much less damaging. Any artificial bottom channel should avoid a wide, flat bottom, e.g., by providing a narrower notch in the bottom for a deeper, more natural flow. Detrimental effects of riparian clearing have been demonstrated, and preservation or replanting of stream bank vegetation is an important management tool. Locations of collections of migratory animals lead to a tentative recommendation that where artificially lined channel bottom must be used, not more than 1.5 km be installed as a continuous length. Common features shared with all high islands of the Pacific suggest that these results may be broadly applicable in the region.

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ABBREVIATIONS

cm	centimeters	Ma	Maui Island
cm^2	square centimeters	Mo	Molokai Island
g	grams	m^3/s	cubic meters per second
H	Hawaii Island	No.	number
JTU	Jackson turbidity unit	O	Oahu
K	Kaneohe Stream	% No.	percentage by number
Ka	Kauai Island	% Wt.	percentage by weight
km	kilometers	µmhos	micromhos
km^2	square kilometers	USGS	United States Geological Survey
m	meters	USFWS	United States Fish and Wildlife Service
M	Manoa Stream	W	Waiahole Stream
		wt	weight

SYMBOLS

°C	degrees, Celsius
°N	degrees, North latitude
°W	degrees, West longitude
= = = =	ditch and tunnel
H'	diversity
J'	evenness
Δ	flow gaging station
<	less than
+	plus
⊗	pump
⁚ ⁚	Channel realigned and/or vegetation removed; natural bottom.
⊡	Elevated culvert. Conduit structures that are comparatively short (typically <60 meters), usually found under highways; artificial bottom.
⊔	Lined channel. An artificial channel having both natural banks and stream bed replaced, usually with concrete; artificial bottom.
◺ ◿	Revetment. Stream banks are reinforced but the channel bed is not; natural bottom.

ACKNOWLEDGMENTS

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INTRODUCTION

This study was undertaken to assess the impact of channel alteration on the environmental conditions and macrobiota of Hawaiian streams. Timbol and Maciolek (1978) found that 15% of Hawaii's permanent streams have been channelized. Channel modification is certain to continue as illustrated by the on-going flood control project constructions in Kaneohe Stream on Oahu Island and Iao Stream on Maui Island.

BACKGROUND

The inhabited islands of Hawaii are all high volcanic relicts. Their relative geologic youth is expressed in high, rugged basalt mountains on all the major islands. The islands lie in the prevailing northeast tradewinds. Where their heights intercept the moist air at elevations between a few hundred and about 2,500 meters, the majority of Hawaii's rainfall is generated. The result is very steep rainfall gradients, increasing with elevation, reasonably well watered windward sides of islands, and arid leeward sides. Essentially all streams have high elevation origin, and most flow to windward. Soil profiles are poorly developed over much of the islands and nonexistent at most high elevations. Most soils and basaltic rock are very porous. Streams are often discontinuous, disappearing at some point in their courses, sometimes emerging again at lower elevations. Only four natural basins in the State have the combination of adequate size, basin sealing, and freshwater supply to form natural freshwater lakes. All natural lakes are small and remotely located and of no value for human water supply. Poor natural basin sealing limits the utility of artificial impoundments. Many streams are temporally intermittent, and the flow of perennial streams varies radically with the immediate rainfall history; maximum discharge is often more than a hundred times mean discharge.

Despite these hydrologic characteristics, extensive irrigation-based plantation agriculture and urbanization have developed in varying degrees on all major high islands. Agricultural, municipal, domestic, and sometimes industrial demands led to diversion of large quantities of stream flow through elaborate systems of pipes, ditches, flumes, and tunnels. Export outside the watershed is common, often despite formidable natural barriers. Encroachment of urban development into floodplains has produced the usual rapid proliferation of channel modifications in the name of flood and erosion control. Channelization has been particularly rapid and severe because of the extremely rapid population growth in the last few decades and the highly volatile nature of Hawaiian streams.

Hawaii's 366 perennial streams (Timbol and Maciolek 1978) have an estimated 12,500 km of perennial stream channel. These streams represent the State's principal natural freshwater environment and habitat for both native and introduced animals (Brock 1960, Kanayama 1968, Maciolek In press). Additional information on Hawaiian freshwater ecosystems is available in the Hawaii State Department of Health 208 Technical Committee Report (1977).

HAWAIIAN STREAM MACROFAUNA

Hawaii has both native and introduced species, with the exotics far outnumbering the natives (see Table 5). The native species are mostly endemic and have a diadromous life cycle, i.e., they reside in streams but their larvae must reach the ocean to develop and re-enter streams as post-larvae. They are therefore more susceptible to channel alteration (channelization) since they need suitable habitat throughout the length of the stream. Some of these native species support ethnic fisheries. The goby, Awaous stamineus (o'opu nakea), the mountain shrimp, Atya bisulcata (opae kalaole, the native prawn, Macrobrachium grandimanus (opae oehaa), and the neritid mollusk, Neritina granosa (hihiwai), are harvested for food. Among the introduced species, the Tahitian prawn, Macrobrachium lar, also provides food, and the smallmouth bass, Micropterus dolomieui, is sought after by sports fishermen. Titcomb (1972) provides additional information on the economic uses of fish in Hawaii's past, and Maciolek (in press) should be consulted for a current description of stream fauna.

CHANNEL ALTERATION

Timbol and Maciolek (1978) found 151 km of altered channels, 134 km (89%) of which were on Oahu Island, the most populous in the State. Six types of alterations were recognized (Table 1 and page viii). Lined channels (type 1), in which the entire wetted channel substrate was artificial construction material, usually concrete, comprised 57+ km. Such an artificial hard stream bottom represents a radical alteration to the natural environment. Type 6 (extended culvert) differed from type 1 only in that the conduit was completely buried below grade. It was much less common and thus less available for meaningful analysis of its effects. Because of their much shorter lengths, the net effect of the artificial channel of elevated culverts (type 3) must be much less than that of open lined channels.

Five of the six types of altered channels can be classified into two groups on the basis of having artificially lined bottom or natural bottom. The former group includes modifications 1, 3, and 6 and comprises 60+ km (or 40%) of the 151 km total altered channels in the State. The second group is composed of modification types 2 and 4 with a total length of 79 km, or 52% statewide. The concrete lined channel is the single most common type of alteration - almost 40% of all the modified length (89% of this occurring on Oahu). All preliminary evidence suggested that major environmental effects on stream communities might be expected from extended lengths of lined channel. Preliminary results obtained by Timbol and Maciolek (1978) showed

Table 1. Statewide Inventory of Stream Channel Alterations by Island[a]

Island	Length of Altered Channel by Type[b] (km)						Total Length of Altered Channel (km)
	1	2	3	4	5	6	
Oahu	57+	36+	1+	31	8	<1	134+
Kauai	0	4	1	3	0	0	8
Maui	<1	2+	<1	2	0	0	5
Hawaii	2	1	<1	<1	0	0	4
Molokai	0	0	<1	0	0	0	<1
Total	60+	43+	4+	36+	8	<1	151
% of Total	40	28	<3	24	5	<1	100%

[a]Adapted from Timbol and Maciolek (1978).

[b]Alteration types:

1 = lined channel
2 = cleared/realigned
3 = elevated culvert
4 = revetment
5 = filled-in
6 = extended culvert

that an average of more than 7° C could be attributed to the warming effect of a lined channel, 4° C for a revetment, and 2° C for a cleared/realigned channel. In terms of extent of modification (both by total channel length and warming effect), concrete lined channels were found to be the most important type of alteration in Hawaii. Therefore, emphasis in this study was placed on communities in such altered channels and comparison with natural channels.

STREAM SELECTION AND RELEVANCE TO OTHER STREAMS

Because of the locations of channel alterations, and time and cost constraints, detailed long-term community comparisons were made only for streams on Oahu Island. The channelized study streams were to be broadly representative of Hawaiian streams on the bases of average size, moderate degradation resulting from channel alteration, and presence of both native and exotic macrofauna. The unchannelized study stream also, was to be broadly representative of unchannelized Hawaiian streams on the bases of size and fauna.

Early results in the inventory of altered streams showed that Manoa and Kaneohe Streams met the three criteria set for study streams. Kahana Stream was pre-selected as representative of unaltered streams based on existing unpublished information. Unfortunately, access to Kahana became so severely restricted that a substitution was necessary. Waiahole Stream drains the next major valley from Kahana. They are similar in elevation of origin, stream gradient, and many physical aspects of their drainage basins. They have similar low levels of human disturbance. Figure 1 is a locator map for the study streams.

Altered Hawaiian streams ranged from serious physical degradation as in Kapalama Stream on Oahu Island (100% altered) to slightly degraded as in Pukihae Stream on Hawaii Island (<1% altered). Based on physical features alone, altered streams may be divided into three groups: slightly degraded, with <1% of their channel length altered; moderately degraded, 1 to 25% altered; and seriously degraded, more than 25% altered. As can be seen in Table 2, Manoa and Kaneohe Stream are moderately degraded, as are 34 other altered streams in the State.

Like Kahana and most streams on Oahu and statewide, Waiahole has irrigation water removed from its upper drainage basin. Its natural stream channel is intact. It is typical of non-channelized streams on Oahu Island.

Based on Timbol and Maciolek (1978) results, these three streams are regarded as representative of Hawaiian streams, and they were found to have most of the animals considered characteristic of Hawaiian streams (see Table 5).

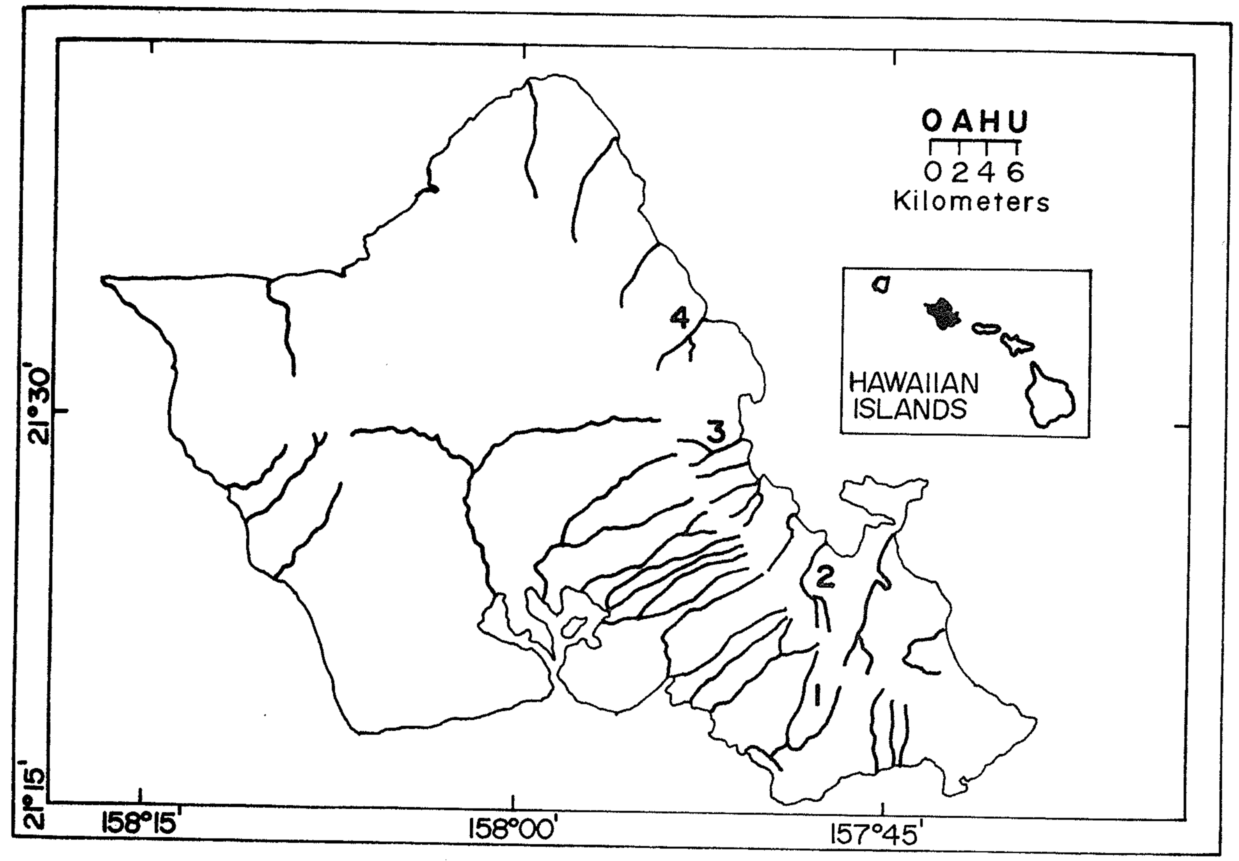

Figure 1. Locations of study streams on Oahu Island - Manoa (1), **Kaneohe** (2), and Waiahole (3). Kahana stream (4) is also shown.

Table 2. Classification of Altered Hawaiian Streams According to Degree of Degradation Stream-Size Rank Based on Total Channel Length. (Adapted from Timbol and Maciolek 1978.)

Slight[a] Stream: Island[d]	Slight[a] Channel Length (km)/ Rank	Moderate[b] Stream: Island[d]	Moderate[b] Channel Length (km)/ Rank	Serious[c] Stream: Island[d]	Serious[c] Channel Length (km)/ Rank
1. Waimea: Ka	373/1	1. Waikele: O	195/2	1. Moanalua: O	44/8
2. Hanapepe: Ka	121/3	2. Waiawa: O	93/5	2. Nuuanu: O	30/14
3. Huleia: Ka	102/4	3. Waimalu: O	46/7	3. Waialaenui: O	14/26
4. Kilauea: Ka	56/6	4. Halawa: O	40/9	4. Makiki: O	10/30
5. Iao: Ma	38/10	5. Kaupuni: O	37/11	5. Kapalama: O	9/31
6. Waipao: Ka	33/13	6. Mailiili: O	34/12	6. Kawa: O	5/34
7. Waikomo: Ka	28/16	7. Manoa[e]: O	34/12	7. Keaahala: O	4/35
8. Waiehu: Ma	23/20	8. Malaekahana: O	30/14	8. Waikoko: Ka	2/37
9. Kamalo: Mo	19/23	9. Maunawili: O	29/15		
10. Pukihae: H	16/25	10. Kaneohe[e]: O	28/16	Total Channel Length	118
11. Anini: Ka	14/26	11. Lawai: Ka	27/17		
		12. Wailoa: H	26/18		
Total Channel Length	823	13. Kahoma: Ma	25/19		
		14. Waikapu: Ma	25/19		
		15. Makaleha: O	23/20		
		16. Kahaluu: O	21/21		
		17. Konohiki: Ka	20/22		
		18. Honokowai: Ma	20/22		
		19. Wahikuli: Ma	19/23		
		20. Kalihi: O	18/24		
		21. Kalauao: O	13/27		
		22. Wailupe: O	13/27		
		23. Waimanalo: O	12/28		

Continued

Table 2. (Concluded)

Slight[a] Stream: Island[d]	Slight[a] Channel Length (km)/ Rank	Moderate[b] Stream: Island[d]	Moderate[b] Channel Length (km)/ Rank	Serious[c] Stream: Island[d]	Serious[c] Channel Length (km)/ Rank
		24. Heeia: O	11/29		
		25. Aiea: O	11/29		
		26. Kaipapau: O	11/29		
		27. Pia: O	11/29		
		28. Kauaula: Ma	10/30		
		29. Oio: O	10/30		
		30. Ulehawa: O	8/32		
		31. Puukumu: Ka	7/33		
		32. Lamimaumau: H	5/34		
		33. Papuaa: H	5/34		
		34. Kuliouou: O	4/35		
		35. Kaalaea: O	4/35		
		36. Kumukumu: Ka	3/36		
		Total Channel Length	928		

[a]Slightly degraded: <1% of total channel length altered.

[b]Moderately degraded: between 1 and 25% of total channel length altered.

[c]Seriously degraded: between 25 and 100% altered.

[d]Symbols used to represent islands are:
H for Hawaii, Ka for Kauai, Ma for Maui, Mo for Molokai, and O for Oahu.

[e]Study streams.

DESCRIPTION OF STUDY AREAS

Fed primarily by orographic rainfall, the study streams originate from the Koolau Range, Manoa draining the leeward, and Kaneohe and Waiahole draining the windward side. The locations are shown in Fig. 1.

Manoa Stream (Fig. 2) is situated in the Honolulu district and is associated with the watershed area known as Manoa Valley. Land use in Manoa Valley reflects a high level of development, with approximately half the total drainage area devoted to urban uses, primarily residential (Chun et al. 1972). Six tributaries contribute to the Manoa Stream discharge, five of which originate from the Koolau Range between Pauoa Flats and Waahila Ridge. The confluence of the mainstream and the sixth tributary (Palolo) occurs at an elevation of about 6 m, 1.7 km above the stream mouth. The stream discharges into the estuarine Ala Wai Canal which empties into Mamala Bay 1.2 km downstream. Approximately 24% of the total 34 km channel length has been altered. Types of modification include the concrete lined channel, realigned channel with vegetation removed, elevated culvert, and revetment (Timbol and Maciolek 1978).

Kaneohe and Waiahole Streams both drain northeasterly to Kaneohe Bay (Fig. 1). However, these two streams are set apart ecologically as a result of land use differences in their respective watershed areas. The Kaneohe Stream drainage basin is located near the southern section of the Kaneohe Bay watershed where considerable urban development has taken place (U.S. Army Corps of Engineers 1975). Kaneohe Stream, as shown in Fig. 3, encompasses four major tributaries. Urbanization in this area has resulted in encroachment of the stream's flood plain (Hawaii Environmental Simulation Laboratory 1974). Current construction of an embankment and concrete spillway structure for a dam will close Kamooalii and Kuou Tributaries to create a 10.5-hectare (26-acre) artificial lake. The completion date for this project is June 1979. Other forms of channel modification in Kaneohe Stream include the concrete lined channel, realigned channel with vegetation removed, and elevated culvert. Nearly 25% of the total 28 km channel length has been modified (Timbol and Maciolek 1978).

In contrast to the Manoa and Kaneohe watershed areas, the Waiahole drainage basin is relatively undeveloped. The basin ranges in elevation from approximately 750 m to sea level, with the limited agricultural and grazing, as well as residential land uses, limited to areas of less than 25 m elevation. There are no commercial or industrial developments in the drainage basin. Waiahole mainstream converges with Uwau tributary at 20 m elevation (Fig. 4). Some water is removed from the drainage basin above both Uwau tributary and Waiahole mainstream.

The gradients of Manoa and Kaneohe Streams are similar and steeper than that of Waiahole Stream. Some other physical features of these drainages are given in Table 3.

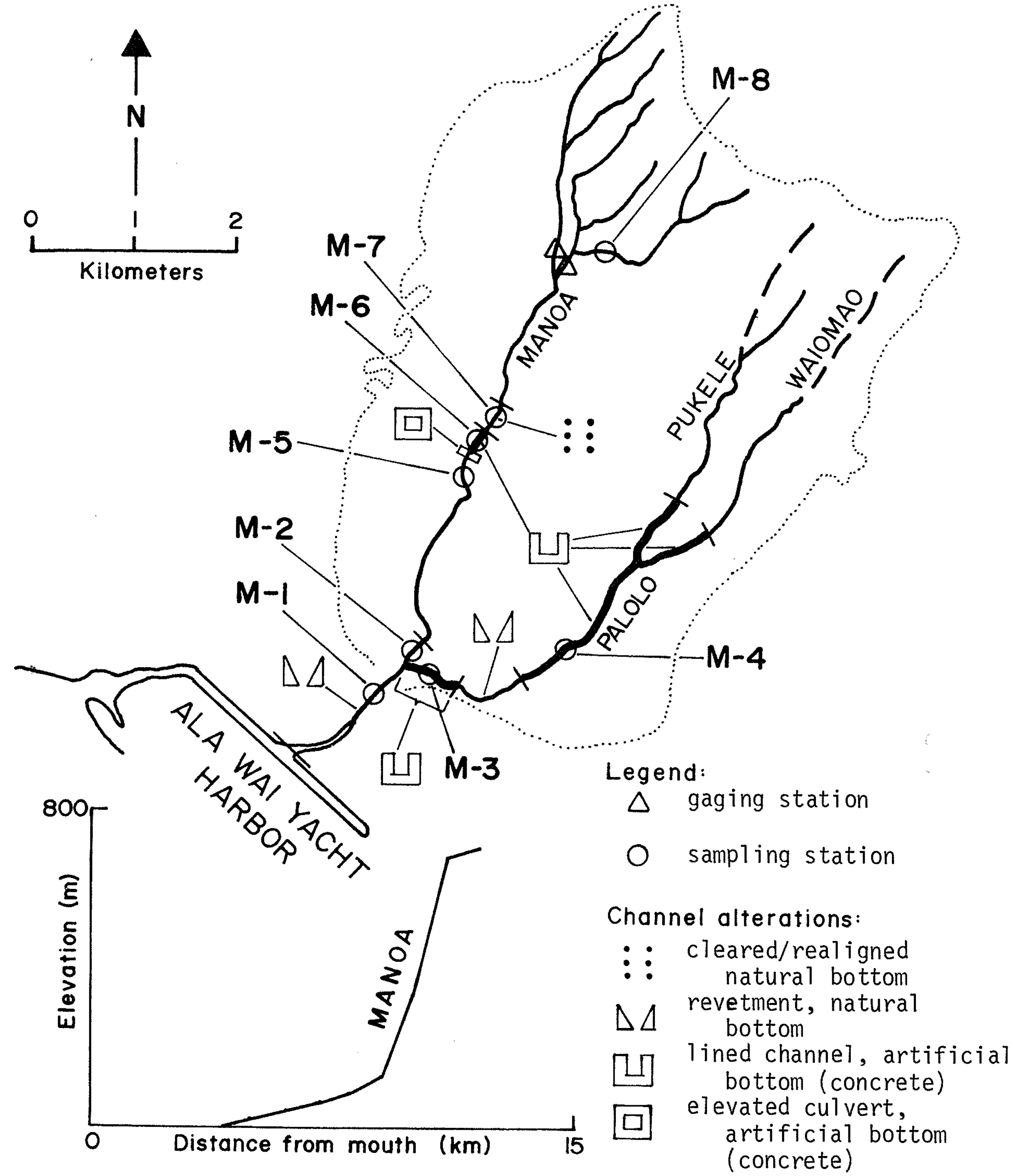

Figure 2. Drainage of Manoa Stream, Oahu, showing locations of sampling stations, flow gaging stations, channelized sections of stream, and watershed limits. Longitudinal gradient of Manoa mainstream (m/km) = 64.

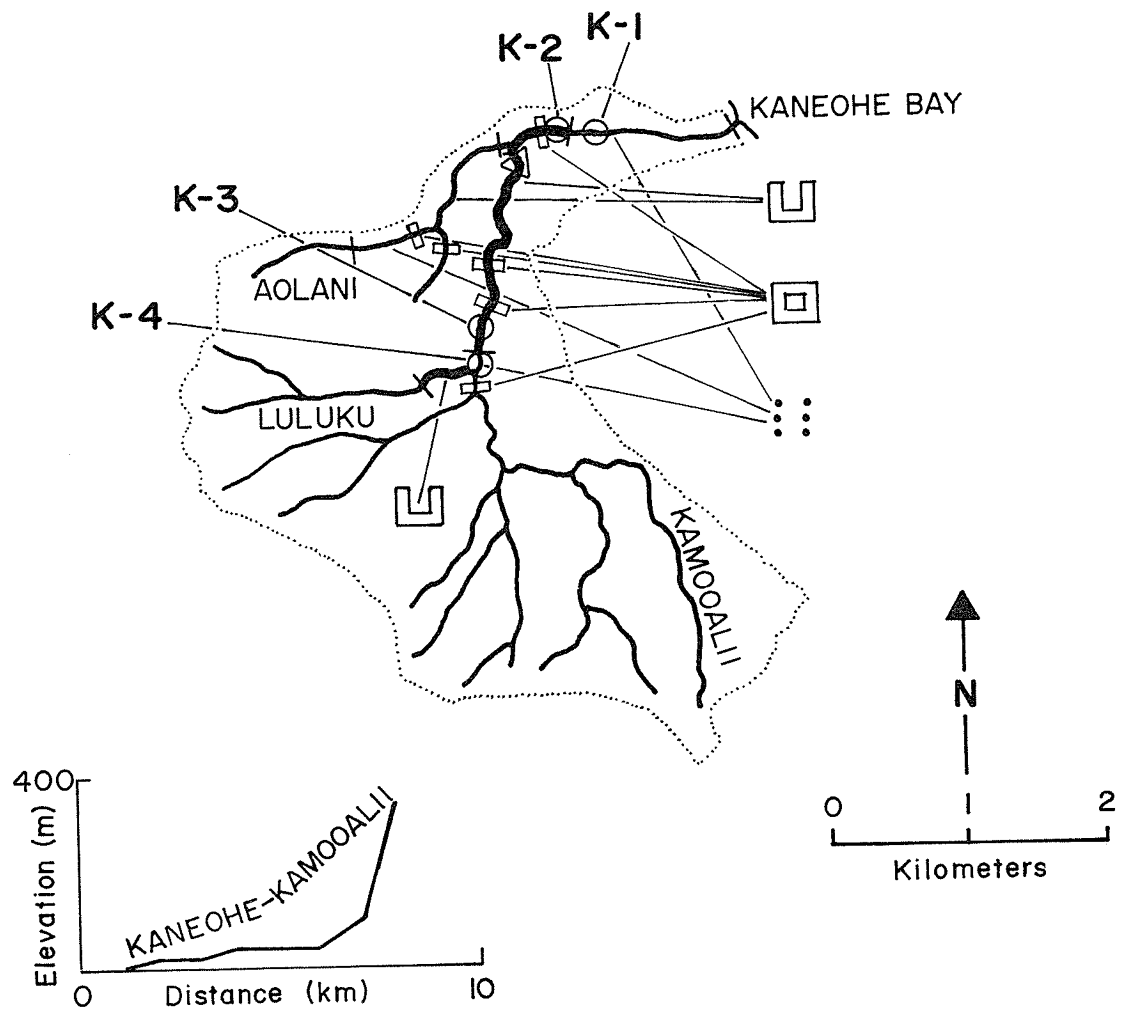

Figure 3. Drainage of Kaneohe Stream, Oahu, showing locations of sampling stations, flow gaging station, channelized sections of stream, and watershed limits. Longitudinal gradient of Kaneohe mainstream (m/km) = 67. Refer to Fig. 2 for symbol definitions.

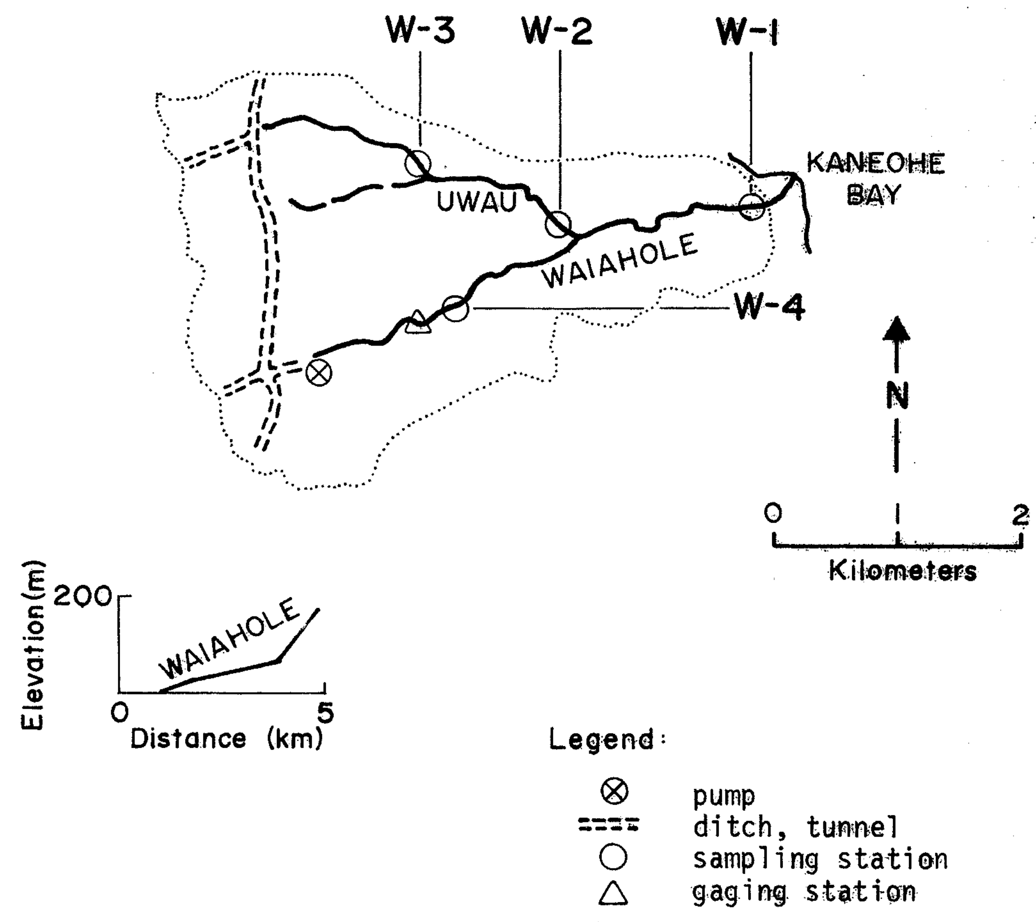

Figure 4. Drainage of Waiahole Stream, Oahu, showing locations of sampling stations, flow gaging station, and watershed limits. Longitudinal gradient of Waiahole mainstream (m/km) = 31. Ditch/tunnel/pump system collects water from watershed above the heads of stream channels.

Table 3. Locations, Physical Dimensions, and Discharge Features[a] of Three Oahu Study Streams

Feature	Streams Manoa	Kaneohe	Waiahole
Drainage Basin (km^2)	27.0	13.0	10.2
Total channel length (km)	34	28	10
Longest tributary length (km)	9.6	9.1	5.5
Longitudinal mainstream gradient (m/km)	64	67	31
Drainage area above gaging stations[a] (km^2)	5.7	11.3	2.6
Mouth coordinates (latitude) (longitude)	21°17'24"N; 157°49'51"W	21°24'56"N; 156°47'09"W	21°29'14"N; 156°51'45"W
Mean flow (m^3/s)	0.25[b]	0.42[c]	0.60[d]
Maximum flow (m^3/s)	179.5	340.0	3.7
Minimum flow (m^3/s)	0.1	0.1	0.1

[a]Discharge data do not represent stream total discharge. See footnotes and figures for specifics of measurements.

[b]58-yr mean, combined flow at two gaging stations (USGS 1977). No diversion. Refer to Fig. 2 for locations of gaging stations.

[c]14-yr mean (USGS 1977). No diversion above gaging station. Refer to Fig. 3 for location of gaging station.

[d]Water year 1968 (USGS 1970). Diversions above gaging station. Location of gaging station and dewatering complex shown in Fig. 4.

METHODS

Full quantitative collections in this study were made at approximately monthly intervals from February 1976 through May 1977. Less complete and quantitative sampling covered a longer period.

SAMPLING STATIONS

Sampling stations were established in the lower and middle reaches of study streams and located with regard to concrete lined channels and accessibility. Manoa Stream had eight stations (Fig. 2): Kaneohe and Waiahole Streams each had four stations (Figs. 3, 4). The stations in Manoa Stream covered the widest elevational range (3 to 110 m) while Kaneohe Stream stations were from 21 to 37 m elevation and Waiahole Stream were from 5 to 67 m elevation. A more detailed description of location and environmental conditions at sampling stations is given in Appendix A.

PHYSICOCHEMICAL

In an attempt to begin assessment of the environmental factors that affect the distribution of macrofauna in streams, water temperature, conductivity, and pH were measured. Water temperature was determined with a mercury thermometer; conductivity was measured with a YSI Model 33 S-C-T meter; and pH was measured with an AM model 107 analytical pocket pH meter. A subsequent report (FWS/OBS-78/18) will treat a range of physicochemical parameters and their effects in much greater detail.

FAUNAL COLLECTION

Fauna was sampled by electrofishing using a small gasoline-powered backpack unit which generated pulsating direct current (Coffelt Electronics model BP-1). Electrofishing appears to be the most practical, effective means of semi-quantitative sampling for fish and large crustaceans (many of which are cryptic) in shallow, rocky Hawaiian streams. Limitations of the method were discussed in Timbol and Maciolek (1978).

Macrofauna were collected from stations approximately 20 m X 1 m in dimensions. Some preliminary work done to test this collection method indicated that as many as 250 animals could be obtained in a single collection and that continued sampling over a longer reach of stream did not yield any new species. The method permits direct comparison of results with more widespread and less intensive sampling of many other altered and unaltered Hawaiian streams (Timbol and Maciolek 1978).

DATA ANALYSIS

Specimens were preserved in 10% formalin and identified in the laboratory. Certain poeciliids were identified by Dr. William Fink of the Smithsonian Institution.

Biomass data were obtained by weighing specimens individually on an analytical balance (Mettler M-15) to the nearest milligram, after excess moisture had been removed. Animals were measured for total length to the nearest millimeter.

Collection data were used to compile faunal inventories, by numbers and biomasses. Species diversity, H', at each sampling station, was computed by the Shannon-Wiener index (Pielou 1975) as

$$H' = -\Sigma p_i \ln_e p_i$$

where p_i was the proportion of the ith species in the population. The evenness measure, J', (Pielou 1975) for the s species in each sample was computed as

$$J' = H'/\ln_e s.$$

RESULTS AND DISCUSSION

ENVIRONMENTAL FEATURES OF SAMPLING STATIONS

The mean values and ranges of the physicochemical parameters measured at monthly intervals, usually during the early afternoon, appear by station in Table 4.

In Manoa Stream, the sample variances for these parameters at stations in lined channels were significantly greater than those at stations on natural bottom (F test, p = 0.01). Extreme high values for these parameters were recorded near the downstream end of long lined channels.

STREAM MACROFAUNA

Within the scope of this study, the term "macrofauna" refers to the larger stream animals, including fishes and crustaceans. Mollusks, annelids, and other lower invertebrates are not included in the samples. The 17 species of fishes and crustaceans recovered from study streams are detailed in Table 5. Based on extensive sampling experience elsewhere in the State, this is 81% (17 of 21) of the total species expected to be present in streams of these sizes.

Description of Species

Collections yielded five native fishes and two native decapod crustaceans (Fig. 5). Three of the five native species of diadromous gobioid fishes were represented, including *Awaous genivittatus* (o'opu naniha), *A. stamineus* (o'opu nakea), and *Eleotris sandwicensis* (o'opu okuhe). O'opu nakea and naniha, as members of the family Gobiidae, possess morphological adaptations facilitating upstream migration. The pelvic fins of these fishes are fused to form a sucking disc in the throat region which enables them to attach to rocks in swift currents. O'opu okuhe, a member of the family Eleotridae, lacks this sucking disc.

O'opu nakea is the only native fish obtained in these collections which is restricted to fresh water during postlarval life (Gosline and Brock 1960). This endemic goby is an omnivore, feeding on filamentous algae and benthic animals. It is the largest of the o'opu, and on Kauai it supports a seasonal fishery (Ego 1956). O'opu naniha and okuhe are euryhaline, inhabiting brackish waters as well as lower reaches of streams. O'opu

Table 4. Physicochemical Features of Water at Sixteen Stations in Manoa (M), Kaneohe (K), and Waiahole (W) Streams, Oahu, Measured between 1300 and 1600 hr at Monthly Intervals from February 1976 to May 1977

Station	Elevation (m)	Temperature (°C)		Conductivity (μmhos)		pH	
		Mean	Range	Mean	Range	Mean	Range
M-1	3	22.5	21.0-24.1	170	133-248	7.7	7.2-8.6
M-2	6	23.3	22.0-25.8	158	112-200	7.8	7.0-8.5
M-3[a]	6	28.6	26.2-36.0	248	203-335	8.8	7.7-10.0
M-4[a]	61	23.8	21.5-26.7	236	118-290	8.4	7.2-9.6
M-5	43	23.3	22.3-25.0	151	102-208	7.7	7.1-8.4
M-6[a]	49	23.0	21.2-25.6	140	83-188	7.8	6.8-8.1
M-7	49	22.8	21.7-25.6	146	95-188	7.6	7.0-8.0
M-8[b]	110	20.8	19.8-22.8	109	53-126	7.3	6.5-8.0
K-1	21	26.0	22.2-27.4	180	150-190	8.2	7.0-9.1
K-2[a,c]	21	26.2	22.2-27.7	178	160-191	8.2	6.9-9.1
K-3[a]	37	24.8	21.0-28.3	163	132-214	7.6	7.1-8.6
K-4	37	24.6	21.0-25.8	164	151-184	7.6	7.0-8.4

Continued

Table 4 (Concluded)

Station	Elevation (m)	Temperature (°C)		Conductivity (μmhos)		pH	
		Mean	Range	Mean	Range	Mean	Range
W-1	5	22.4	21.1-23.8	143	128-160	7.2	6.8-7.8
W-2	24	22.3	21.1-24.7	132	124-152	7.2	6.3-7.8
W-3	61	21.4	20.0-23.0	135	120-183	7.1	6.9-7.5
W-4	67	21.0	20.2-22.1	124	109-138	7.2	6.9-7.6

[a]Stations on concrete lined channels.

[b]Turbidity was 3 JTU on December 19, 1977, and 4 JTU on May 4, 1978, at this station (USGS 1977).

[c]Turbidity was 10 JTU on May 13, 1978, at this station (USGS 1977).

Table 5. Nomenclature and Origins of Aquatic Macrofauna in Three Oahu Streams (Manoa, Kaneohe, and Waiahole)

Scientific Name	Common Name	Status[a]
Fishes		
Awaous genivittatus	goby, o'opu naniha	indigenous
Awaous stamineus	goby, o'opu nakea	endemic
Clarias fuscus	Chinese catfish	introduced
Eleotris sandwicensis	sleeper, o'opu okuhe	endemic
Gambusia affinis	mosquitofish	introduced
Kuhlia sandvicensis	aholehole	endemic
Misgurnus anguillicaudatus	Oriental weatherfish, dojo loach	introduced
Mugil cephalus	striped mullet, amaama	indigenous
Poecilia mexicana	shortfin molly	introduced
Poecilia reticulata	guppy	introduced
Tilapia [=Sarotherodon] mossambica	tilapia, Mossambique mouthbrooder	introduced
Xiphophorus helleri	green swordtail	introduced
Xiphophorus maculatus	southern platyfish	introduced
Crustaceans		
Atya bisulcata	opae kalaole	endemic
Macrobrachium grandimanus	opae oehaa	endemic

Continued

Table 5 (Concluded)

Scientific Name	Common Name	Status[a]
Macrobrachium lar	Tahitian prawn	introduced
Procambarus clarkii	crayfish	introduced

[a]Terms used: Endemic - occurring naturally in Hawaii only. Indigenous - occurring naturally in Hawaii and elsewhere. Introduced - brought to Hawaii either intentionally or accidentally; exotic.

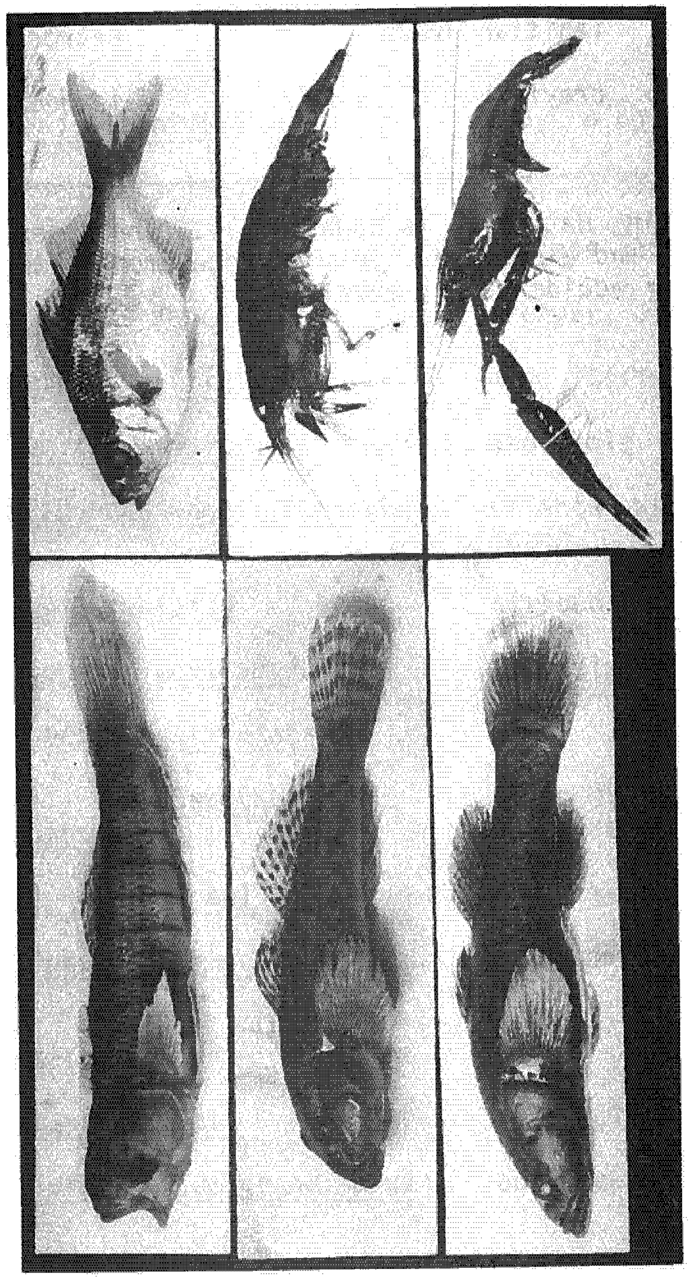

Figure 5. Four native fishes and two native crustaceans collected from three Oahu study streams.

a. Awaous genivittatus
b. Awaous stamineus
c. Eleotris sandwicensis
d. Kuhlia sandvicensis
e. Atya bisulcata
f. Macrobrachium grandimanus

naniha is an omnivore that also occurs on other Pacific islands, and o'opu okuhe is a predacious endemic species. Two other euryhaline fishes were collected in this study. The endemic Kuhlia sandvicensis (aholehole) and the indigenous Mugil cephalus (amaama) are characteristically marine and estuarine. However, as juveniles they frequent the lower reaches of streams.

Five of the eight species of exotic fishes represented in the collection are members of the family Poeciliidae, including Gambusia affinis (mosquitofish), Poecilia mexicana (shortfin molly), P. reticulata (guppy), Xiphophorus helleri (green swordtail), and X. maculatus (southern platyfish) (Fig. 6). This group of livebearing topminnows originates from the American tropics and subtropics. Males have an intromittent organ, the gonopodium, and fertilization is internal. Intervals between broods are approximately 30 days, with the young emerging live from females (Breder and Rosen 1966). These fishes feed on minute insects and other small animals (Eddy 1969).

Other exotic fishes collected in this study include Clarias fuscus (Chinese catfish), Tilapia mossambica (tilapia), and Misgurnus anguillicaudatus (dojo). The Chinese catfish and dojo have the capacity to acquire oxygen from the air. The Chinese catfish can live in stagnant waters, often with soft bottoms, and may survive out of water for relatively long periods (Sterba 1962). This fish is omnivorous. Dojo inhabiting muddy areas are known for their burrowing activities (Sterba 1962). Tilapia exhibit high growth rates and rapid reproduction (Bridges 1970). Common in fresh and brackish waters, these fish are voracious feeders with omnivorous tendencies (Sterba 1962).

Both the diadromous, endemic shrimps inhabiting Hawaiian streams were present in these collections. Atya bisulcata (opae kalaole) is primarily a detrital filter feeder and typically occurs in great numbers at higher elevations (Couret 1976). Macrobrachium grandimanus (opae oehaa) is a larger, euryhaline decapod. This animal prefers downstream habitats and estuaries. Opae, especially opae kalaole, are used as food items and also serve as fishbait.

Exotic crustaceans in the collections included Macrobrachium lar (Tahitian prawn) and Procambarus clarkii (crayfish). The Tahitian prawn is morphologically very similar to M. grandimanus but considerably larger. It prefers shady, sheltered habitats and has been characterized as a nocturnal omnivore. This diadromous animal is euryhaline, occurring in estuaries and extending far upstream (Kubota 1972). In contrast, the crayfish is limited to freshwater. It is also nocturnal and feeds opportunistically on both plant and animal material. In streams, crayfish avoid currents by hiding beneath sheltering rocks (Usinger 1967).

Faunal Collections

Sampling of fauna at 16 stations in the three study streams over the course of this study yielded 11,644 specimens of these 17 species of fishes

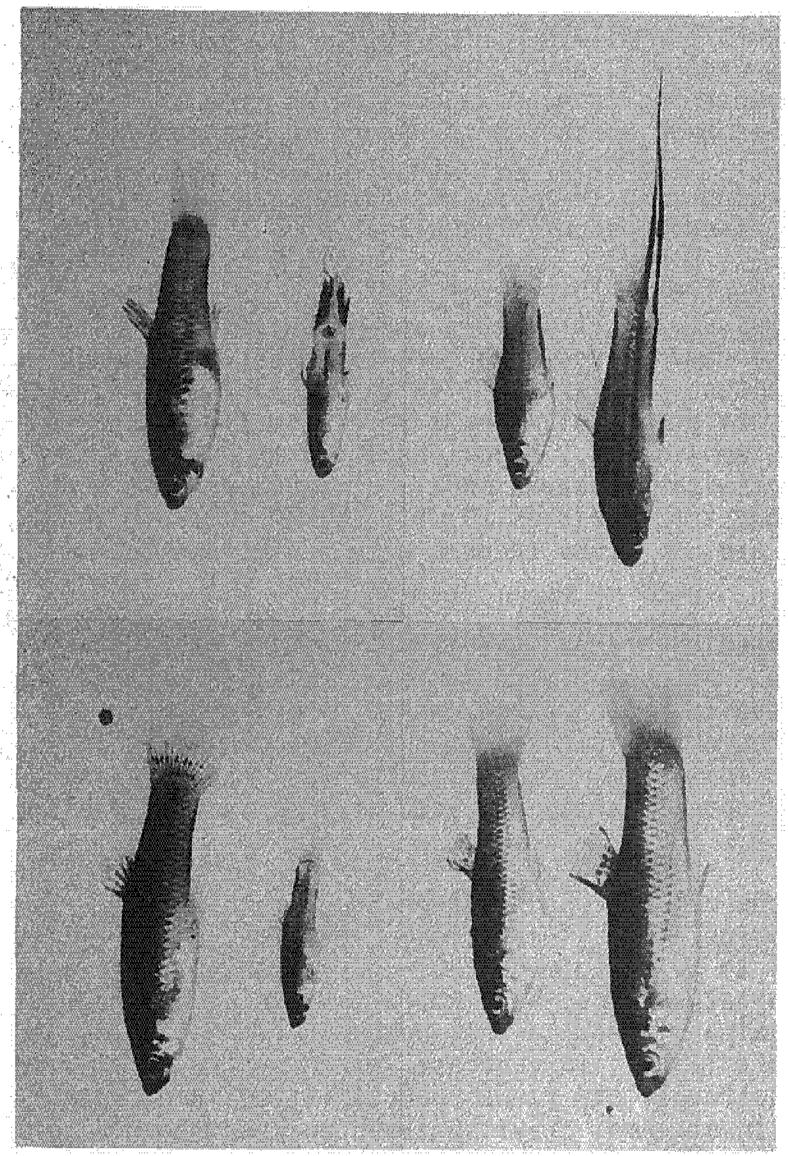

Figure 6. Four exotic poeciliid fishes, both sexes, collected from three Oahu study streams. Top: female. Bottom: male.

a. Gambusia affinis
b. Poecilia mexicana
c. Poecilia reticulata
d. Xiphophorus helleri

and crustaceans (Table 5). The number of complete collections procured from each station ranged from 10 to 13; mean collection yields are given in Table 6. The nature of the macrofaunal communities in the individual study streams will be described before comparing streams.

Manoa Stream. A total of 16 species was collected from Manoa Stream. The mean number and weight of each species per collection from each sampling station, along with the species diversity and evenness values, are presented in Tables 7 and 8, respectively. These data indicate that exotic fishes were dominant members of the macrofaunal communities in Manoa Stream. Exotic fishes of the family Poeciliidae were the most numerous animals at the seven downstream stations, while the exotic crustacean, Procambarus clarkii, was more numerous at the upstream station, M-8.

Collections from stations in concrete lined channels generally yielded fewer species of animals than those from stations on natural bottoms. No native species were recovered from concrete lined channels in Manoa Stream. Regular inhabitants of these areas included two species of topminnows, Poecilia mexicana and P. reticulata. Crayfish, dojo, and Chinese catfish were incidental members of these communities, and the specimens recovered were usually relatively small.

Biomass yields from concrete lined channel stations in Manoa Stream were significantly lower than those from natural bottom stations (Wilcoxon test for nonparametric data, p = 0.05; Sokal and Rohlf 1969). However, the mean numbers of animals obtained from two concrete lined channel stations, M-3 and M-6, were significantly higher than those from natural bottom stations (Wilcoxon test for nonparametric data, p = 0.05). This observation reflects the maintenance of high density populations of Poecilia mexicana within these concrete lined stream segments.

Kaneohe Stream. Collections from four stations in Kaneohe Stream located in and adjacent to both ends of a concrete lined channel yielded nine species. The mean abundance of each species per collection at each station and the diversity and evenness values are recorded in Table 9.

Exotic fishes were prominent in collections from all stations and Poecilia mexicana was the most abundant fish. No native fishes were recovered from concrete lined channel stations, in contrast to natural bottom stations which harbored Awaous stamineus.

Both native prawns were recovered from Kaneohe Stream stations. While one Macrobrachium grandimanus individual was found in one collection from each of the concrete lined channel stations, it occurred much more frequently at the downstream natural bottom station. Atya bisulcata was present at the natural bottom station upstream of the concrete lined channel modification. It is significant that diadromous, native animals (A. stamineus and A. bisulcata) occurred upstream from the concrete lined channel, indicating their ability to traverse 1.8 km of continuous concrete lined channel. The exotic crustacean, Procambarus clarkii, was abundant

Table 6. Mean Collection Yields of Aquatic Macrofauna from Sixteen Stations on Manoa (M), Kaneohe (K), and Waiahole (W) Streams between February 1976 and May 1977

Station	Elevation (m)	No. of Samples	No. of Species	Mean No. of Animals	Mean Wt. of Animals (g)
M-1	3	12	12	27	87
M-2	6	11	10	28	100
M-3[a]	6	11	6	135	30
M-4[a]	61	12	7	26	25
M-5	43	12	6	19	51
M-6[a]	49	12	5	69	41
M-7	49	12	7	37	123
M-8	110	12	4	34	67
K-1	21	13	8	96	195
K-2[a]	21	13	5	91	118
K-3[a]	37	12	7	128	73
K-4	37	12	7	68	91
W-1	5	11	7	44	34
W-2	24	11	6	24	12
W-3	61	10	7	25	61
W-4	67	11	6	139	56

[a]Artificial (concrete) bottom channel.

Table 7. Mean Numbers of Animals Per Sample from Manoa Stream Stations between February 1976 and May 1977. See Tables 6 and 11 for Numbers of Collections from Stations and Total Numbers of Animals in Manoa Stream Collections, Respectively

Species	Stations							
	M-1	M-2	M-3[a]	M-4[a]	M-5	M-6[a]	M-7	M-8
Pisces								
Native								
Awaous genivittatus	0.8	1.0						
Awaous stamineus		0.3					0.6	
Eleotris sandwicensis	2.4							
Kuhlia sandvicensis	0.1							
Mugil cephalus	0.3							
Exotic								
Clarias fuscus		0.1		0.1				
Gambusia affinis	9.9	5.8	0.3	0.2	2.5	0.1	0.2	
Misgurnus anguillicaudatus				0.1	0.1	0.2	0.3	
Poecilia mexicana	3.8	13.4	118.1	12.1	5.1	64.3	26.4	
Poecilia reticulata	0.8	4.5	16.0	12.6	5.8	4.1	6.3	13.3
Tilapia mossambica	0.3	0.5						
Xiphophorus helleri	0.3				1.5		2.3	
Xiphophorus maculatus	7.1		0.3					

Continued

Table 7. (Concluded)

Species	Stations M-1	M-2	M-3[a]	M-4[a]	M-5	M-6[a]	M-7	M-8
Crustacea								
Native								
Atya bisulcata								1.7
Macrobrachium grandimanus	0.2							
Exotic								
Procambarus clarkii	1.2	1.4	0.1	0.8	3.9	0.4	2.9	16.3
Total	27.2	28.3	134.8	25.9	18.9	69.1	37.3	33.6
Diversity (H')	1.73	1.49	0.40	0.87	1.52	0.28	0.93	1.04
Evenness (J')	0.70	0.68	0.25	0.49	0.85	0.18	0.48	0.76

[a]Concrete lined channel station.

Table 8. Mean Weights (g) of Animals Per Sample from Manoa Stream Stations between February 1976 and May 1977. See Tables 6 and 11 for Numbers of Collections from Stations and Total Numbers of Animals in Manoa Stream Collections, Respectively

Species	Stations M-1	M-2	M-3[a]	M-4[a]	M-5	M-6[a]	M-7	M-8
Pisces								
Native								
Awaous genivittatus	2.71	4.14						
Awaous stamineus		5.24					8.53	
Eleotris sandwicensis	15.42	10.23						
Kuhlia sandvicensis	0.05							
Mugil cephalus	0.76							
Exotic								
Clarias fuscus		3.64		3.33				
Gambusia affinis	3.19	1.10	0.02	0.01	0.26	0.01		
Misgurnus anguillicaudatus				0.42	0.42	0.13	1.27	
Poecilia mexicana	4.32	34.40	28.82	16.61	4.48	40.06	59.00	
Poecilia reticulata	0.17	0.50	1.09	3.08	0.97	0.74	1.13	2.85
Tilapia mossambica	35.48	15.45					34.08	
Xiphophorus helleri	0.44				0.85			2.45
Xiphophorus maculatus	0.07		0.08					

Continued

Table 8. (Concluded)

Species	Stations M-1	M-2	M-3[a]	M-4[a]	M-5	M-6[a]	M-7	M-8
Crustacea								
Native								
Atya bisulcata								1.70
Macrobrachium grandimanus	0.22							
Exotic								
Procambarus clarkii	24.56	25.30	0.01	2.02	44.00	0.49	18.47	60.47
Total	87.39	100.00	30.02	25.47	50.98	41.43	122.51	67.47
Diversity (H')	1.51	1.72	0.17	1.06	0.55	0.17	1.27	0.43
Evenness (J')	0.61	0.78	0.11	0.59	0.31	0.11	0.65	0.32

[a]Concrete lined channel station.

Table 9. Mean Numbers and Weights (g) of Animals Per Sample from Kaneohe Stream Stations between February 1976 and May 1977. See Tables 6 and 11 for Numbers of Collections from Stations and Total Numbers of Animals in Kaneohe Stream Collections, Respectively

Species	Stations K-1		K-2[a]		K-3[a]		K-4	
	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.
Pisces								
Native								
Awaous stamineus	0.3	3.69					0.3	3.00
Exotic								
Gambusia affinis	3.1	0.76	0.2	0.01	3.4	0.44	7.4	1.09
Poecilia mexicana	85.7	188.59	89.2	118.24	109.8	48.97	46.8	44.62
Poecilia reticulata	5.7	0.78	1.2	0.17	13.3	1.63	4.4	0.66
Xiphophorus helleri	0.1	0.16			0.5	0.55	1.3	0.48
Crustacea								
Native								
Atya bisulcata							0.1	0.88
Macrobrachium grandimanus	0.9	0.75	0.1	0.02	0.1	0.03		

Continued

Table 9. (Continued)

Species	K-1 No.	K-1 Wt.	K-2[a] No.	K-2[a] Wt.	K-3[a] No.	K-3[a] Wt.	K-4 No.	K-4 Wt.
Exotic								
Macrobrachium lar	0.2	0.10			0.2	2.43		
Procambarus clarkii	0.2	0.33	0.1	0.01	0.3	18.98	23.8	41.12
Total	96.2	195.16	90.8	118.45	127.6	73.03	84.1	91.05
Diversity (H')	0.48	0.19	0.09	0.01	0.51	0.88	1.14	0.94
Evenness (J')	0.23	0.09	0.06	0.01	0.28	0.45	0.59	0.48

[a]Concrete lined channel section.

upstream from the concrete lined channel (K-4). Most crayfish within concrete lined channels were small (40% less than 20 mm total length within a range extending to 110 mm).

Biomass yields at concrete lined channel stations were less than those at natural bottom stations at similar elevations, but greater numbers of animals occurred at the upstream (37 m elevation) concrete lined channel station compared to the upstream natural bottom station. These differences were not statistically significant (Wilcoxon test for nonparametric data, $p = 0.05$).

Waiahole Stream. Among the 11 species collected in Waiahole Stream, two fishes and two crustaceans were common to all four sampling stations. The mean abundance of each species per collection at each station and the species diversity and evenness values are reported in Table 10.

Native crustaceans were dominant at stations with the highest and lowest elevations. At Station W-4 (67 m), large numbers of one endemic shrimp, *Atya bisulcata*, were recovered. The other endemic prawn, *Macrobrachium grandimanus*, was common at downstream Station W-1 (5 m elevation). Exotic crustaceans occurred less frequently than natives in Waiahole Stream.

Native fishes occurred at three of the four stations, but their abundances were relatively low compared to exotic fishes. Assemblages of exotic fishes in Waiahole Stream were comprised, for the most part, of topminnows. *Poecilia reticulata* and *Xiphophorus helleri* were more abundant than *P. mexicana*.

Inter-Stream Comparisons

Species inventories were compiled in order to compare the composition of macrofauna in the three streams (Table 11).

The composition of macrofauna in the various channel types was also compared. This process was facilitated by grouping animals into four classes: native fishes, exotic fishes, native crustaceans, and exotic crustaceans (Table 12). Exotic fishes were prominent in both concrete lined and natural bottom channel sections in altered streams. They comprised a greater proportion of the numbers and biomasses of animals in the concrete lined channel stations than in the natural bottom stations. These results generally agree with results of an earlier study under the same project (Timbol and Maciolek 1978). In the unaltered stream, both exotic fishes and native crustaceans were prominent.

Table 10. Mean Numbers and Weights (g) of Animals Per Sample from Waiahole Stream Stations between February 1976 and May 1977. See Tables 6 and 11 for Numbers of Collections from Stations and Total Numbers of Animals in Waiahole Stream Collections, Respectively

Species	W-1 No.	W-1 Wt.	W-2 No.	W-2 Wt.	W-3 No.	W-3 Wt.	W-4 No.	W-4 Wt.
Pisces								
Native								
Awaous genivittatus	0.4	1.38						
Awaous stamineus					0.3	5.90	0.2	0.39
Eleotris sandwicensis	0.4	3.42						
Exotic								
Clarias fuscus					0.1	4.09		
Poecilia mexicana			1.1	2.77				
Poecilia reticulata	3.3	1.09	20.7	4.71	14.4	3.76	7.4	2.21
Xiphophorus helleri	2.6	8.95	1.6	2.80	2.6	4.99	2.6	4.38
Crustacea								
Native								
Atya bisulcata	21.6	0.26	0.1	0.01	4.2	1.67	127.2	37.60
Macrobrachium grandimanus	14.8	17.84	0.7	0.69	2.4	3.73		

Continued

Table 10. (Concluded)

Species	W-1 No.	W-1 Wt.	W-2 No.	W-2 Wt.	W-3 No.	W-3 Wt.	W-4 No.	W-4 Wt.
Exotic								
Macrobrachium lar	1.5	4.23	0.2	0.82	1.4	36.95	0.8	8.78
Procambarus clarkii							0.5	2.75
Total	44.6	34.17	24.4	11.80	25.4	61.09	138.7	56.11
Diversity (H')	1.29	1.41	0.61	1.38	1.30	1.35	0.36	1.06
Evenness (J')	0.66	0.73	0.34	0.77	0.67	0.69	0.20	0.59

Table 11. Mean Number of Animals per Sample from Three Study Streams between February 1976 and May 1977

Species	Streams: Manoa	Kaneohe	Waiahole
Pisces			
Native			
Awaous genivittatus	0.2		0.1
Awaous stamineus	0.1	0.1	0.1
Eleotris sandwicensis	0.5		0.1
Kuhlia sandvicensis	0.01		
Mugil cephalus	0.03		
Exotic			
Clarias fuscus	0.02		0.02
Gambusia affinis	2.4	3.4	
Misgurnus anguillicaudatus	0.1		
Poecilia mexicana	29.6	83.2	0.3
Poecilia reticulata	7.9	6.0	11.4
Tilapia mossambica	0.2		
Xiphophorus helleri	0.5	0.5	2.3
Xiphophorus maculatus	0.9		
Crustacea			
Native			
Atya bisulcata	0.2	0.02	39.1
Macrobrachium grandimanus	0.02	0.3	4.5
Exotic			
Macrobrachium lar		0.1	1.0
Procambarus clarkii	3.5	1.9	0.1
Total	46.2	95.5	59.0

Table 12. Relative Abundances of Native and Exotic Faunal Groups in Different Channel Types, Collected from Three Study Streams between February 1976 and May 1977

Faunal Group	Altered Streams: Concrete Lined % No.	Concrete Lined % Wt.	Altered Streams: Natural Bottom % No.	Natural Bottom % Wt.	Unaltered Stream: Natural Bottom % No.	Natural Bottom % Wt.
Native Fishes	0	0	4	8	1	6
Exotic Fishes	99	92	79	50	46	37
Native Crustaceans	0	0	1	1	50	32
Exotic Crustaceans	1	8	16	41	3	25

The mean values of diversity and evenness for the channel types were:

Station Channel Type	Diversity; Evenness by Number	Diversity; Evenness by Biomass
Concrete lined	0.43; 0.25	0.46; 0.25
Natural bottom (altered stream)	1.19; 0.61	0.94; 0.46
Natural bottom (unaltered stream)	0.89; 0.47	1.30; 0.70

Both diversity and evenness values were significantly lower in concrete lined channel sections of streams compared to natural bottom sections (Wilcoxon test for nonparametric data; $p = 0.05$).

SUMMARY AND CONCLUSIONS

PHYSICOCHEMICAL FACTORS

Water Temperature

The two altered streams studied showed different temperature regimes. Kaneohe, on the windward side, exhibited slightly higher temperatures than Manoa, on the leeward side. The differences are consistent with differences in ambient air temperature and precipitation. Water temperatures were, however, considerably higher and more variable in the altered streams than in the unaltered one.

Conductivity

Conductivity was higher and more variable in altered streams than in unaltered ones. Conductivity was not correlated with the type of channel bottom.

pH

Altered streams had very high and variable pH, often exceeding the 8.0 units proposed maximum for Hawaiian fresh waters. The parameter was not correlated with bottom type. The unaltered stream had stable, near neutral values and did not exceed the recommended maximum for pH.

BIOLOGICAL FEATURES

The distribution and relative abundances of fishes and crustaceans in altered and unaltered streams on Oahu were studied.

Manoa Stream

Exotic fishes were dominant members of the macrofaunal communities in Manoa Stream. The exotic poeciliids were dominant in the lower elevations while the exotic crustacean, Procambarus clarkii, was more numerous at the higher elevations.

Fewer species were found in concrete lined channel stations than in natural bottom stations. No native species were found in concrete lined channel stations. Regular inhabitants of concrete lined channel stations were two species of topminnows, Poecilia mexicana and P. reticulata. Biomass yields from concrete lined channel stations were significantly lower than those from natural bottom stations, but the mean numbers were significantly higher due to high densities of small Poecilia mexicana.

Kaneohe Stream

Exotic fishes were dominant in collections from all stations, and Poecilia mexicana was the most abundant. No native fish was recovered from concrete lined channel stations, and the native crustacean, Macrobrachium grandimanus, also appeared to avoid the concrete substrate.

Biomass yields at concrete lined stations were less than those at natural bottom stations at similar elevations, but greater numbers of animals were collected.

Waiahole Stream

Native animals were dominant in the highest and lowest elevation stations in this unaltered stream. Native fishes were less abundant than exotics at all stations. Exotic fishes consisted mainly of poeciliids; Poecilia reticulata was more abundant than Poecilia mexicana.

Inter-Stream Comparison

Manoa Stream had the highest number of species, followed by Waiahole and Kaneohe in decreasing order.

Exotic fishes were dominant in both artificial and natural bottom channels in altered streams. In unaltered streams, both exotic fishes and native crustaceans were prominent. Species diversity was lower in concrete lined channel stations compared to natural bottom stations.

STREAM MANAGEMENT IMPLICATIONS

Hawaii's native stream fauna is unique in several ways. It is also very fragile. Hawaiian stream animals are particularly adapted to the rocky, precipitous, freshet-flow nature of Hawaiian streams. The numbers of species within a given taxon are few but most of them are endemic. Excluding insects, all larger native stream species are diadromous (having marine larval development) as a consequence of oceanic insular evolution. The impact of stream channel alteration on fauna of oceanic islands such as Hawaii can be especially severe inasmuch as the most extensive modifications are developed mainly in the lower reaches of streams which, in addition to being habitats of some species, are the essential migratory pathways for both seaward-moving larvae and returning juveniles of all the larger native species inhabiting the upper reaches. Perhaps it is no coincidence that Lentipes concolor, originally described in part from Oahu, where today stream channel alteration is most extensive, is now unknown on that island.

Commentaries relevant to management of Hawaiian streams are made for two purposes. First, there is a recognition both of the demands for agricultural and domestic water supplies for the economic and population growth in the State, and the need to protect unique biota and conserve fishery resources and recreational opportunities. Further, all "high island" streams in the Pacific have enough common features to make results transferable. Thus, results of this Hawaii channelization study can, with proper caution, be applied to high islands of Guam, Commonwealth of the Northern Marianas, Micronesia, American Samoa, and some other Pacific high islands. Some details regarding transferability of information are forthcoming (USFWS, in preparation).

IMPACT OF CHANNEL ALTERATION

Stream management must address the possible effects which channel alterations may have on the diadromous native animals, the possible reasons for adverse effects, and possible mitigative actions that might be taken. A related preliminary study addressing the potential impacts of hydroelectric and support facilities on the Hawaiian stream macrofauna has been done by Timbol (1977).

Environmental Factors

An immediate effect of almost any type of channel alteration is a reduction in the heterogeneity of the habitat, particularly the substrate.

Shade and bottom shelter are usually reduced. This normally results in more extreme values of environmental variables (e.g., water temperatures). The magnitude of the impact depends on the nature of the alteration, with highest impacts occurring within artificially lined channel bottoms. In addition, alteration of a portion of a channel may have degrading effects on total stream quality; in the present study, natural bottom sections of altered streams exhibited more variable physicochemical features than natural bottoms of unaltered streams.

When administrators are faced with no alternative but to allow some form of channel alteration in a stream, an alteration leaving the stream bottom in a natural state is much the best choice ecologically. The worst choice is a concrete lined channel which replaces the diverse character of the natural stream channel with a smooth, featureless channel of uniform cross-section, current and substrate. Flow in such a lined channel is typically in a uniform, very thin sheet. These characteristics lead to poor water quality, e.g. extreme temperatures, pH as high as 10 (two units higher than the maximum specified in Hawaii's water quality standards).

Concomitant with channel alteration is riparian clearing. It should be kept to a minimum, and where devegetation is unavoidable, replanting of riparian trees should be part of stream management. Devegetation eliminates overhead cover, resulting in excessive radiant heat transfer, which leads to wider ranges in temperature (e.g., very high in the afternoons and very low in the early mornings). Intense daytime light and heat promote excessive algal growth. The photosynthetic activity causes strong diel fluctuations in pH and dissolved oxygen content and creates an unnatural benthic floral community.

Biological Implications

If the stream course is straightened, as is usually done in channel alterations, hydraulic resistance is lessened, resulting in increased water velocity. Gebhards (1973) stated that increased water velocity and loss of shelter are prime factors that affect stream macrofauna. He estimated that channel alteration in two trout streams in Idaho reduced game fish production by 87%. Reductions in game fish in other altered streams were: North Carolina, 76%; Missouri, 79%; and Montana, 90%. In game fish exceeding six inches in length, a 90% reduction in both weight and number occurred in North Carolina streams following channelization (Bayless and Smith 1964). Loss of shelter can be highly detrimental to the survival of fishes in streams, particularly to demersal, cryptic forms such as all the native Hawaiian stream species. Although these fishes are fair swimmers in short bursts, lactic acid accumulates rapidly, and shelters for frequent resting are required. Thus, the maintenance of long sections of natural channel bottom is particularly important to these substrate dependent species.

Habitat features resulting from stream channel alteration in Hawaii favor exotic fishes, particularly poeciliids, over native species. Except in a few cases of recreational fishery importance, exotic species are

considered pests in Hawaiian streams. They appear to compete with native species for food and shelter, and at least some predation occurs (e.g., Tomihama (1972) observed the exotic Tahitian prawn capturing the native goby, Sicydium stimpsoni). Often exotic species have broader environmental tolerances than native species and flourish in degraded streams as in the case of topminnows (P. mexicana) in Manoa and Kaneohe Streams. Preliminary results of the final portion of this study support this impression; definitive results are forthcoming in Part C (FWS/OBS-78/18).

In the present study, fewer macrofaunal species thrived in artificial bottom channels than in natural bottom channels. Biomass yield was likewise lower but numbers were higher due to high densities of the topminnows. Artificial bottom stations, especially those lined with concrete, appear to serve as nurseries for these ubiquitous topminnows, undesirable species compared with any of the native species of gobies that they appear to be displacing. In an earlier study, Timbol and Maciolek (1978) found that exotic fishes and crustaceans strongly dominated all artificial bottom channels both by number (97%) and weight (92%).

MITIGATIVE ACTIONS

Most of the native Hawaiian stream fish and crustaceans are diadromous. They need suitable passageway throughout the stream length for their larvae to reach the ocean and the postlarvae to return upstream to their adult habitat. In particular, the endemic goby, Awaous stamineus, which supports a seasonal fishery on Kauai Island, migrates downstream to spawn. Their larvae spend from four to seven months in the sea as plankton before they migrate upstream as postlarvae (Ego 1956). To provide a suitable habitat for this valuable fish as well as other native diadromous fishes and crustaceans, the following actions may be taken.

Alteration of the stream bed should be minimized or avoided whenever possible. When an artificially lined channel is unavoidable, it is desirable to concentrate the stream flow into a deeper water column by either a v-notch on the new channel bottom or a slanting channel bottom. The present common method of channel alteration whereby a sinuous channel is replaced with a straight, and consequently shorter channel, should be modified. The new stream channel should have the same total channel length as the one it replaced. Straight channels reduce sheltering slack water adjacent to banks at times of rising flow which results in populations of native animals being swept to the ocean where most adults cannot survive for any length of time.

The most obvious effect of channel alteration is scenic degradation. The straight and angular channels in the lower reaches of Manoa Stream compared with its almost pristine and scenic channels at higher elevations is but one example. This type of degradation is detrimental both to the native stream animals and to the tourist industry.

To provide a suitable habitat for diadromous native animals, reduce scenic degradation, and at the same time provide for cultural needs for a growing human population, it seems prudent to recommend tentatively that a continuous length of concrete lined channel should be no more than 1.5 km before a natural bottom section is provided. Results of this study indicated that at least one native prawn and one native goby negotiated a 1.8 km length of lined channel. A figure of 1.5 km is recommended as a conservative value considering species population requirements.

This study showed that the removal of stream cover resulted in adverse physicochemical conditions. Permanent removal of tree cover can result in the disappearance of the native *Macrobrachium*, as was the case with two *Macrobrachium* spp. in Malaya (Johnson 1966). It can also be expected to lead to the continued decrease of the endemic *M. grandimanus* and the displacement of this endemic prawn in freshwater habitat by the exotic *M. lar*. *M. lar* has been observed to kill *M. grandimanus* in the absence of cover (Kubota 1972).

To provide mitigative conditions, riparian vegetation should be planted along the new channel to replace young trees and shrubs removed. The recommended formula is one-for-one of particular species (U.S. Fish and Wildlife Service 1974) with the additional proviso that woodlands should be replaced by planting 1 1/2 acres of young plants for each acre cleared. There are no Hawaiian data comparable to the U.S. Fish and Wildlife Service recommendations. There is some evidence that Hawaiian riparian trees and shrubs will thrive under conditions other than their natural environment as can be seen in the use of strawberry guava trees, *Psidium cattleianum*, in Honolulu's Ala Moana Shopping Center and the wetland hau, *Hibiscus tiliaceus*, for shade trees in Waikiki. This revegetation also replaces some of the lost sources of organic input in the stream waters, which according to Fisher and Likens (1973), is 99% of the annual energy input to the stream system.

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Appendix A. Physical Features of Sampling Stations

The following is a brief description of the sampling stations including the location, elevation, mean stream width, depth range, bottom type, and flow characteristics (riffle/pool). It should be noted that the information provided below does not reflect conditions which may prevail during periods of peak flow. Compare with text Figs. 2, 3, and 4.

MANOA STREAM

M-1 Adjacent to Kaimuki High School, 3 m elevation; 3.5 m wide; 15-31 cm deep; pebble and cobble bottom; riffle.

M-2 15 m upstream of the Manoa-Palolo confluence; 6 m elevation; 7.5 m wide; 6-15 cm deep; boulder and pebble bottom; riffle.

M-3 Palolo Tributary concrete lined channel 20 m upstream of the Manoa-Palolo confluence; 6 m elevation; 3.5 m wide; 3-6 cm deep; concrete bottom; riffle.

M-4 Palolo Tributary concrete lined channel adjacent to Palolo School; 61 m elevation; 4 m wide; 5-9 cm deep; concrete bottom; riffle.

M-5 30 m downstream from Woodlawn Drive crossing; 43 m elevation; 10 m wide; 40-60 cm deep; mud and silt over pebble bottom; pool.

M-6 Concrete lined channel adjacent to Manoa Park; 49 m elevation; 5.5 m wide; 5-8 cm deep; concrete bottom; riffle.

M-7 Adjacent to Manoa Park; 49 m elevation; 7.5 m wide; 34-38 cm deep; pebble and cobble bottom; riffle.

M-8 Upstream of the 4th bridge on Waaloa Way; 110 m elevation; 2.0 m wide; 10-16 cm deep; boulder and cobble bottom with some silt; riffle.

KANEOHE STREAM

K-1 Adjacent to Kaneohe Public Library; 21 m elevation; 10.5 m wide; 16-21 cm deep; mud and silt over pebble and cobble bottom; riffle.

K-2 Concrete lined channel adjacent to Kaneohe Public Library; 21 m elevation; 17.7 m wide; 5-10 cm deep; concrete bottom; riffle.

K-3 Uppermost section of Kamooalii tributary concrete lined channel; 37 m elevation; 6.7 m wide; 5-8 cm deep; concrete bottom; riffle.

K-4 Kamooalii tributary 50 m upstream of concrete lined channel; 37 m elevation; 9.5 m wide; 14-17 cm deep; silt and mud over pebble bottom; riffle.

WAIAHOLE STREAM

W-1 Approximately 0.2 km from highway, adjacent to Waiahole Valley Road; 5 m elevation; 4.9 m wide; 22-23 cm deep; pebble bottom with mud and silt; riffle.

W-2 Uwau tributary 20 m downstream of bridge crossing of south fork of Waiahole Valley Road; 24 m elevation; 2.1 m wide; 12-29 cm deep; mud over pebble bottom; riffle.

W-3 Uwau tributary at end of north fork of Waiahole Valley Road; 61 m elevation; 3.6 m wide; 12-21 cm deep; boulder and pebble bottom; riffle.

W-4 Approximately 0.4 km along Hawaiian Electric Company trail at end of south fork of Waiahole Valley Road; 67 m elevation; 4.1 m wide; 18-33 cm deep; boulder and pebble bottom; riffle.

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Effects of channelization on native Hawaiian stream fauna were assessed by making physio-chemical measurements and analyzing and comparing macrofaunal communities in channelized and unchannelized streams. The altered study streams had higher mean water temperature, pH, and conductivity and wider ranges of these variables than the unaltered stream. Channel sections with concrete bottom had higher values than sections with natural bottom. Exotic fishes predominated in altered streams; exotic fishes and native crustaceans predominated in unaltered streams. Native fishes appeared to be especially reduced in heavily channelized streams. Channels with artifical bottom seemed to provide nurseries for the exotic poeciliids, Poecilia mexicana and P. reticulata; species diversity was lower in these channels.

Extreme channelization seems to stress the diadromous native fauna. Channel alterations, particularly artificially lined channels, appear to favor worthless exotics in replacing native species. Channelization in Hawaii should be minimized to protect native fauna. Where it is unavoidable, natural bottom channels seem least damaging. Artificial bottom channels, if used, should provide for reasonable water depth at low flow, and the length of continuous sections should be minimized. Riparian bank vegetation should be maintained. Results of this study are relevant to many tropical oceanic high islands.

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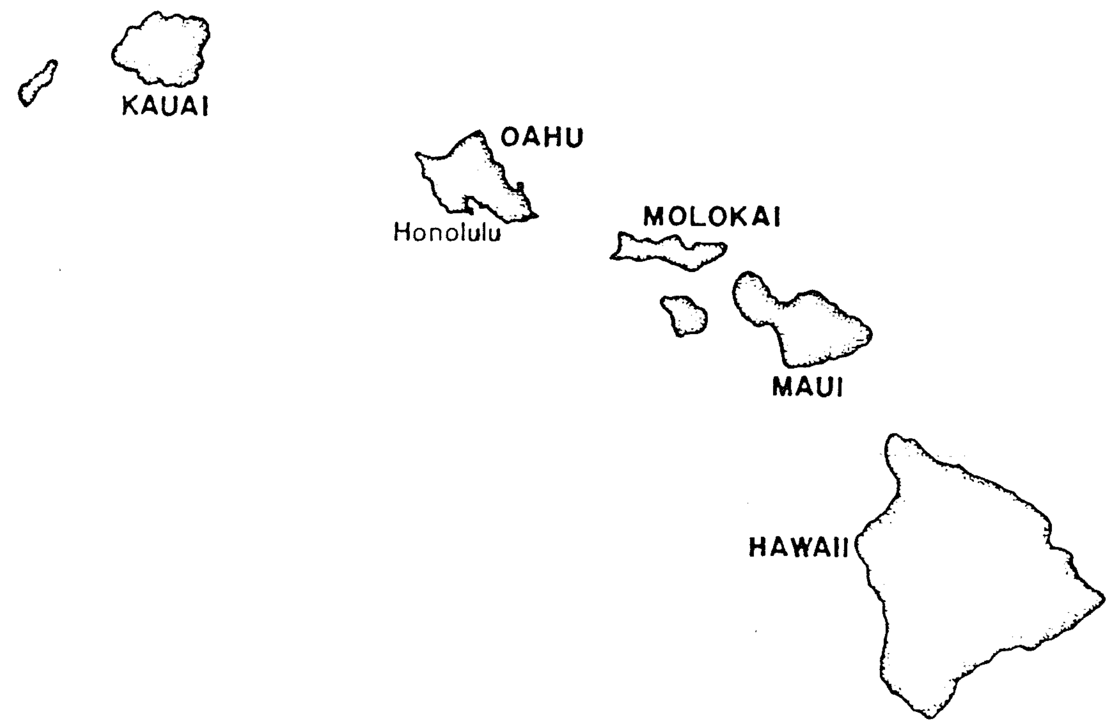
Stream Channel Modification in Hawaii. Part C: Tolerance of Native Stream Species to Observed Levels of Environmental Variability



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FWS/OBS-78/18
October 1978

STREAM CHANNEL MODIFICATION IN HAWAII
PART C: TOLERANCE OF NATIVE STREAM SPECIES TO OBSERVED LEVELS OF ENVIRONMENTAL VARIABILITY

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PREFACE

This is the third of a four-part series on Stream Channel Modification (Channelization) in Hawaii and Its Effects on Native Fauna. Part A (FWS/OBS-78/16, Timbol and Maciolek 1968) contains a statewide inventory of perennial streams, channel alterations and aquatic macrofauna. Part B (FWS/OBS-78/17, Norton et al. 1968) contains an intensive year-round study of macrofaunal communities in selected streams and contrasts channelized and natural channels. Part D (FWS/OBS-78/19, Parrish et al. 1978) will contain a general summary of project results. The present report contains a detailed description of enviromental conditions in streams that are relevant to the welfare of native species and indicates how channelization affects these parameters. It also reports results of tolerance of native and some exotic species to relevant levels of these parameters. Conclusions regarding the results of channelization for the biota are presented. Data and analysis from January 1977 through October 1978 are included in this report.

This report is part of a thesis submitted to the Graduate Division of the University of Hawaii in partial fulfillment of the requirements for the Master of Science degree in Zoology.

Any suggestions or questions regarding Channel Modification in Hawaii should be directed to:

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EXECUTIVE SUMMARY

Streams in Hawaii have been subjected to water diversion, exotic introductions, and several forms of channelization. The latter have included realignment, clearing of riparian vegetation, and construction of artificial bank and bed structures. Channel modification has been correlated with increases in physicochemical variability and reductions in numbers of several endemic gobiid fishes in altered streams. The amphidromous migratory behavior of the native fauna prevents the isolation of any species from the effects of channelization on water quality.

Daytime values of conductivity, pH and dissolved oxygen were found to be considerably higher in altered streams than in unaltered streams. Temperature was monitored weekly for one year at 20 stations to assess the relative effects of different channel types on thermal fluctuations. All stations located downstream from channel modifications had higher diurnal peak temperatures than upstream and unaltered stream stations. Temperature extremes of 36.2°C and 17.8°C were recorded at the downstream end of a concrete lined channel. Diel changes in temperature of 12°C were not uncommon at this site. High illumination due to clearing of the vegetative canopy, and shallow water depths in lined channels appear to be responsible for the excessive heating.

Tolerances of native species and key exotics to elevated temperatures were determined using a gradual heating method designed to simulate <u>in situ</u> diurnal heating. Growth of post-larval migrating forms of several gobiids was measured following one-month exposures to different fluctuating thermal regimes. Upper lethal temperatures correlated with altitudinal distributions of adult fishes and crustaceans. Lethal limits of those species absent or rare in altered streams fell within the range of temperatures recorded in such degraded habitats. Dominant introduced fishes showed greater resistance to high temperatures than native animals. Maximum growth rates occurred in fluctuating temperatures whose diel maxima were 7-8°C below upper lethal limits.

Where future channel modification cannot be avoided, channelized sections should be kept as short as possible, with natural sections interspersed between them along the length of the stream. Nearstream vegetation should be maintained. Lined channels should contain V-shaped notches at mid-channel or a slanting bottom in order to maximize depth during low flow conditions. Mitigation for existing channels should include revegetation of stream banks.

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LIST OF ABBREVIATIONS AND SYMBOLS IN TEXT

ABBREVIATIONS

cm	centimeters
E.I.F.A.C.	European Inland Fisheries Advisory Commission
hrs.	hours of the day
km	kilometers
km^2	square kilometers
m	meters
min	minutes
NS	not statistically significant
NTU	nephologmetric turbidity unit
pH	$-\log_{10}$ hydrogen ion concentration
ppm	parts per million
PVC	polyvinyl chloride
U.S.E.P.A.	United States Environmental Protection Agency
U.S.G.S.	United States Geological Survey
µmhos	micromhos

SYMBOLS

a	coefficient in length-weight relationship
CO_2	carbon dioxide
F	statistical test based on F distribution
K	condition factor
LD_{50}	lethal temperature at time of 50% mortality
N	exponent in length-weight relationship
NH_4	ammonium ion
$NH_3 \cdot H_2O$	ammonia associated with water
P	statistical probability
r	correlation coefficient
r^2	coefficient of determination
SD	standard deviation
t	statistical test based on t distribution
$\overline{X}$	mean
$\overline{X}_d$	mean for downstream station
$\overline{X}_u$	mean for upstream station
○	sampling station
⁞ ⁞	realigned/cleared stream channel

◺◿	revetment of stream banks
⊔	lined stream channel
°C	degrees, Celsius
°N	degrees, north latitude
°W	degrees, west longitude
%	percent
°/₀₀	salinity, parts per thousand

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INTRODUCTION

The high islands of the Hawaiian archipelago stretch from southeast (19°N, 155°W) to northwest (22°N, 160°W) below the Tropic of Cancer. The five islands of Hawaii, Maui, Molokai, Oahu and Kauai make up 96% of the total land area of the island chain and contain the only substantial fresh waters. The 366 perennial or possibly perennial streams represent the dominant freshwater ecosystem (Timbol and Maciolek 1978). Streams tend to be rocky and precipitous, particularly in their upper and middle reaches, with entry into the ocean ranging from waterfalls with rapid mixing to the flood plain situation with river-estuary.

The insular evolution of the indigenous Hawaiian freshwater macrofauna has been influenced by the great distances to the Melanesian faunal source areas (MacArthur and Wilson 1963) and the relative lack of larvae dispersing currents in the vicinity of the islands' mid-gyre position in the North Pacific. The high degree of endemism (78%) among the nine species of native freshwater fishes, shrimps and mollusks illustrates the adaptive radiation to be expected on high islands in such locations.

The five gobioid fish species include *Awaous genivittatus*, *A. stamineus*, *Sicydium stimpsoni*, *Lentipes concolor*, and *Eleotris sandwicensis*. All are endemic with the exception of *A. genivittatus*, which has been reported from Samoa (Jordan and Seale 1906). A sixth endemic species, *Kuhlia sandvicensis* is a euryhaline opportunist, and as such will not be considered as part of the freshwater fauna.

Two endemic shrimps comprise the native macro-crustacean fauna. *Atya bisulcata* belongs to the family Atyidae. One of 16 genera, *Atya* is found in fresh waters throughout the tropical and sub-tropical Indo-Pacific region. *Macrobrachium grandimanus* is one of the Indo-Pacific circumtropical family Palaemonidae, whose representatives are typically euryhaline.

Two varieties of macro-mollusks are native inhabitants of streams in Hawaii. *Neritina granosa*, an endemic neritid snail, and several unidentified thiarid snails of the genus *Melania*, represent the larger Hawaiian aquatic gastropods.

With the exception of *Melania spp.*, the freshwater fauna is "amphidromous", according to the definition of Myers (1949), engaging in life stage dependent, non-gametic migration. This behavior involves the passive downstream passage of eggs or larvae to the ocean during freshet flow with later active upstream migration. It is particularly adapted to the variable discharge and rugged nature of Hawaiian streams.

In Hawaii and throughout the developed world, the expansion of metropolitan environments has resulted in drastic modifications of freshwater habitats through efforts aimed at increasing flood control capabilities. Two of the first stream alteration projects in Hawaii were initiated in or around 1920, in the interrupted Makiki Stream in Honolulu and Wailoa River in Hilo. At present, over 15% of the State's streams have been subjected to channel modification involving removal of vegetation, realignment, and/or construction of culverts, bank revetments and concrete lined channels. Lined channels are rectangular or V-shaped artificial bank and channel structures. Revetments are reinforced banks without stream bed alteration. These two types of channel modification, along with a third type involving only realignment and removal of vegetative cover, make up 92% of all channelization statewide. Timbol and Maciolek (1978) considered the lined channel to be the most ecologically and numerically significant form of alteration. Although first used in Honolulu's Kapalama Stream in 1938, most in existence today were built within the last two decades. Other activities leading to the further degradation of natural conditions are irrigation dewatering (53% of streams diverted) and the introduction of freshwater exotic species (above data and definitions from Timbol and Maciolek 1978). Brock (1960) reported a 70% success ratio for exotic introductions.

The U.S. Fish and Wildlife Service has supported studies on the impact of channelization in over 20 states. With the exception of water velocity versus fatigue experiments, most of the investigations completed or in progress have dealt with the correlation of physical and chemical parameter measurements with species composition in natural and degraded habitats or examined the effectiveness of mitigation structures in the restoration of game fish (e.g. trout) populations (U.S. Fish and Wildlife Service 1976).

An intensive inventory of Hawaii's streams showed that those containing altered sections had greater means and ranges in temperature, pH and conductivity. The extreme values for these parameters (36.2°C, 10.4 pH units, 368 µmhos respectively; unpublished data, Hawaii Cooperative Fishery Research Unit) were measured on Oahu where 57% of all perennial streams are channelized (Timbol and Maciolek 1978). The gobiid Sicydium stimpsoni, the mollusk Neritina granosa and the prawn Macrobrachium grandimanus are rare on Oahu, where few if any pristine streams remain. The goby Lentipes concolor may be absent. Miller (1972) has included three Hawaiian endemics in his categories of "threatened" freshwater fishes: Lentipes concolor, "rare" and "endangered" throughout the State; Sicydium stimpsoni, "rare" on Oahu; and Awaous stamineus, "depleted" on Oahu.

Norton et al. (1978) showed that numbers of native animals and total diversity were lower in two altered streams than in an unaltered stream on Oahu. She found no indigenous species in lined channels and hypothesized that the poor water quality and lack of shelter in such locations favored domination by the highly tolerant exotic poeciliid fishes. Timbol and

Maciolek (1978) also reported that no native species were collected in lined channels, suggesting the existence of migration blocks in many streams.

The migratory behavior of the Hawaiian fauna prevents the isolation of any native animal from the effects of channelization on downstream water quality, if not from the necessity of traversing altered sections. Many channelization studies focus on the destruction of physical features known to influence certain key populations, thereby lowering the game fish potential of a stream (e.g. Lewis 1969, Schaplow 1976). The economic and recreational motivation for such works distinguishes them from the situation in Hawaii (in which entire streams become the critical habitats for small populations of organisms of inherent biological value). The present work is an investigation into the role of physicochemical variability induced by stream channel modification in the decline of native animal populations. The emphasis will be given to temperature rather than to those chemical parameters which are measures of complex, often temperature sensitive, ionic interactions not readily simulated in experimental work. This study will examine the dynamics of variation in key water parameters and the effects of elevated temperature on indigenous species.

The literature concerning the effects of temperature on aquatic life is voluminous, with the majority of the work devoted to fishes (e.g. Brett 1956; Doudoroff 1957; Fry 1971). The direct effects of temperature on the physiology and behavior of the individual organism are perhaps less complex than those ways by which temperature may indirectly affect an individual through influences on the entire community. The latter, however, are dependent on the sum total of direct effects on all community members. These effects can be divided among lethal, metabolic and behavioral categories. Fry (1967) uses the corresponding terms "lethal, controlling and directive". Lethal temperatures generally define the range within which the organism will necessarily die in a finite time of causes not related to the metabolic rate. The metabolic and behavioral categories contain what may be considered sub-lethal effects. While the lethal range is one of resistance, the sub-lethal region is that of tolerance. Metabolic effects have been referred to as "delayed action" effects of high temperature(Andrewartha and Birch 1954). An example would be an acceleration of growth resulting in the inability to reach and/or pass a critical point in the life cycle. Behavioral effects include the immediate positive and negative responses to a temperature stimulus and are usually approached with techniques aimed at exploring preference and electivity.

Symons et al. (1976) determined the upper lethal and preferred temperatures of the slimy sculpin in an effort to predict the possible consequences of stream water temperature elevation following clear cutting in the southern part of its range. The present work uses a similar approach in attempting to explain the already apparent results of channelization of streams in Hawaii. Lethal temperatures are determined for native species and the effect of temperature on the post-larval growth of several gobiid fishes is studied. Assuming variability within a population sample's response to lethal and sub-lethal temperatures, data collected may answer some questions concerning the subtle effects of temperature on population decline despite reproduction (i.e. growth rate constant r<0). However, the effect of environmental variables on population dynamics is beyond the temporal and logistical scope of this and most biometeorological studies.

The existing stream habitat data for Hawaiian streams are sparse and unreliable, particularly in regard to altered streams, where great diel variation necessitates temporal controls on sampling. A goal of this study is the improvement of the significance, if not accuracy, of existing physicochemical data. Guidelines for future proposed stream modifications must be based on evidence detailing the mechanisms by which the distribution and abundance of Hawaiian stream fauna (Norton et al. 1978) are affected by the results of stream channelization. This investigation should provide the evidence for one of these mechanisms.

METHODS

PHYSICOCHEMICAL SAMPLING

An intensive program of monitoring temperature and other key water parameters was conducted at 20 stream channel stations representing a diversity of channelized and natural habitats (Table 1). Stations were located in the Manoa-Palolo watershed on leeward Oahu and in the Waiahole and Maunawili watersheds on windward Oahu (Fig. 1-4). Two of the Maunawili stations, not shown in Fig. 4 are MW-3, located between MW-1 and MW-4, and MW-5, a sewage outfall adjacent to MW-4. Several of the sites are identical to sites included in a previous study of faunal distribution and abundance (Norton et al. 1978). In most cases, stations were defined more by their relationship to a specific type of upstream or downstream channel than by the morphology of the site itself. This allowed for assessment of the net change in specific parameters following flow through such areas.

Preliminary studies showed that maximum daily water temperatures generally occurred in mid-afternoon, between 1400 and 1500 hours. Weekly measurement of peak diurnal water temperatures by hand held mercury thermometer began in October 1977 at most stations, and ended in September 1978. Addition of stations to the survey after October was prompted by recognition of possible confounding effects due to changes in flow between stations (e.g. sewage outfalls, Station MW-5) and of the need for more precise information from within and between certain neighboring sites.

Measurements of conductivity (YSI Model 33, S-C-T meter), pH (AM Inc. Model 107 Pocket Meter), and dissolved oxygen (YSI Model 57 Oxygen Meter) were included in the latter half of the survey approximately once a month. Water was sampled at depths of 2-10 cm and, where possible at shallow water sites, at the cross-channel position of maximum flow velocity. In order to insure a high degree of statistical authenticity for between-site comparisons, all measurements were made during the same one-hour period, one day each week on windward Oahu and one day on leeward Oahu.

Ranges, means and standard deviations were calculated for all parameters at all stations. A second set of mean temperatures and their standard deviations were determined for each station for comparison with that of the neighboring up- and downstream stations, using only data collected during same-hour, same-day sampling at both stations. Significance of the differences in mean and variance between stations was tested using the "Student's" t statistic, and change in temperature per meter of stream channel

Table 1. Water Quality Sampling Stations

Station	Watershed	Drainage Area (km^2)	Elevation (m)	Width (m)	Distance from Mouth (km)	Channelization[a]	Observation Period
W-1[b]	Waiahole	10.2	5	3	0.5	none	Oct 77-Sep 78
W-2[b]	"		67	4	3.9	none	"
MW-1	Maunawili	13.9	21	1	9.4	none	"
MW-2	"		21	2	9.4	none	"
MW-3	"		21	1	9.4	none	"
MW-4	"		23	5	9.5	lined channel	Jan 78-Sep 78
MW-5	Maunawili (sewage outfall)		23		9.5		"
MP-1	Manoa-Palolo	7.0	0	50	0.2	drainage canal	Oct 77-Sep 78
MP-2	"		0	20	2.3	realignment	"
MP-3	"		5	7	3.6	revetment	"
M-4[b]	"		6	3	3.7	revetment	"
M-5	"		44	3	6.2	lined channel	"
M-6[b]	"		49	5	6.7	revetment,cleared	Jan 78-Sep 78
M-7	"		50	6	6.7	none	Oct 77-Sep 78

Continued

Table 1 (Concluded)

Station	Watershed	Drainage Area (km^2)	Elevation (m)	Width (m)	Distance from Mouth (km)	Channelization[a]	Observation Period
M-8	Manoa-Palolo		85	2	8.9	none	Feb 78-Sep 78
M-9[b]	"		104	1	9.3	none	"
P-4[b]	"		6	5	3.7	lined channel	Oct 77-Sep 78
P-5	"		31	5	4.8	lined channel	"
P-6	"	7.0	82	2	7.2	none	Jan 78-Sep 78
P-7	"		104	2	7.7	none	Oct 77-Sep 78

[a]Any major alteration to stream bed, channel or banks immediately upstream from station

[b]Corresponds with station in Norton et al. (1978)

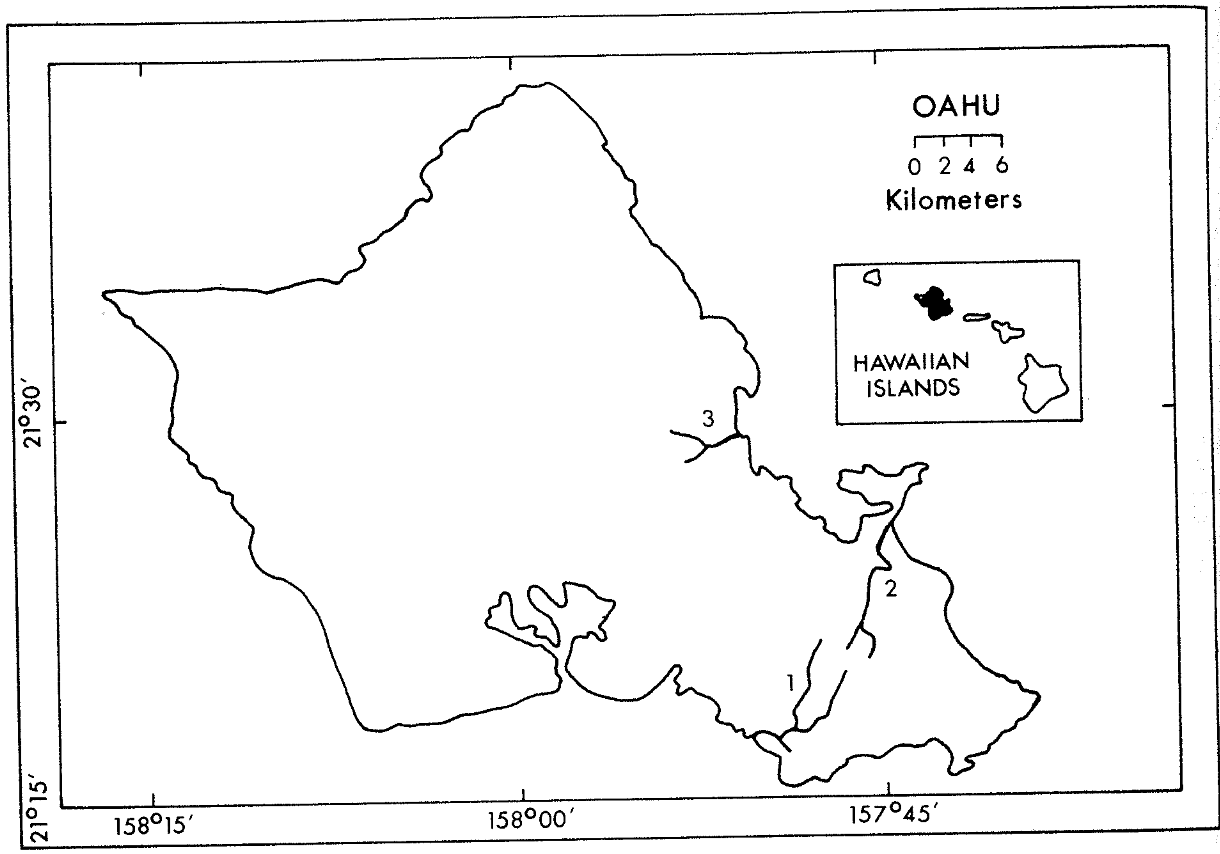

Figure 1. Locations of study streams on Island of Oahu: Manoa-Palolo (1), Maunawili (2), and Waiahole (3).

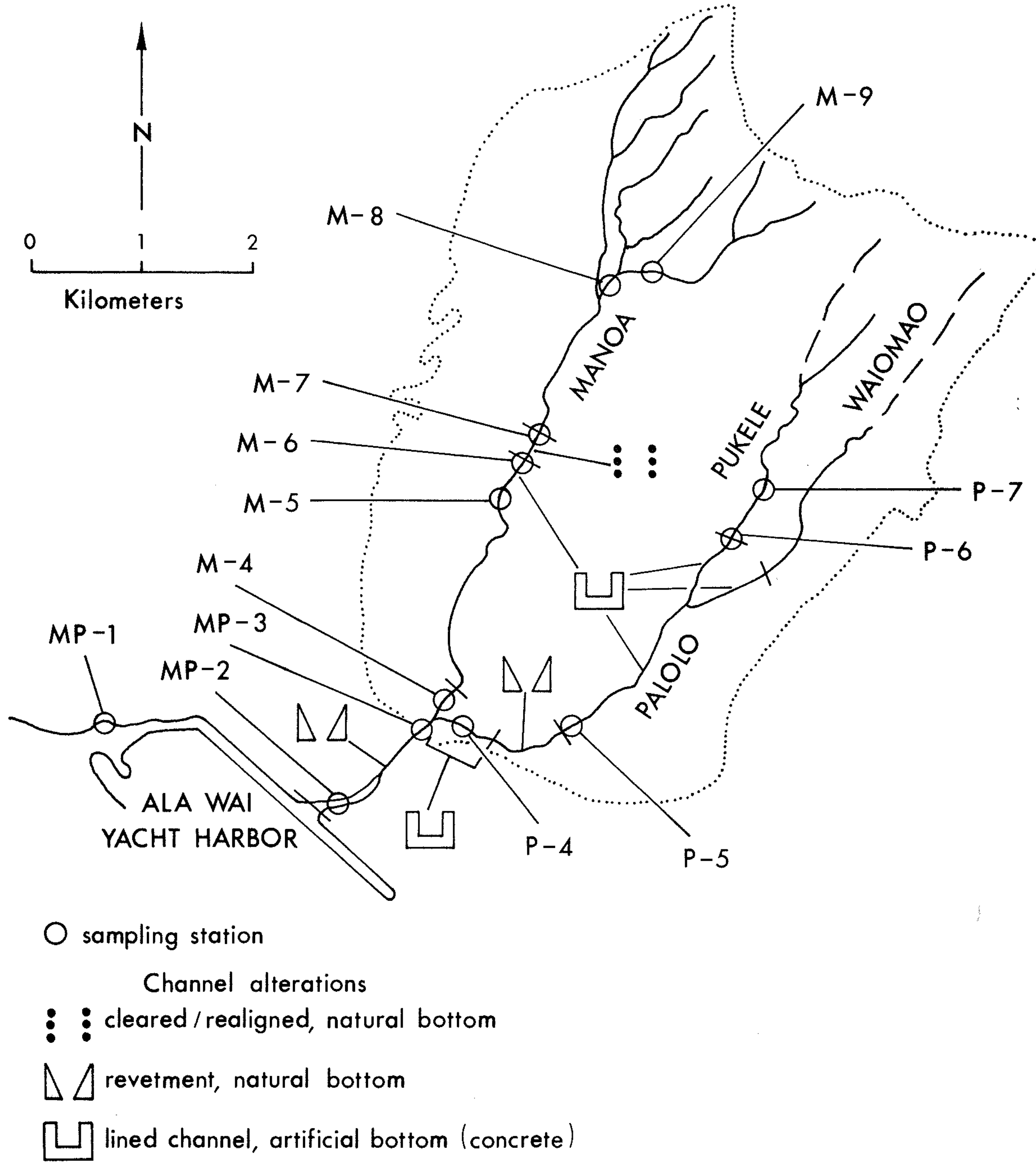

Figure 2. Drainage of Manoa and Palolo Streams, Oahu, showing locations of sampling stations, channelized sections of stream, and watershed limits.

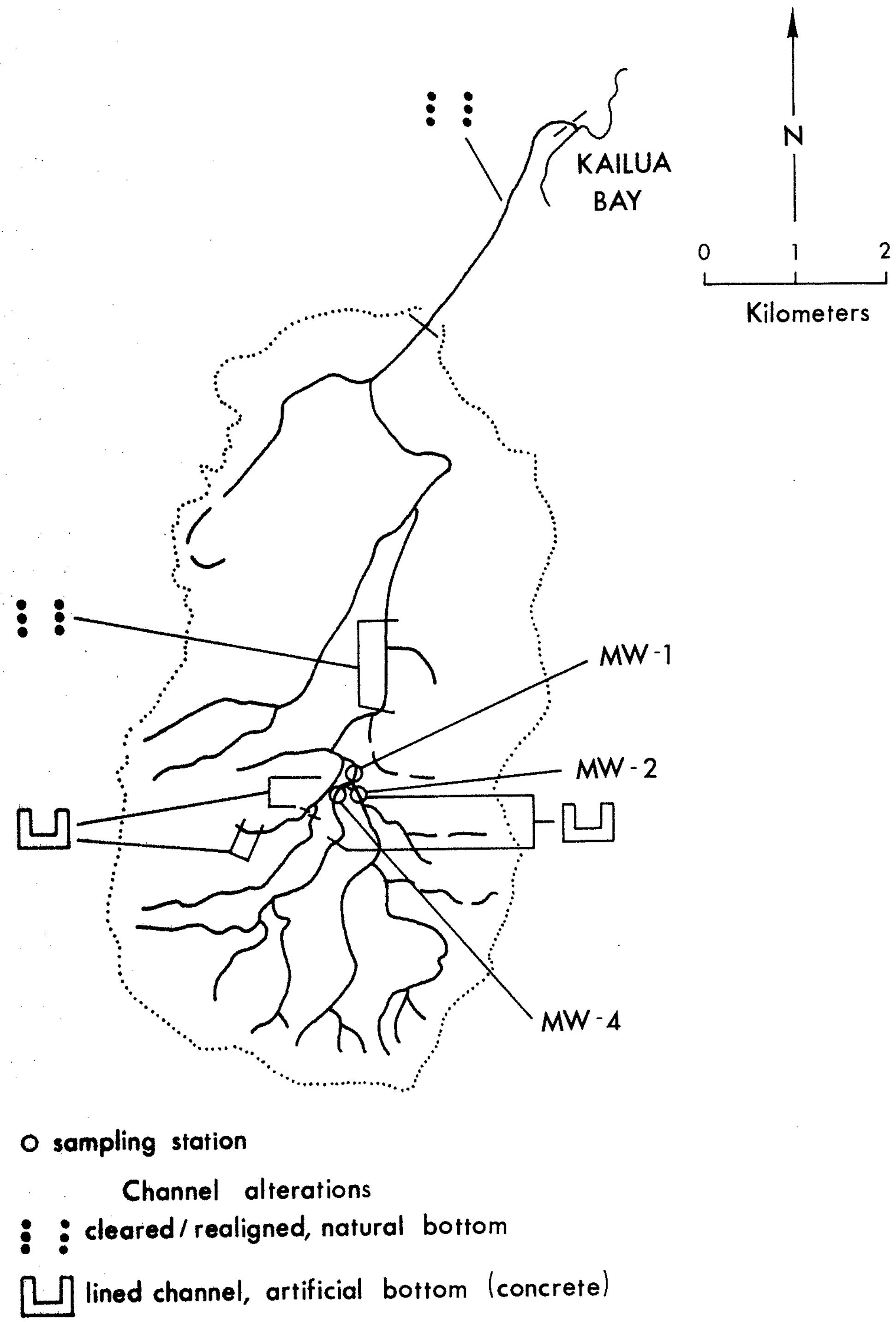

Figure 3. **Drainage of** Maunawili Stream, Oahu, showing locations of **sampling stations**, channelized sections of stream, and watershed **limits.**

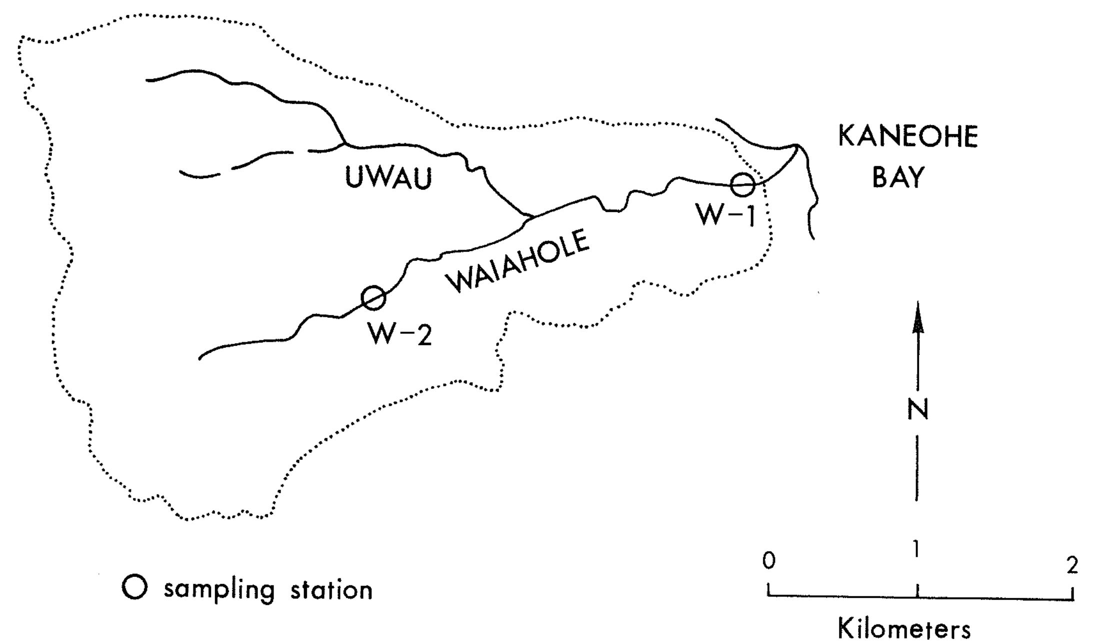

Figure 4. Drainage of Waiahole Stream, Oahu, showing locations of sampling stations and watershed limits.

was calculated. Monthly temperature means for all stations were examined for significant seasonal variation using a one-way analysis of variance.

Stations P-7 and P-5, representing the upstream natural and downstream lined channel conditions respectively, were sampled daily (1400-1500) for one week in April 1978 to examine fluctuations in temperature, pH and conductivity over a six-day period. Twenty-four hour variation in temperature, pH, conductivity and dissolved oxygen at the same two stations was recorded by hourly measurements on one day in September 1978. Diel variation in temperature and pH was recorded at Station P-4 in July 1977.

Illumination (ℓux) was measured in the shade and in the open (direct unshaded line to sun or region of maximum brightness) at three stations on windward Oahu (W-1, W-2, MW-4) and three stations on leeward Oahu (M-4, P-5 and P-7). All measurements were made with a LI-COR Model Li-185A Photometer, 0.5-1.0 m above the water surface. The probe was oriented upwards at several angles until a maximum reading was obtained, and this value was recorded. Measurements were made between 0800 and 0900, 1100 and 1200, and 1400 and 1500, in February and in late July or early August of 1978.

Water samples were taken for measurement of turbidity (NTU) for several weeks at the regular weekly monitoring time (1400-1500) in August 1978. Only non-freshet flow conditions were sampled, however several stations were sampled during periods of high flow in September 1978 for comparative purposes. Measurements were made using a Hach Model 2100A Turbidimeter.

LABORATORY INVESTIGATIONS

Specimens

Native animals were collected in various streams on the islands of Oahu, Kauai and Maui. Fishes and crustaceans were taken by pole net, dip net, or with a Coffelt Electronics Electro-Shocker Model BP-2 or BP-3. Mollusks were collected by hand. Unless otherwise stated, specimens brought to the laboratory were introduced immediately into 60-liter aquaria with under-gravel aeration and activated charcoal filters. Lava rocks similar to those found in natural stream beds were placed on top of gravel to provide shelter. Lengths of PVC plastic piping (8-12 cm long, 4-5 cm inside diameter) were occasionally used to supplement rock shelter, particularly in tanks containing the prawn M. grandimanus. Aquaria were filled with tap water (pH 7.8-8.2, conductivity 250-280 μmhos). Aquaria water temperatures showed a diurnal range of approximately 21-24°C, which compares well with the natural variation in middle and lower reaches of unaltered streams. All aquaria received prophylactic treatments through addition of 1-3 drops of a commercial copper sulfate solution prior to introduction of animals. Henceforth, the above conditions shall be referred to as "standard laboratory conditions."

Upper Lethal Temperature Determination

The upper lethal temperatures were determined for all adult and many post-larval/juvenile sub-groups of all indigenous species. Specimens were acclimated to standard laboratory conditions for three days prior to testing. This time period is considered adequate primarily because of the similarity in temperatures of stream collection sites and laboratory aquaria.

Following acclimation, temperature was raised in the original tanks with two 100 watt heaters at a rate of approximately 0.03°C/min until all animals were dead. "Death" was taken to be cessation of opercular movement in fishes, end of physical movements in general in crustaceans, and loss of hold on substrate and/or end of movements in mollusks. The latter is of more ecological importance than it is an indicator of physiological death. For the fishes and crustaceans, the "death" points fall somewhere between the critical thermal maxima (Cowles and Bogert 1944) and true physiological death.

Throughout the study, emphasis was placed on maximum daily temperatures (1400-1500) and the nature of the rate of temperature elevation. In lethal testing, heating was timed so as to simulate natural daily increases in stream temperature, with final temperatures coming in middle to late afternoon. Laboratory mortalities thus compare with those occurring in situ when an organism encounters a diurnal temperature elevation to levels outside its zone of tolerance. When the final temperature was above 37-38°C, heating rate fell to approximately 0.01°C/min, however such decreases in heating rate are also observed in the field.

The time and temperature of death for each individual was recorded, and the interval of time and temperature for 100% mortality, as well as LD_{50}, was determined. All animals were measured, and if possible sexed, in order to examine variations in resistance due to size or sex. Fishes were also weighed, and condition factors ($K=(Weight/Length^3) \times 10^5$; Carlander 1969) were calculated for comparisons between species and populations.

There are certainly numerous ecological instances when constant temperature lethal testing is called for, particularly in situations of constant thermal effluent from power plants (e.g. Thermal Ecology Program publications, Savannah River Ecology Laboratory, Univ. of Georgia). In the present study, the use of constant temperature techniques appears inappropriate on both ecological and practical grounds: 1) elevated temperatures in streams are not a result of a point source derived effluent, but rather an extension of natural ranges in diel variation; 2) migratory animals are presumably exposed to rapid changes in temperature regime without lengthy acclimation; and 3) availability of most species restricts the testing design.

A major problem in methods of upper lethal determination employing gradual heating concerns the continued elevation of temperature beyond that final point from which survival would be possible. To briefly explore this dilemma, only in order to better clarify results of the upper lethal tests, a short-term test was performed. Following 3-day acclimation to standard laboratory conditions, samples of several species were subjected to temperature elevation to 33°C on each of two consecutive days. Temperature was allowed to fall to ambient levels for approximately 18 hours following the attainment of the 33°C peak, both prior to and following heating on the second day. Mortalities were recorded.

Long Term Metabolic Effects - Growth

A series of experiments was performed to determine the effect of daily temperature elevation on gross growth in post-larval/juvenile samples of *Awaous genivittatus*. Individuals were collected by pole net in the lower reaches of Honolulu's Nuuanu Stream. Lengths of all fish were measured immediately after capture, and fish were divided into groups of 10 among buckets for transportation to the laboratory. Each group was introduced into a separate aquarium under standard laboratory conditions.

For 1 month following capture, the temperature of each test tank was elevated daily to a set temperature by means of subsurface heaters. Effort was made to simulate natural heating both in rate and approximate time of peak (1400-1500). Water was then allowed to cool naturally until the following morning, at which time heating would again commence. Average temperatures in treatment tanks were above those in streams with identical maximum temperatures primarily because of slower cooling rates in the laboratory situation.

Each series of experiments involved one, two or three test tanks, and one control in which temperature was allowed to rise naturally to about 24°C each day. The daily minimum temperature in all tanks was approximately 21-22°C. A commercial flake food was introduced into all test tanks daily. Fish were presumably fed to satiation as evidenced by only slight accumulations of uneaten food over the gravel throughout the test period.

At the end of the 30-day periods, mortalities were recorded and lengths of all surviving fish were again measured. By means of the formula

$$\text{Weight} = a \cdot \text{Length}^N$$

(Carlander 1969), lengths at capture and at end of the test period were converted to weights (see Appendix A for species specific values for the "a" and "N" constants). Mean percent increase in weight and mean percent change in variance within each temperature group were calculated. These values were plotted against daily maximum temperature during the test period for each series. The curves produced were examined in relation to the model of Gibbons (1976) which relates population success to thermal loading.

Non-destructive identification of post-larval forms of the genus *Awaous* is difficult. This resulted in the introduction into experimental tanks of some *A. stamineus* in addition to *A. genivittatus*. *A. stamineus* individuals

tended to be the smallest fishes in collection groups, and suspected members of the species were noted. When the same number of *A. stamineus* were positively identified after the 30-day growth period, this group was analyzed separately from the *A. genivittatus*.

A final series of experiments sought to examine the growth-temperature relationship in post-larval *Lentipes concolor*.

Effects of Reduced Streambed Heterogeneity and Water Depth

The absence of shelter and pool-riffle depth variability in the lined channel distinguishes it most from the unaltered channel. A simple test was devised to obtain preliminary data on the possible deleterious consequences of streambed denudation. Two adult *Awaous stamineus* and two adult *Sicydium stimpsoni* were obtained from unaltered streams on Kauai. One fish from each pair was placed in one of two 20-liter aquaria, containing a gravel bottom cover, rock shelters and water to a depth of 20 cm. The other two fishes were placed into identical aquaria except that rock shelters were absent and water depth was held at 8 cm, both attempts to simulate the lined channel morphological situation. Temperature fluctuation in all aquaria was that to be expected under standard laboratory conditions. Fishes were fed a commercial flake preparation every two days. Water was changed and feces collected in each tank approximately once a week.

Following a 130-day period, survivors were subjected to upper lethal temperature tests, and the lethal limit and condition factor of each was compared with that of the other conspecific in the pair, as well as with those of conspecifics utilized in previous testing.

RESULTS

PHYSICOCHEMICAL SAMPLING

Ranges, means and standard deviation of temperature, pH, conductivity and dissolved oxygen, measured between 1400 and 1500 over the entire study, for the twenty sampling stations are shown in Tables 2-5. Mean conductivity, pH and dissolved oxygen all tended to increase with downstream flow. Mean temperature and variance about the mean tended to increase significantly ($P<.05$) with downstream flow. Temperature increase per meter of channel length is shown in Table 6 to be greatest in lined channels. There is, however, variability in heating rates between similar channel types.

Figues 5-8 show the 24-hour fluctuation of the four parameters at the upstream natural bottom station P-7 and its downstream lined channel counterpart P-5. Figure 9 presents 24-hour fluctuation of pH and temperature at station P-4. Only temperature showed maximum values in the 1400-1500 period; pH and dissolved oxygen reached maximum values near 1200. Peak conductivity readings occurred at each station around 1200-1300, however, a larger second peak occurred around 2200 at the lined channel station.

Temperature

Two cases are represented in which water flowing from a lined channel joins that from a much less degraded stream branch (Fig. 2, 3). Stations P-4 and MW-4 were situated at the downstream ends of lined channels slightly upstream of the confluence. They showed higher mean peak temperature, pH and dissolved oxygen than the neighboring stations, M-4 and MW-2 respectively, which were upstream of the junction on the opposing branch.

Distinct thermal stratification was observed below the confluence of "warm" Palolo and "cool" Manoa streams. However, temperatures recorded below the junction at MP-3 were found to be little different from those taken at intervals for some 300 m downstream, and can be considered representative of the water mass created at the confluence.

Stations MP-1 and MP-2 were stratified with respect to both salinity and temperature. Sampling near the surface at these sites produced higher temperature and lower conductivity/salinity readings.

Table 2. Temperature Ranges and Means at 1400-1500 hrs. as Measured over the Entire Study for 20 Sampling Stations

Station	No. of Observations	Range (°C)	Mean (°C)	SD (°C)
W-1	49	20.9-25.7	23.1	1.3
W-2	48	19.8-21.9	20.9	0.6
MW-1	49	20.5-24.8	22.9	1.1
MW-2	46	19.7-23.8	22.0	1.1
MW-3	48	21.0-27.3	24.3	1.5
MW-4	37	20.6-26.8	23.8	1.4
MW-5	35	24.4-27.0	25.8	0.8
MP-1	38	24.1-29.0	26.4	1.4
MP-2	49	24.7-31.1	28.2	1.5
MP-3	55	20.5-29.7	26.6	1.8
M-4	61	20.2-27.9	25.2	1.7
M-5	50	20.8-27.5	24.7	1.5
M-6	36	20.4-26.4	23.8	1.2
M-7	50	20.2-25.1	23.2	1.1
M-8	33	19.7-22.7	21.6	0.7
M-9	33	19.5-22.1	21.2	0.7

Continued

Table 2 (Concluded)

Station	No. of Observations	Range (°C)	Mean (°C)	SD (°C)
P-4	61	21.3-35.6	29.9	3.2
P-5	54	23.1-36.2	30.0	3.4
P-6	35	20.8-24.6	23.0	0.9
P-7	55	20.0-23.6	22.3	0.7

Table 3. Ranges and Means of pH at 1400-1500 hrs. for 20 Sampling Stations

Station	No. of Observations	Range	Mean	SD
W-1	7	(6.9-7.2)	7.0	0.1
W-2	7	(6.9-7.4)	7.1	0.2
MW-1	7	(6.8-7.8)	7.4	0.3
MW-2	7	(6.6-7.7)	7.1	0.3
MW-3	7	(7.7-8.1)	8.0	0.1
MW-4	7	(8.0-8.5)	8.3	0.2
MW-5	7	(5.1-7.2)	6.4	0.7
MP-1	3	----	8.0	0
MP-2	6	(7.9-8.6)	8.2	0.3
MP-3	7	(8.4-9.5)	8.9	0.4
M-4	7	(7.4-8.7)	8.1	0.5
M-5	7	(7.4-8.1)	7.8	0.2
M-6	7	(7.1-8.0)	7.5	0.4
M-7	7	(6.9-7.7)	7.2	0.2
M-8	6	(6.6-7.7)	7.1	0.4
M-9	6	(6.7-7.9)	7.3	0.4

Continued

Table 3 (Concluded)

Station	No. of Observations	Range	Mean	SD
P-4	7	(9.3-10.4)	9.9	0.4
P-5	7	(9.0-10.4)	9.8	0.5
P-6	7	(6.9-7.9)	7.4	0.4
P-7	7	(6.5-7.7)	7.2	0.4

Table 4. Conductivity Ranges and Means at 1400-1500 hrs. for 20 Sampling Stations

Station	No. of Observations	Range (μmhos)	Mean (μmhos)	SD (μmhos)	Mean Salinity (°/₀₀)
W-1	5	(154-165)	159	4	
W-2	5	(122-141)	133	7	
MW-1	5	(175-195)	183	9	
MW-2	5	(178-199)	193	9	
MW-3	5	(160-181)	169	9	
MW-4	5	(150-169)	157	8	
MW-5	5	(260-372)	319	40	
MP-1	1				31
MP-2	5				25
MP-3	5	(143-219)	185	28	
M-4	5	(149-201)	173	19	
M-5	5	(118-167)	153	20	
M-6	5	(115-174)	150	22	
M-7	5	(110-171)	148	24	
M-8	5	(77-116)	107	17	
M-9	5	(70-127)	111	24	

Continued

Table 4 (Concluded)

Station	No. of Observations	Range (μmhos)	Mean (μmhos)	SD (μmhos)	Mean Salinity (°/∘∘)
P-4	6	(187-358)	269	62	
P-5	6	(122-368)	272	85	
P-6	6	(99-220)	195	48	
P-7	6	(90-204)	181	45	

Table 5. Dissolved Oxygen Ranges and Means at 1400-1500 hrs. for 20 Sampling Stations

Station	No. of Observations	Range (ppm)	Mean (ppm)	SD (ppm)	Mean % Saturation	SD (%)
W-1	4	7.9-8.4	8.1	0.2	95	4.6
W-2	4	8.6-9.0	8.8	0.2	99	1.3
MW-1	4	7.8-8.7	8.4	0.4	98	3.8
MW-2	4	7.8-8.8	8.3	0.5	95	3.8
MW-3	4	8.5-9.3	9.1	0.4	107	4.8
MW-4	4	8.9-10.1	9.6	0.5	113	7.1
MW-5	4	7.2-8.1	7.6	0.4	93	5.1
MP-1	0					
MP-2	4	7.8-9.6	8.7	0.7	111	9.0
MP-3	4	9.3-9.8	9.5	0.2	119	3.0
M-4	4	9.1-9.5	9.3	0.2	110	2.6
M-5	4	10.1-10.7	10.4	0.3	124	4.2
M-6	4	9.0-9.2	9.1	0.1	107	1.3
M-7	4	8.7-9.0	8.8	0.2	102	0.8
M-8	4	8.6-9.2	8.9	0.3	100	2.8
M-9	4	8.5-9.3	8.9	0.4	100	4.6

Continued

Table 5 (Concluded)

Station	No. of Observations	Range (ppm)	Mean (ppm)	SD (ppm)	Mean % Saturation	SD (%)
P-4	4	11.4-15.2	13.5	1.8	181	24.8
P-5	4	10.6-13.9	12.0	1.4	160	18.3
P-6	3	8.7-9.0	8.9	0.2	103	0.6
P-7	4	8.8-9.0	8.9	0.1	102	0.5

Table 6. Comparisons of Mean Peak Temperatures Derived from Paired Samples at Neighboring Stations

Stations[a]	No. of Observations	$\overline{X}_d-\overline{X}_u$ [b] (°C)		Channel Type[c]	Distance[d] (m)	°C/m
W-2, W-1	48	2.1	P<.01	1	3400	6.2×10^{-4}
M-9, M-8	33	0.5	P<.01	1	425	1.2×10^{-3}
M-8, M-7	33	1.5	P<.01	1	2200	6.8×10^{-4}
M-7, M-6	36	0.6	P<.05	2,3	200	3.0×10^{-3}
M-6, M-5	36	0.9	P<.01	4	350	2.6×10^{-3}
M-5, M-4	50	---	NS	1,2,3	2500	-------
P-7, P-6	34	0.5	P<.01	1	450	1.1×10^{-3}
P-6, P-5	34	7.8	P<.001	4	2400	3.3×10^{-3}
P-5, P-4	48	---	NS	1,2,3,4	900	-------

[a] Upstream station listed first.

[b] d=downstream station, u=upstream station.

[c] Alterations between stations: 1-unaltered, 2-bank revetment, 3-vegetation cleared, 4-lined channel.

[d] Horizontal length of channel between neighboring stations.

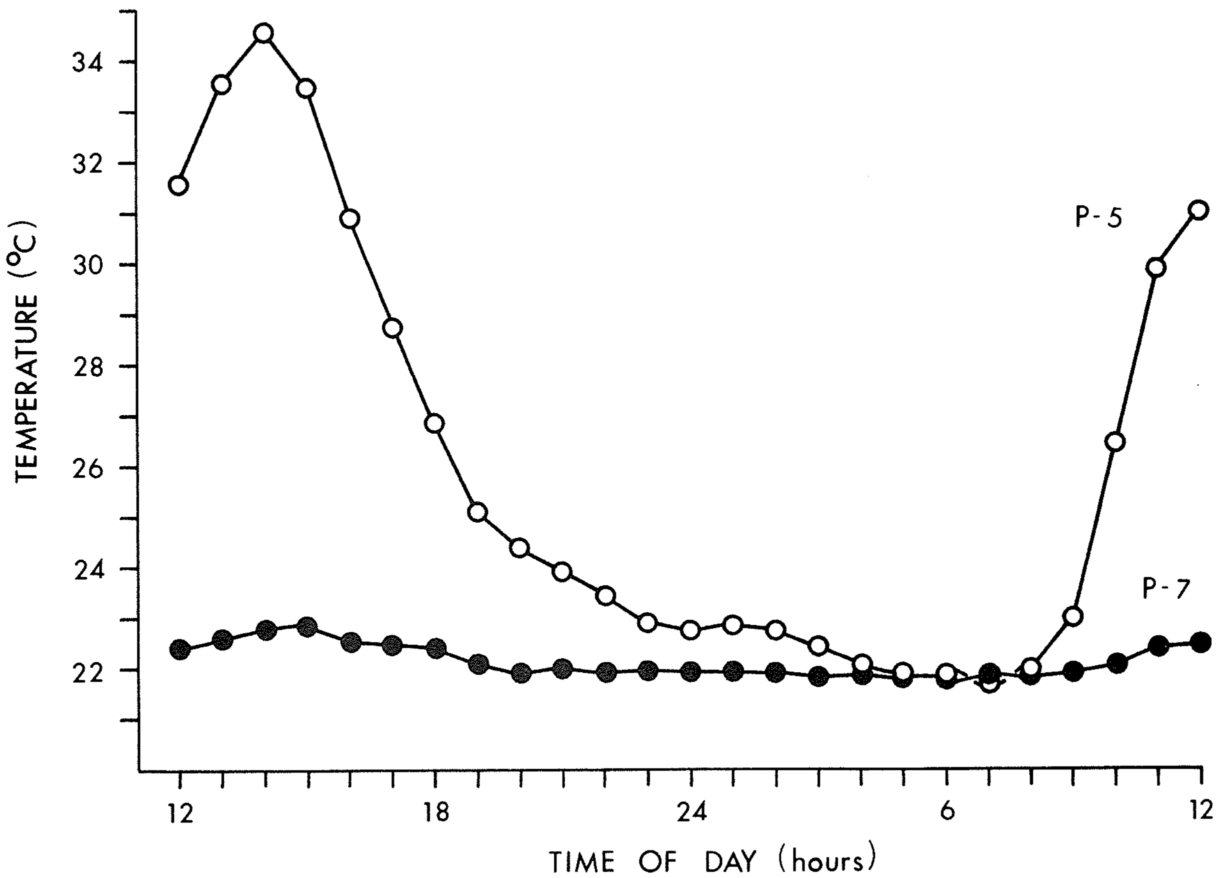

Figure 5. Diel changes in temperature at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

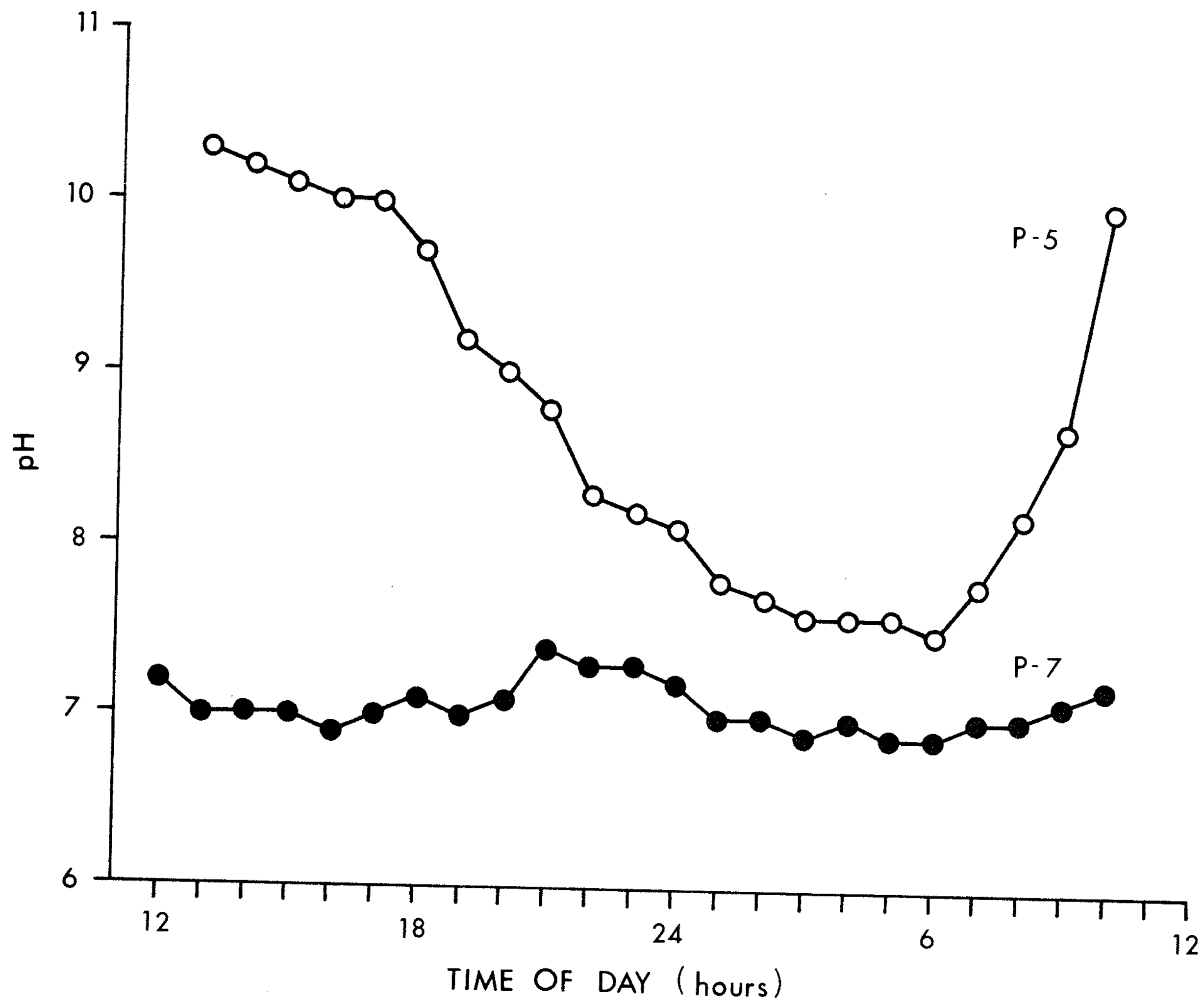

Figure 6. Diel changes in pH at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

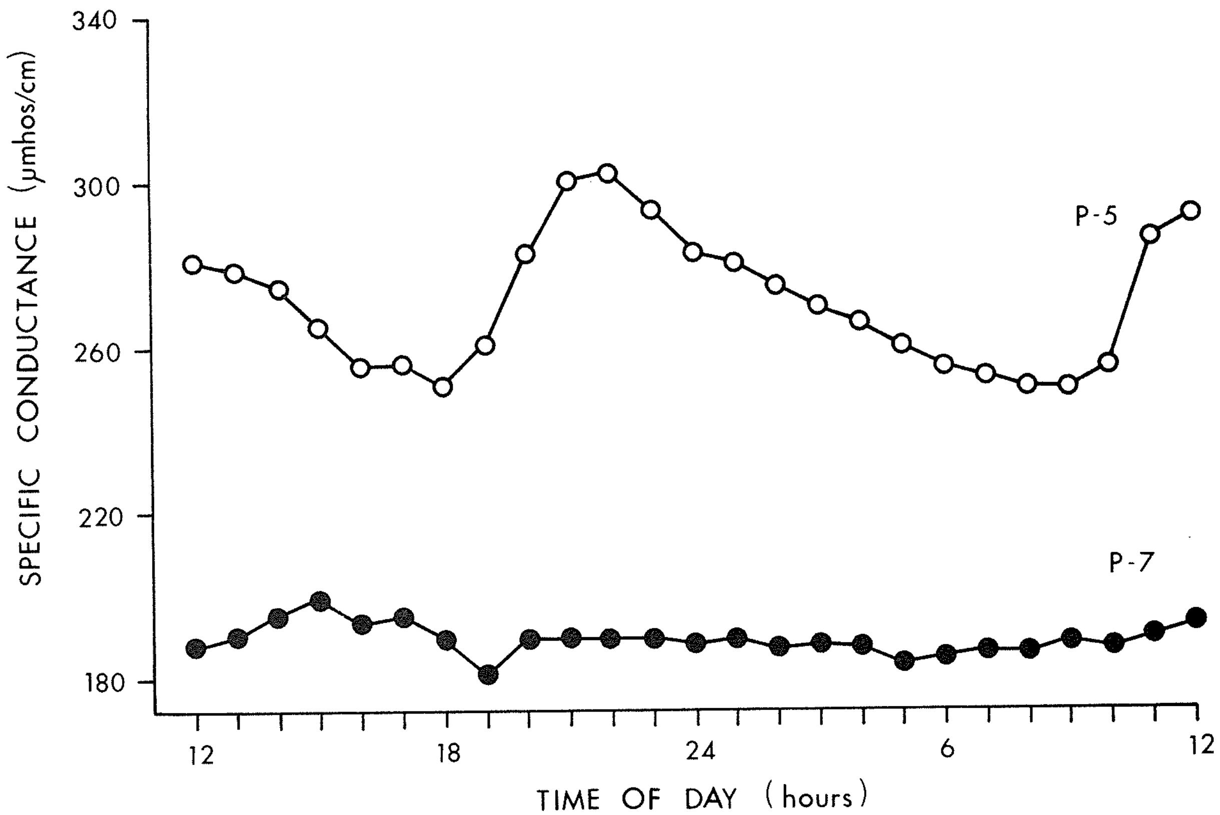

Figure 7. Diel changes in conductivity at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

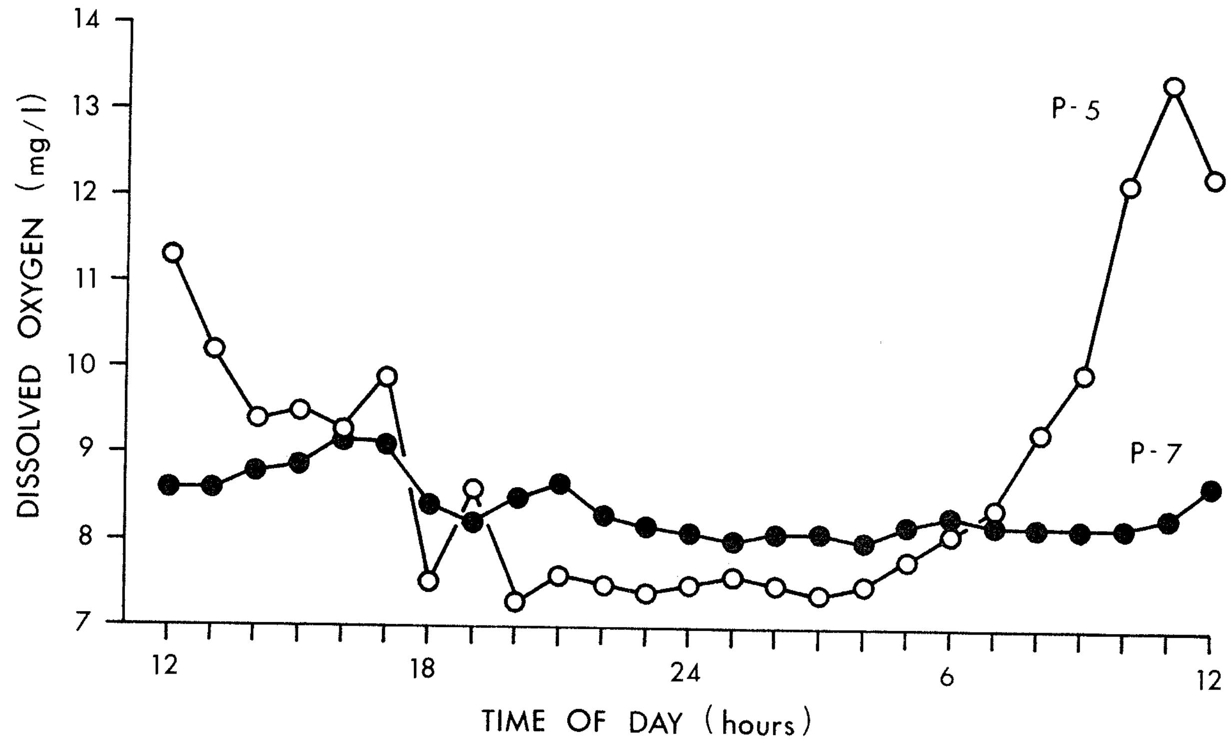

Figure 8. Diel changes in dissolved oxygen at upstream (unaltered) station P-7 and downstream (lined channel) station P-5 in Palolo Stream, 26-27 September 1978.

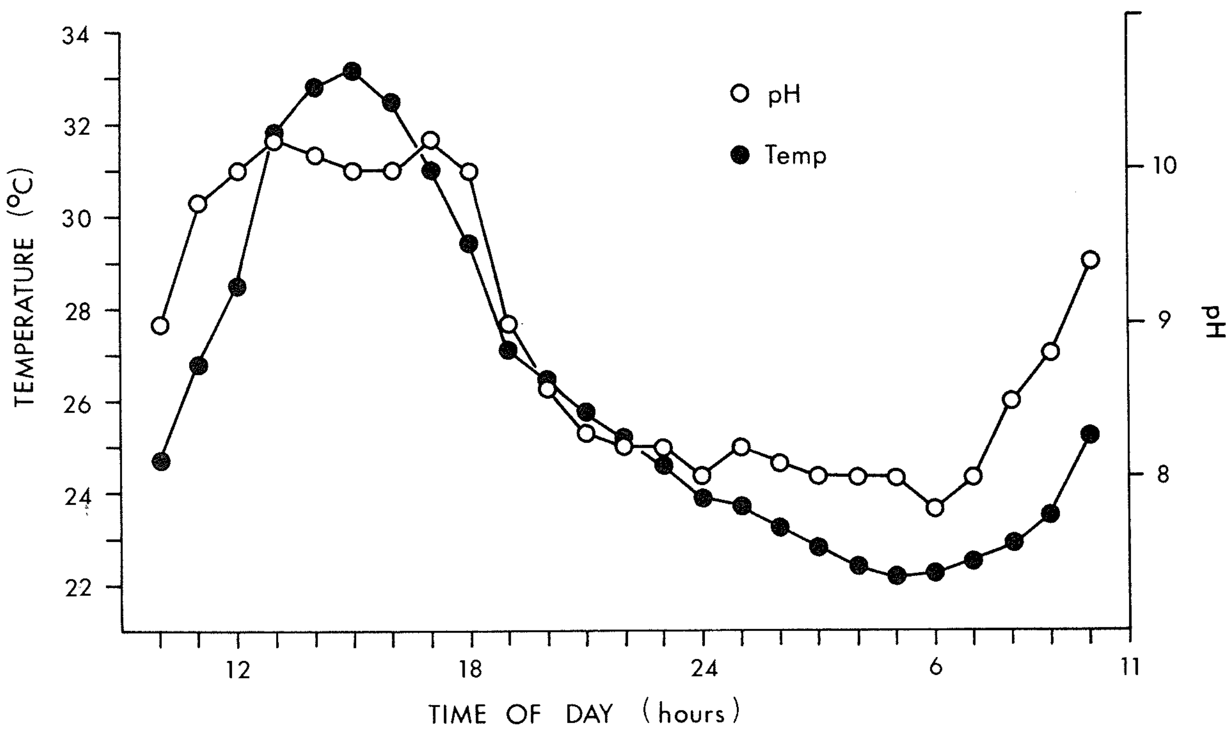

Figure 9. Diel changes in temperature and pH at downstream (lined-channel) station P-4 in Palolo Stream, 21-22 July 1977.

While this study focused on elevated temperatures through examination of daily maxima, minimum temperatures were encountered during work on 24-hour fluctuations and morning illumination measurements. On 10 Feb 78 between 0800 and 0900, the following temperatures were recorded at the stations listed:

P-7	20.8°C
P-5	17.8°C
P-4	19.8°C
M-4	18.8°C

This was the only occasion during the course of the study when temperatures below 19.0°C were recorded in any stream. It was also the only occasion when temperature below a length of lined channel (P-5) was found to be considerably lower than that in the upstream unaltered channel (P-7).

It would be expected that temperature measurement in daylight hours in the region of flow with greatest velocity (typically mid-channel) at most stations would yield the minimum value for the particular station at the particular time (Weekly physicochemical sampling was conducted at mid-channel). It was in fact observed that water in midstream in lined channels had higher velocity and lower temperature than at the edges. Several instances of this phenomenon at station P-5 are shown below:

Time of Day	Temperature at mid-channel (°C)	Temperature at edge (°C)
1400-1500	27.1	31.6
1400-1500	31.9	34.8
1400-1500	36.2	37.2
0730	23.3	23.6

Fluctuations in 1400-1500 temperature, pH and conductivity at stations P-5 and P-7 for six consecutive days in April 1978 are shown in Table 7. It is seen that variances of the measurements about the mean for the six days are comparable to the variances about the annual means for the two stations.

A one-way analysis of variance showed temperature variation between months to account for a significant (F, $P<.05$) proportion of the variation in the annual mean at all stations except P-5 and E-5, which are located at the downstream ends of lined channels. (Stations MP-3, MP-2, and MP-1 were not included in this analysis). All stations had maximum monthly mean temperatures in the period August-October and minimum monthly means in the period December-March. Seasonal progression of monthly mean temperatures was found only at stations M-8, M-7, M-6, P-7, P-6, W-2, W-1, and MW-2.

Table 7. Temperature, pH and Conductivity at 1400-1500 hrs. for Six Consecutive Days

Date	Station P-5			Station P-7		
	Temp. (°C)	pH	Conductivity (μmhos)	Temp. (°C)	pH	Conductivity (μmhos)
9 Apr 78	28.1	9.9	251	22.1	7.1	209
10 "	25.9	8.6	163	20.7	6.8	129
11 "	23.1	8.6	119	20.0	7.0	100
12 "	29.3	9.4	213	21.8	6.6	170
13 "	29.8	9.8	263	22.2	6.6	189
14 "	28.8	9.8	290	22.0	6.6	192
Mean	27.5	9.4	217	21.5	6.8	165
SD	2.5	0.6	65	0.9	0.2	42

These represent all stations located upstream from channelized stream sections with the exception of upstream station M-9, which did not show regular seasonal variation.

Illumination

Only those measurements of illumination made during periods of an exposed sun were considered. This restriction decreased variability in the results but limited the number of possible times for recording.

Maximum values (ℓux) were measured during noon and afternoon periods. Illumination appeared to be slightly higher in July-August than in February, but values from the different seasons were generally similar.

Maximum illumination values recorded at six stations in both open and shaded conditions are given in Table 8.

Table 8. Representative Maximum Illumination at Six Sampling Stations

Station	Open (ℓux)	Shaded (ℓux)	Channelization
W-2	105,000	530	none
W-1	114,000	3300	none
P-7	114,000	2100	none
MW-4	135,000	6500	lined channel
P-5	147,000	23,400	lined channel
M-4	135,000	12,600	revetment

Mean temperatures from these six stations (Table 2) correlated with the above illumination values from both open (r=.90) and shaded (r=.99) conditions.

Turbidity

Ranges, means and standard deviations at 1400-1500 of turbidity at the 20 sampling stations are presented in Table 9. All measurements were made at times of moderate flow (i.e. after or during average meteorological conditions). Turbidity tended to increase with downstream flow. This increase appeared to be higher in natural channels than in lined channels, but the trend was not consistent. Representative values for turbidity during freshet flow for several stations are shown in Table 10.

Table 9. Turbidity Ranges and Means at 1400-1500 hrs. for 20 Sampling Stations

Station	No. of Observations	Range (NTU)	Mean (NTU)	SD
W-1	4	3.4-4.7	4.1	.7
W-2	4	1.1-2.7	1.6	.8
MW-1	4	2.7-12.0	5.7	4.2
MW-2	4	2.5-16.0	6.1	6.6
MW-3	4	2.3-7.7	4.9	2.4
MW-4	4	2.5-7.7	3.9	2.6
MW-5	4	4.5-72.0	22.7	32.9
MP-1	1	----	2.4	--
MP-2	3	2.7-3.0	2.9	.2
MP-3	3	1.6-2.5	2.0	.5
M-4	3	1.7-3.4	2.3	1.0
M-5	3	2.1-2.8	2.5	.4
M-6	3	2.3-2.9	2.6	.3
M-7	3	2.1-3.1	2.5	.5
M-8	3	1.7-3.2	2.6	.8
M-9	3	1.4-2.8	2.2	.7

Continued

Table 9 (Concluded)

Station	No. of Observations	Range (NTU)	Mean (NTU)	SD
P-4	3	1.3-2.2	1.6	.5
P-5	3	1.4-2.5	2.1	.6
P-6	3	1.5-1.7	1.6	.1
P-7	3	1.1-1.2	1.1	.1

Table 10. Representative Turbidity Values for Eight Sampling Stations During Freshet Flow

Station	Turbidity (NTU)
MP-3	11
M-4	13
M-5	41
M-6	37
M-7	25
M-8	31
M-9	12
P-4	4

LABORATORY INVESTIGATIONS

Upper Lethal Temperatures

The upper lethal temperatures for nine indigenous and two exotic species are shown in Table 11. Only in *Eleotris sandwicensis* trial 1 did acclimation mortality account for a significant portion of the sample. However, the dead individuals were observed to be suffering from leech and parasite infestation at the time of capture. Post-larval samples showed greater tolerance than adults in all cases examined. However, visually observed acute stress appeared at lower temperatures in the former.

There was no relationship between tolerance and size, sex or condition factor. It was hypothesized that any selection caused by degraded environments on upstream migrants would be reflected by a relationship between tolerance and collection site. Trials 1 and 2 for both *Awaous stamineus* and *Eleotris sandwicensis* adults utilized organisms from natural (Manoa Stream, Kauai and Waiahole Stream, Oahu respectively) and degraded (Palolo Stream[1] and Moanalua Stream, Oahu respectively) environments. There were

[1]*A. stamineus* was collected between station P-6 and P-7, upstream from the extensive Palolo lined channel. Small numbers were also regularly observed in a mid-channel pool in the funnel of a spillway approximately 200 m upstream from station P-5. Norton et al. (1978) collected no native fishes in this or any other lined channel. Native fishes above the Palolo lined channel have not been reported heretofore.

Table 11. Upper Lethal Temperature Limits of Native and Selected Exotic Species

Species	Sample	Trial No.	Time[a] (min)	Temperature[a] (°C)	LD_{50}[b] (°C)
Mollusks					
Neritina granosa	12 adult	1	170	38.4-40.1	38.8
Melania sp.	20 adult	1	89	36.7-38.6	37.5
Crustaceans					
Atya bisulcata	15 adult	1	27	34.0-34.5	34.2
"	25 post-larvae	1	40	34.9-36.1	----
Macrobrachium grandimanus	27 adult	1	35	36.4-36.5	36.5
"	21 adult	2 (33‰)	81	36.8-37.3	37.2
Pisces					
Awaous genivittatus	10 adult	1	44	39.2-39.7	----
"	16 adult	2	34	39.4-39.7	39.7
"	10 post-larvae	1	38	39.5-40.1	39.9
Awaous stamineus	5 adult	1	55	37.2-38.7	38.1
"	4 adult	2	45	37.2-38.8	38.4

Continued

Table 11 (Concluded)

Species	Sample	Trial No.	Time[a] (min)	Temperature[a] (°C)	LD_{50}[b] (°C)
Awaous stamineus	25 post-larvae	1	23	39.0-39.3	39.3
Eleotris sandwicensis	1 adult	1	--	39.2	----
"	6 adult	2	30	39.2-39.6	39.3
Sicydium stimpsoni	3 adult	1	7	35.7-35.8	35.8
"	4 adult	2	14	35.4-35.6	35.5
Lentipes concolor	6 adult	1	5	35.9-36.1	36.0
"	9 adult	2 (33°/oo)	15	36.1-36.3	36.2
S. stimpsoni/L. concolor	11 post-larvae	1	23	36.2-36.5	36.4
Poecilia mexicana	12 adult	1	25	41.2-41.4	41.3
Sarotherodon sp.	12 adult	1	17	42.7-43.1	42.9

[a]Range for mortality interval (first death to final death).

[b]Temperature at time of 50% mortality.

no population differences in tolerance within the small samples. Mean condition factor did not vary significantly between populations.

Acclimation to near 100% seawater resulted in increased tolerance to elevated temperatures in both Macrobrachium grandimanus and Lentipes concolor. Euryhaline species typically show greater resistance in saline media. (Remane and Schlieper 1971). Previous investigations showed that neither species of Awaous could survive in salt solutions above 15°/oo. (Hawaii Cooperative Fishery Research Unit, unpublished data).

Temperature elevation to 33°C on two consecutive days resulted in no mortality in Awaous genivittatus, A. stamineus, Lentipes concolor or Neritina granosa. The shrimp Atya bisulcata suffered 24% mortality in an adult group and 3% in a post-larval group.

In a separate trial without organisms, dissolved oxygen levels were found to decrease from 8.1 ppm at 22.8°C to 6.1 ppm at 38.1°C. Such concentrations should not pose any physiological problems to the organisms. Saturation remained above 90% throughout the test.

Temperature Effects on Growth

The results of four series of tests on the effect of daily temperature elevation on the growth of post-larval gobies are summarized in Table 12 and Figures 10 and 11. In each series, there were no significant differences between initial mean weights among temperature/species groups. With the exception of Series 6C, the month-long tests resulted in significant growth ($P<.01$) in all temperature groups. However, in few cases were differences between final mean weights of series groups significant. Treatment mortalities were insignificant with the exception of total mortality in Series 6C at 35°C.

All series show the trend of growth enhancement with increasing temperature up to a temperature for apparent optimal growth. Percent change in standard deviation within the sample has a similar relationship to temperature. However, while in phase with changes in growth, differences in change in standard deviation between series groups tend to be more pronounced.

Lack of shelter appeared to have little effect on gross growth in Awaous genivittatus. In A. stamineus, the lower growth in tanks without shelter was more pronounced. Increase in variance was less for both species in tanks without shelter. The effect of absence of rock shelters is comparable to the effect of temperature elevations above that for optimal growth.

Differences between series were considerable. Average initial weight in temperature groups was not clearly related to discrepancies in mean growth for identical treatments. Species sample size appeared to account for more of these differences, particularly in the mixed Awaous groups of Series 6B.

Table 12. Summary of Results of Growth vs Temperature Tests

Series	Species	Sample Size	Mortality (No.)	Temp.[a] (°C)	% Mean Increase[b]	% Change SD [c]
6	Awaous genivittatus	10	0	C[d]	202	165
6	"	9	0	30	268	723
6	A. stamineus	1	0	30	125	---
6A	A. genivittatus	11	0	C[d]	193	340
6A	"	10	0	28	342	650
6A	"	10	0	32	400	746
6A	"	8	1	34	362	444
6A	A. stamineus	1	0	34	127	---
6B	A. genivittatus	7	0	C[d]	300	700
6B	"	6	0	30 w/shelter	658	1700
6B	"	6	1	30 w/o shelter	646	1054
6B	"	8	1	36	555	1317

Continued

Table 12 (Concluded)

Series	Species	Sample Size	Mortality (No.)	Temp.[a] (°C)	% Mean Increase[b]	% Change SD [c]
6B	A. stamineus	3	1	C[d]	146	359
6B	"	4	0	30 w/shelter	884	1630
6B	"	4	0	30 w/o shelter	741	540
6B	"	2	0	36	224	-536
6C	Lentipes concolor	6	0	C[d]	9	-17
6C	"	5	0	30	0	9
6C	"	6	6	35	---	---

[a]Daily maximum temperature during month test period.

[b]Increase in weight as calculated from species specific weight vs length formulas.

[c]Change in standard deviation about the mean weights.

[d]C=Control test tanks; daily maximum temperature=24°C.

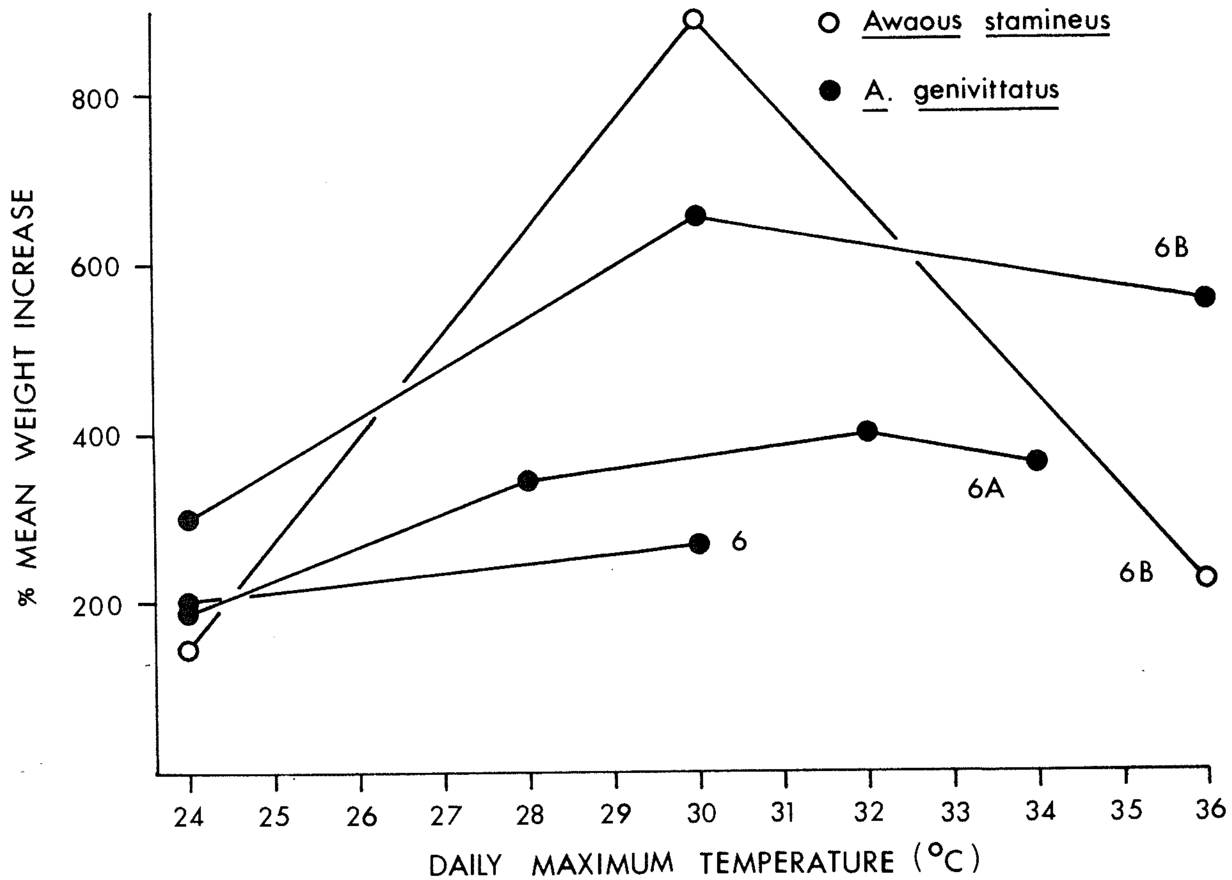

Figure 10. Growth of Awaous genivittatus (Series 6, 6A and 6B) and A. stamineus (Series 6B) during one month of exposure to different fluctuating temperature regimes.

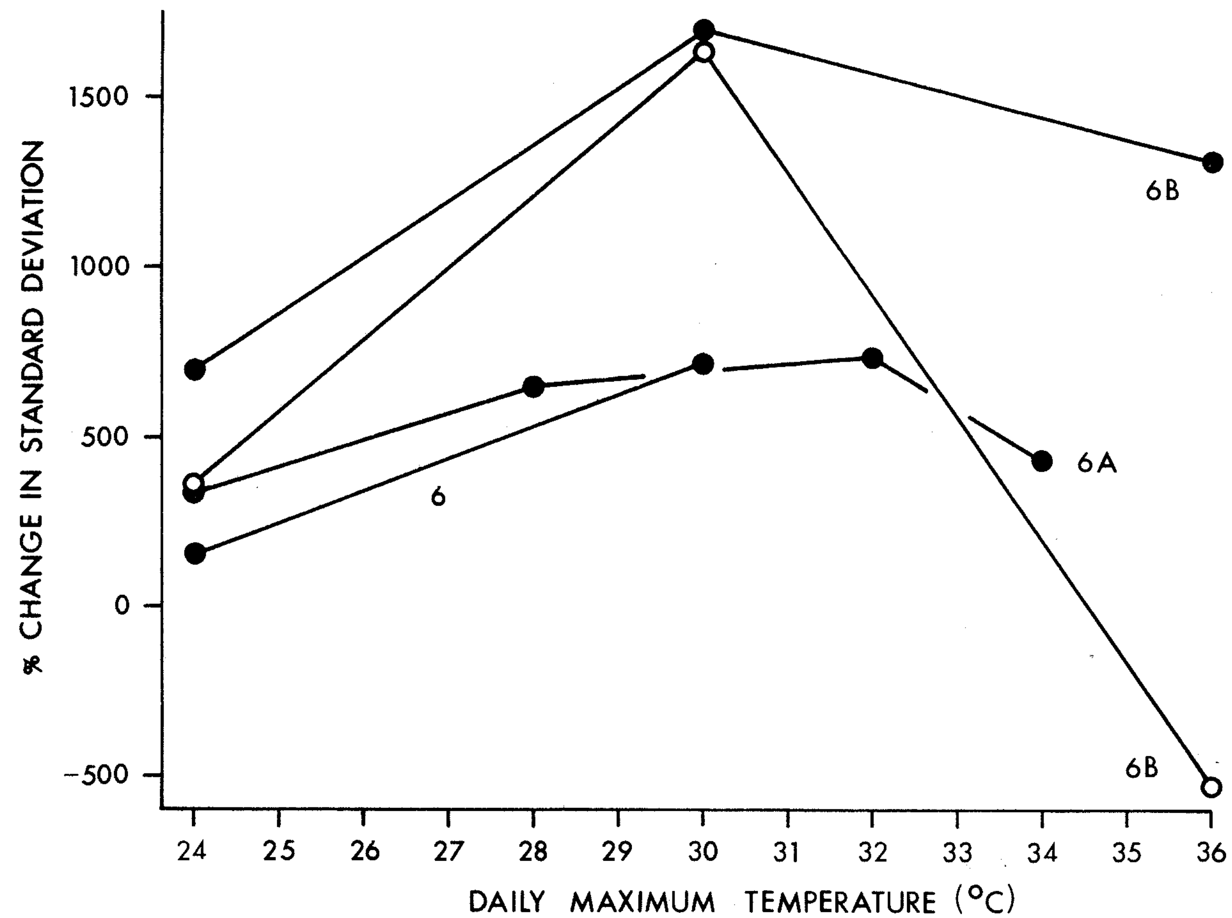

Figure 11. Percent change in standard deviation of mean growth in Awaous genivittatus (Series 6, 6A and 6B; closed circles) and A. stamineus (Series 6B; open circles) in different fluctuating temperature regimes.

Effects of Reduced Streambed Heterogeneity and Water Depth

No mortalities among the four test fishes occurred over the 130-day period. Upper lethal temperatures did not differ significantly between treatments and were within the range for mortality of conspecifics previously tested (Table 11). The results of this test were generally inconclusive.

DISCUSSION

Stream channelization attempts to accomodate and counter the deleterious effects of high flow in areas of variable rainfall and run-off. In populated areas of Hawaii housing is dense, close-spaced, and often very close to streams. Removal of ground cover and impervious land use have made stream bank and bed modification the accepted first defense against flooding. However, such alterations have recently been correlated to changes in the biological and physicochemical characteristics of entire streams (Norton et al. 1978; Timbol and Maciolek 1978). The present study has focused on the tolerance of native stream organisms to the kind of elevated temperatures that must necessarily be encountered by specific life stages in channelized streams.

ENVIRONMENTAL VARIABILITY

Chemical Parameters

The elevation of chemical parameters (pH, dissolved oxygen, conductivity) is clearly related to the presence of channelized stream sections, particularly lined channels. The increases in pH and dissolved oxygen with flow in altered Manoa and Palolo streams contrast with decreases over the same distances in the unchannelized Waiahole Stream. Diel variations in pH and dissolved oxygen were generally in phase, and mid-afternoon maxima in downstream lined channel stations (P-5, P-4) greatly exceeded those above the alteration (P-7) (Fig. 6, 8, 9). Algal photosynthetic activity in highly insolated stream sections may account for these elevations (EIFAC 1969). An examination of U.S. Geological Survey water data for Palolo Stream for 1975-76 (U.S.G.S. 1977) revealed that for the two days on which their sampling was conducted, the only significant chemical changes resulting from downstream flow from the vicinity of station P-7 to P-5 were increased dissolved iron, increased pH, increased conductivity and decreased free CO_2. Dissolved oxygen was not included in their measurements.

Only within downstream lined channel stations P-4 and P-5 in Palolo Stream did mean pH exceed values generally considered suitable for mixed aquatic fauna (Ellis 1937; Doudoroff 1957; State of Hawaii 1978; U.S.E.P.A. 1976). Mean mid-afternoon pH and temperature for stations P-4 and P-5 in lined channels would, in addition, maintain a potentially hazardous level (72%) of toxic unionized ammonia ($[NH_3 \cdot H_2O]/[NH_3+NH_4]$; U.S.E.P.A. 1976).

Conductivity increase during flow through lined channels exceeds that in natural channels. However, tributary (MW-2 vs MW-4) and watershed (Manoa vs Palolo) differences and the unexplained bimodal diel fluctuations (station P-5) discourage more precise statement of the relationship to channelization. Stations P-4 and P-5 have not infrequently yielded conductivity values in excess of the 300 μmhos maximum criterion for Hawaiian stream water quality (State of Hawaii 1978). However, the generally high tolerance of salinity by the diadromous native fauna suggests that such levels would not be critical (Hawaii Cooperative Fishery Research Unit, unpublished data).

Turbidity

Turbidity values reported in this study compare well with values recorded in similar channel types under similar flow conditions (U.S.G.S 1977). The lack of exposed sediment within lined channels and the urbanization of leeward Oahu account for the lower stream turbidity in the Manoa-Palolo system as compared to that of the Maunawili and Waiahole drainages. Higher variation in turbidity in windward Oahu streams may result from higher rainfall in that area. The principal problem associated with high turbidity in lotic waters is the disappearance of spawning habitat where suspended loads finally settle. The nature of amphidromous behavior coupled with the short incubation periods for the gobioid eggs (Ego 1956; Tomihama 1972) make this less of a problem. Only during the alteration construction itself should turbidity become a potential concern.

Temperature

Mean diurnal peak temperatures for stations W-1, W-2, M-4, M-6, M-9, and P-4 were higher than mean temperatures for the same sites as reported by Norton et al. (1978). This is explained by the rigid temporal control on sampling in the present study which ensured measurement of maximum daily values.

Mean peak temperatures at stations located downstream from some form of channel alteration (Tables 1,2) exceeded that of the downstream station W-1, in the unaltered Waiahole Stream. With the exception of stations MW-4 and M-6, such stations below channelization thus exceeded published criteria for Hawaiian stream water quality, namely, a departure of 1°C from "natural conditions" (State of Hawaii 1978). The high variance about the mean peak temperatures at stations below channelized sections may result in as great a stress as the elevated average. Lined channel station P-5 showed higher variance than the "natural" upstream station P-7 in both daily and hourly temperature fluctuations.

The average diel variation in temperature at stations P-4 and P-5 exceeded the annual variation in many unaltered streams (e.g. Waiahole). That extreme forms of channelization may also result in excessive cooling as well as heating is suggested by the single measurement of morning temperatures in lined channels well below those upstream and above the alteration. Such occurrences are considered infrequent. On the occasion of the observation, unusually low air temperatures and high wind velocity

persisted throughout the night prior to the sampling. However, it is not surprising that a channel without cover should exaggerate heat exchange in both directions. There are observations that shaded temperate region streams are the coolest streams in summer and the warmest in winter (Edington 1965).

The increase in temperature per meter of channel length during mid-afternoon downstream flow is a function of the temperature of the water entering a particular type of channel as well as the type of channel itself. The potential for heating "cool" upstream water during passage through exposed channels is best illustrated by the changes in water temperature between stations P-6 and P-5. With the exception of P-5, all freshwater stations had minimum 1400-1500 temperatures around 20-21°C. The effect of the long lined channel on water temperature is maintained despite high flow and adverse meteorological conditions which tend to buffer physicochemical changes with downstream flow through most channel types.

The 2400 meters of uninterrupted lined channel between P-6 and P-5 was shown to result in an average temperature increase of 7.8°C during mid-afternoon. The temperature elevation per meter of channel averaged over this 2400 meters was the highest determined in this study. However, sampling during the 1400-1500 period at several locations between P-6 and P-5 revealed that heating between the two stations was not always a linear process. Large temperature increases and significant decreases were found to occur over relatively short lengths of channel. Temperatures slightly higher than those recorded at station P-5 were measured during the same time period at a location approximately mid-way between P-6 and P-5.

Increased convective heat transfer from water to ambient as water temperature increases, coupled with rapid cooling of heated water during flow through shaded areas, could explain this non-linearity. This general capacity for sustained though diminishing temperature elevation is of great biological importance. Becker (1975) showed that a rise of 1.0°C often separated zero and total mortality. The results of the upper lethal tests in this study support this result. Thus, while short sections of exposed lined channel can result in rapid water heating, longer sections can be responsible for continued slower heating, and cooling of heated water is a function of the degree of shade cover and the length of channel through such cover.

In the two cases where no significant difference was found between mean peak temperatures from neighboring stations, the upstream station was located at the downstream end of a lined channel. Water at such a point is likely to increase in temperature with further flow only if the channel immediately downstream is also concrete lined. This was not the case in either instance.

The large increase in temperature between stations M-9 and M-8 within an unaltered stream region may be due to run-off of heated surface water used in nearby small scale horticulture operations. It may also be the result of a slight decrease in shade cover or increased exposure to afternoon sun following emergence from behind a steep ridge. The tributary adding water to the flow from station M-9 just upstream from M-8 is not a source of warmer water.

The slightly higher rate of heating in the revetted/cleared section between stations M-7 and M-6 as compared to that within the lined channel immediately downstream may be another example of higher longitudinal heating rate at lower water temperature. However, the lined channel between stations M-6 and M-5 has an unusual amount of shade cover over part of its length. The shallow depth of flow throughout may have resulted in the continued heating to station M-5. This sheet-like flow over the smooth concrete bottom of the lined channel and the high heat transfer by concrete would appear to augment the basic effects of increased insolation.

Illumination

The high rates of heating occurring in revetted, cleared and lined channels suggest that a combination of intense insolation and reduced cover accounts for most of the temperature increase. Numerous studies have documented increases in downstream maximum temperatures following riparian woodland clearing in upstream areas (e.g. Brown and Krygier 1970; Gray and Edington 1969). In the present study, mean temperatures at six stations showed high correlation with illumination.

The illumination data generally reflect the amount of nearstream vegetation available at the site. A small clearing in a high elevation, natural channel (W-2, P-7) will receive less illumination due to blocking of light from portions of the cosine detection arc of the probe. More extensive clearing and absence of tall vegetation in altered and downstream areas increases the amount of light reaching the stream. Differences between similar stations from windward and leeward Oahu may be due in part to the shade provided by steep mountain ridges on the windward side. Only in topographically flat areas of the same latitude will temporal light patterns be the same (Horn 1971).

It is apparent from Table 8 that the major difference between stations (i.e. channel types) lies in the illumination beneath shade rather than that in the open. The low light levels beneath shade at lined channel station MW-4 compared to those at lined channel station P-5 reflect the maintenance of the natural overhead cover. The 60° angle of the concrete walls of the Maunawili lined channel, as compared to the vertical walls of the Palolo lined channel, may be the result of construction which does not require heavy removal of nearstream vegetation.

Where riparian cover removal has been nearly equal, as at stations P-5 and M-4, water in the lined channel receives more illumination than in the revetment type channel. This is likely due to the reflection of sunlight from the vertical concrete walls. (Revetted walls are seldom vertical and usually have broken surfaces of rock and masonry). This focusing effect of the rectangular lined channel may be important to diurnal heating.

Nocturnal cooling by back radiation would theoretically be facilitated more by the more open, sloped wall lined channel.

Seasonal Variation

Hawaii is generally considered to have two annual seasons. While short-term stream temperature variation at all stations in this study appeared comparable to the annual variation, natural channel stream sections generally adhered to the cool, wet winter vs. warm, dry summer climatic picture. Channelization appeared to obscure the effects of seasonal variation on stream temperatures. This is the result of increased daily and weekly variability, suggesting that alteration makes a stream section more vulnerable to the vagaries of local weather conditions. It is unlikely that this confusion of seasonal cycles would pose major problems to stream inhabitants. In view of the low level of annual variation in the natural stream channel it seems unlikely that animals have developed a reliance on critical temperatures for migration, spawning or egg hatching such as exists in temperate communities.

TEMPERATURE TOLERANCE

Upper Lethal Temperatures

Upper lethal limits determined in this study represent the maximum stream temperatures for species survival. This assumes exposure to the continuum of sub-lethal temperatures during elevation and thermal acclimatization comparable to that of the individuals tested. Temperature elevation to slightly lower temperatures would in practice cause total mortality because of the lethal effects of prolonged exposure to sub-lethal temperatures during cooling. It was shown that Atya bisulcata was the only species to suffer mortality during or following temperature elevation to 33°C on two consecutive days. A. bisulcata also had the lowest upper lethal limit of any species tested. This relationship between the lethal limits determined and the effect of heating to and cooling from a slightly lower sub-lethal temperature is shown in growth series 6C. Lentipes concolor suffered total mortality following temperature elevation to 35°C. Its previously determined lethal limit was 36.0°C.

Temperatures were measured in the Palolo lined channel which exceeded the lethal limits of Atya bisulcata, Lentipes concolor and Sicydium stimpsoni. There are no known records of these species from the middle or upper reaches of Palolo Stream. However, A. bisulcata is present in Manoa Stream today, and there are records of S. stimpsoni from "Manoa Valley" (C.H. Edmondson, 1928: Bernice P. Bishop Museum specimen #4841). There is little reason to believe that the two species did not once inhabit "Palolo Valley". L. concolor was reported from Oahu by Gunther (1880). The collection site was listed as "Honolulu", however this does not necessarily indicate presence within what are now the boundaries of the city proper. Nevertheless, the elimination of A. bisulcata and S. stimpsoni from Palolo Stream as a result of acute thermal stress remains an intriguing possibility.

Lined channel "edge" temperatures are likely more significant to the ecology of the post-larval upstream migrant than are those from mid-channel. During most discharge conditions, water velocities at mid-channel would likely prevent stream ascent or at least create an energetically unfeasible situation. Temperatures exceeding the lethal limit of Macrobrachium grandimanus (and therefore those of the three species mentioned previously) were recorded at channel edge in the Palolo lined channel.

Crustaceans showed lower thermal tolerance than sympatric fishes. Fish and crustacean lethal limits were lower for species whose adult habitat is at higher elevations, with the exception of L. concolor which showed greater tolerance than its downstream neighbor, S. stimpsoni. Mizuoka (1962) found the same relationship between tolerance and stream elevation in studies on two Japanese gobiids. He also showed that population differences in tolerance for the lower stream species were related to altitudinal distribution. In this study, the trend was not observed in the two species of mollusks. The ecological death point indicated higher tolerance in Neritina granosa, which inhabits riffles and necessarily maintains a stronger hold on substrate than do the Melania species.

The role of the lined channel in excessive nocturnal cooling of stream water during downstream flow was not formally addressed in this study. The data collected suggest that such cooling is uncommon in comparison to the heating which occurs most regularly. However, Fry (1960) points out that acclimation response is more rapid at high temperatures than at low temperatures, and consequently, in fluctuating temperatures a fish becomes more resistant to high temperatures and more sensitive to the low temperatures. A single occurrence of an extreme temperature drop in the lined channel could be a lethal event if organisms became exposed to conditions below their upward adjusted tolerance ranges.

Numerous studies have shown that fishes will move to cooler waters when subjected to the stress of high temperatures (e.g. Graham 1974). Such behavioral modification is most common in the vicinity of point source effluent outfall. The situation in Hawaiian streams does not allow for horizontal or vertical evasion of the heated water. The existence of the lined channel along a migratory route poses two similar problems. Downstream migrants or wanderers would experience a rapid rise in temperature upon entering a lined channel at mid-day or a slow rise when entering during a cooler period. Fishes which cannot partially acclimate during temperature elevation would experience less stress if the rise were rapid (Jacobs 1918). However, the time of exposure would then become more critical. The upstream migrant would in all cases experience a slow rise in temperature within or below the lined channel. Based on the diurnal behavior patterns of the Hawaiian gobioids as observed in field and laboratory, it seems unlikely that migration would be restricted to the nocturnal period, even as a means of avoiding thermal stress.

Hoar (1953) found that positive rheotaxis in salmon fry decreased with increasing temperature to a point of negative rheotaxis. It was suggested

that this might aid in the initiation of downstream runs as temperatures rose in spring and early summer. For the Hawaiian goby fry, the point of negative rheotaxis would be a point of high stress dependent on the magnitude and duration of the stressor. The length of the lined channel section in which the heating occurs would determine the duration of exposure, and is thus critical to all migration.

Effects of Sub-lethal Temperatures: Growth

The theoretical responses of growth to temperature elevations are 1) initial increased growth with temperature up to a level for "optimal" growth; 2) decreased growth with further temperature increase down to a level of zero growth; 3) shrinkage occurring within a small temperature range, until 4) death (Gibbons 1976). Stages 1, 2 and 4 were observed in the responses of the three gobiids to different fluctuating thermal regimes. Growth appears to decrease with increasing temperature above 30°C for Awaous stamineus and 32°C for A. genivittatus. The maximum growth rate for Lentipes concolor is likely to be found at some temperature below 30°C. Results from a continuum of thermal regimes would define the relationships in detail, but such an extensive investigation was beyond the scope of this work.

The temperatures for "optimal" (i.e. most rapid) growth were approximately 7-8°C below upper lethal limits for each species. No general statement can be made concerning the deleterious effects of rapid growth. Ferens and Murphy (1974) found larger mosquito fishes in the cooler areas of a pond than in the warmer areas, suggesting that the growth rate differential due to high temperatures is only a temporary phenomenon. In temperate regions, high water temperatures could encourage feeding during winter months and result in the attainment of a larger than normal size. This would not be possible in a tropical climate. Andrews and Stickney (1972) found that growth in channel catfish increased with temperature to 30°C but fell off at 34°C. They showed that temperatures which elicit rapid weight gain also elicit higher lipid content and thus abnormal body composition. In this study, in which food was non-limiting, rapid growth at high temperatures may have been due primarily to high consumption and rapid digestion (Clark 1969).

Standard deviation about the mean weights changed with increased temperature in the same manner as did mean weight. While it is to be expected that standard deviation will increase with the mean, normalized standard deviations, $SD/\bar{X}$, showed trends similar to standard deviations alone. Increase in standard deviation could be interpreted as increase in individual variability in response to temperature within the sample. The point of peak standard deviation would represent the beginning of a common species response to stress.

This study has shown that conditions which would prove fatal to at least four species of native organisms exist in some altered streams containing lined channels. The number of species increases when the effect of prolonged exposure to sub-lethal temperatures during cooling is considered. If the temperatures for optimum growth are indeed around 7 or 8°C below the lethal limits determined, then potentially harmful conditions may exist for more species and in less severely degraded streams during the dry season. The overall situation would likely be shown to be more critical if the effect of elevated temperatures on early life stages and reproductive behavior were investigated. It has been generally established that, just as the thermal range for growth is narrower than that for activity, ranges continue to narrow as embryo survival and spawning parameters are considered (Brungs 1971; Fry 1967; U.S.E.P.A. 1976).

Shelter

Laboratory and field observations suggest that native species are dependent to some degree on shelter. Lentipes concolor, Sicydium stimpsoni, Neritina granosa and Atya bisulcata are commonly found in riffles, which are micro-habitats whose existence implies considerable bottom heterogeneity. With the exception of Awaous genivittatus and Eleotris sandwicensis from the lower stream reaches, the fauna shows strong orientation to rocks and boulders which dominate the natural substrate.

Despite this apparent attraction to shelter, little physiological stress was demonstrated to result from long-term exposures to unsheltered laboratory test conditions. Studies on predation were not feasible here, but lack of shelter would likely increase the susceptibility of post-larval forms to predation, e.g. from Eleotris sandwicensis and the introduced Tahitian prawn, Macrobrachium lar. Shelter loss resulting from lined channel and culvert construction appears to have two general effects. It aids in making the immediate bottom environment so unattractive to native fauna that few can be expected to be found there (Norton et al. 1978). Total available habitat within the stream is thus reduced. Lack of shelter also increases the vulnerability of upstream migrants to high flow, because all objects capable of producing eddies or regions of calm water have been eliminated.

SUMMARY AND CONCLUSIONS

The effects of channelization on certain aquatic biota are well documented. The data required, however, for improving construction designs so as to minimize the biological impact are seldom sought (Karr and Schlosser 1978). This study focused on those morphological variables which influence thermal variability to the immediate and long-term survival of native macrofauna.

Temperature, pH, conductivity and dissolved oxygen in altered streams exceeded levels in unaltered streams during the day, but 24-hour sampling showed that nighttime minima were generally similar. Lack of shelter in concrete lined channels make them unsuitable habitat for native organisms and more difficult to traverse during migrations. Significant channelization effects on turbidity appeared to be limited to increases during the construction phase. Norton et al. (1978) showed that the percentage of native organisms inhabiting a natural bottom channel was significantly lower in streams containing lined channels and other forms of channelization than in unaltered streams.

Temperature elevation was correlated with the amount of insolation reaching stream water in natural and altered channels; thus heating was high where shade cover was low. Extreme heating in lined channels appeared to also be the result of shallow water depths, focusing of solar radiation by vertical walls, and high heat transfer in concrete. Recorded temperatures in lined channels were shown to be above the lethal limits of several native species. Conditions in less extensively degraded stream sections were shown to be capable of long-term metabolic effects on growth and probably reproduction.

The secondary effects of temperature and its synergistic involvement with other water parameters were not considered. However, Holland et al. (1974) suggest that the directional selection imposed by two or more stressors acting simultaneously may be most critical to organisms. The domination of communities in altered streams by the introduced fauna suggests that a major effect of channelization involves the presence of exotics. Darwin has emphasized that species are likely "limited in their ranges by the competition of other organic beings quite as much as, or more than, by adaptation to particular climates" (Darwin 1859, p. 140). The next step in the consideration of the decline of Hawaiian endemics should be an investigation into the competitive and predatory interactions between indigenous and introduced species.

Future modification of stream channels should be avoided where possible. The construction of artifical bank and bed structures, as in lined channels, can be considered the most damaging type of alteration. The wall revetment type of modification appears to have less overall impact on physicochemical variability and the biota than the vertical concrete walls and smooth bottom of the lined channel. In both cases, however, the removal of nearstream shade vegetation is the major cause of stream temperature elevation.

Lined channel sections should be kept short, and unaltered sections should be provided immediately downstream. These areas would serve as buffer zones where temperature would be allowed to decrease, and they would significantly lower the amount of time an organism would be required to spend in a lined channel during migration. Lined channels should be constructed with narrower, perhaps V-shaped notches in the bottom at mid-channel or with slanting bottoms, so as to provide greater water depth during low flow conditions. Smooth concrete bottoms should be replaced by irregular bottoms, perhaps containing structures designed to provide shelter. A concrete lined channel presently under construction in Iao Stream on Maui contains such a "rough" bottom. Mitigation in presently channelized streams should include revegetation of stream banks to increase or reestablish an overhead canopy.

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Appendix A. Weight vs. Length Relationship for Three Species of Gobiid Fishes Used in Growth Experiment Analysis

Lengths and weights of specimens in samples of *Awaous genivittatus*, *A. stamineus* and *Lentipes concolor* were recorded. The *Awaous* individuals were collected at Nuuanu Stream in Honolulu. All *Awaous* used in the growth experimental series were also collected at this site. Data for *Lentipes concolor* came from the individuals utilized in growth series 6C, which were collected on East Maui.

For each species, lengths and weights were fitted to the power curve,

$$\text{Weight} = a \cdot \text{Length}^N \quad ,$$

using the Hewlett-Packard HP-67 Programmable Pocket Calculator program SD-03A. Values for a, N and r^2 (coefficient of determination) for the three species are shown below:

Species	a	N	r^2
A. genivittatus	1.74×10^{-6}	3.43	.99
A. stamineus	6.55×10^{-8}	4.63	.66
L. concolor	1.43×10^{-6}	3.47	.93

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16. Abstract (Limit: 200 words)

Channel modification in Hawaii has been correlated with increases in physicochemical variability and reductions in numbers of several endemic gobiid fishes in altered streams. The amphidromous migratory behavior of the native fauna prevents the isolation of any species from the effects of channelization on water quality. Daytime values of conductivity, pH and dissolved oxygen were found to be considerably higher in altered streams than in unaltered streams. All stations located downstream from channel modifications had higher diurnal peak temperatures than upstream and unaltered stream stations. Temperature extremes of 36.2°C and 17.8°C were recorded at the downstream end of a concrete lined channel. Diel changes in temperature of 12°C were not uncommon. High illumination due to clearing of the vegetative canopy, and shallow water depths in lined channels appear to be responsible for the excessive heating. Upper lethal temperatures correlated with altitudinal distributions of adult fishes and crustaceans. Lethal limits of those species absent or rare in altered streams fell within the range of temperatures recorded in such degraded habitats. Dominant introduced fishes showed greater resistance to high temperatures than native animals. Maximum growth rates occurred in fluctuating temperatures whose diel maxima were 7-8°C below upper lethal limits.

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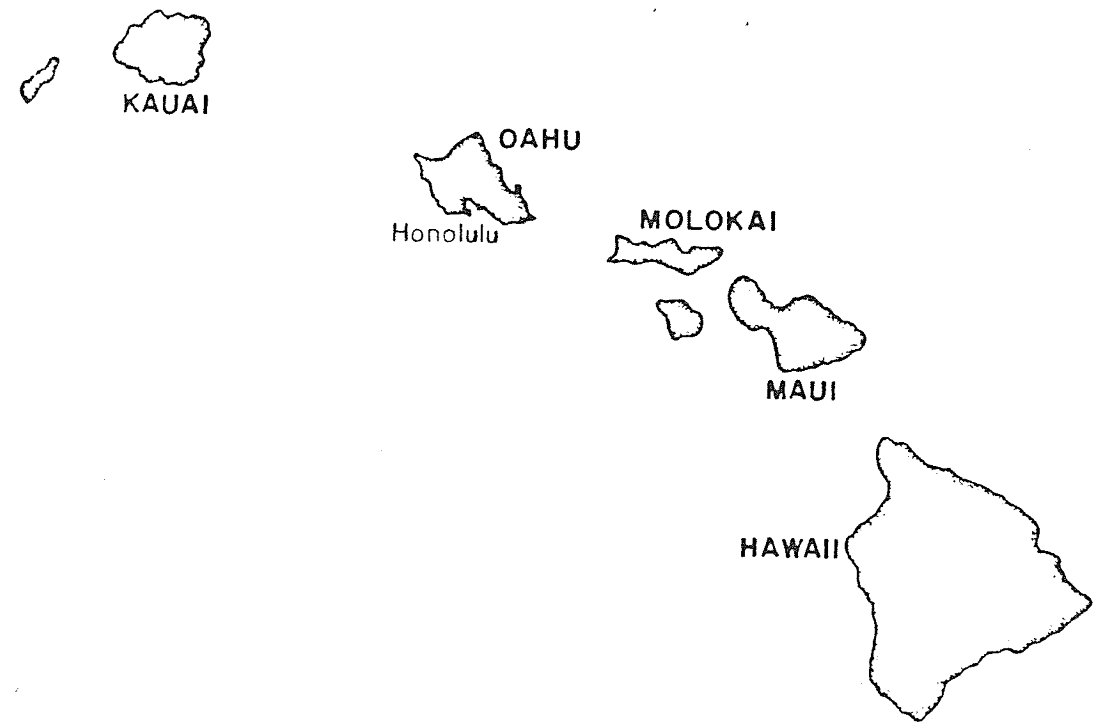

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FWS/OBS-78/19
October 1978

STREAM CHANNEL MODIFICATION IN HAWAII
PART D: SUMMARY REPORT

by

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PREFACE

This is the last of a four-part series on Stream Channel Modification (Channelization) in Hawaii and Its Effects on Native Fauna. The four parts (FWS/OBS-78/16, 17, 18, and 19) were prepared for the National Stream Alteration Team to provide the much-needed baselines for evaluating future stream alteration proposals as well as ecological information applicable to the protection and preservation of native Hawaiian stream fauna. This report contains a general summary of project results and a guide to the location of more detailed information reported in Parts A, B and C. A general discussion of conclusions and management recommendations is included. This report is based on data and analysis covering the entire contract period: July 1975 through October 1978.

Any suggestions or questions regarding Channel Modification in Hawaii should be directed to:

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EXECUTIVE SUMMARY

A 3-year, statewide study was made of the occurrence and consequences of channelization in Hawaiian streams. The 366 perennial streams of the State were inventoried for the first time, and some basic information was catalogued on their physical characteristics, complete status of channel alteration, and macrofaunal communities. Fifteen percent of the State's streams have channels altered in at least 1 of 6 forms. There are 151 km of altered channel, 89% of which is on Oahu. Forty percent of the modified channel length is concrete lined - the form of alteration found to be most ecologically damaging.

Field measurements showed that channel alterations commonly caused large changes in environmental parameters. Whereas the average pH value in natural streams was 7.2, the yearly mean mid-afternoon pH in lined channels was as high as 9.9. Conductivity and dissolved oxygen were significantly increased. The range of daily temperatures in lined channels was 17.8 - 36.2°C as compared to 19.5 - 26.8°C in natural channels. The diel insolation cycle of exposed, artificial channels caused extreme diel change in all these environmental parameters. The native species tested in the laboratory had less tolerance of high temperatures than exotics, and some natives had upper lethal temperature limits within the temperature range measured in channelized streams.

Twenty-five species of fish and decapod crustaceans were collected statewide, of which only 8 were native. Native species were not abundant in most areas intensively surveyed; they appeared to thrive only in areas remote from development. Certain introduced species, notably poeciliid fishes, were abundant in the most heavily channelized sections, whereas native species were almost entirely absent.

Channelization in its various forms (1) increases turbidity, (2) destroys natural substrate habitat, (3) creates wide, shallow, unnatural flows, (4) causes excessive illumination, water temperatures, and pH levels, and (5) creates topographical difficulties for upstream migration. Effects (2) and (4) are believed to create especially serious problems for the native macrofauna that is benthic/demersal, cryptic, and obligately diadromous. As a result, present channelization practices appear to be damaging the quality of extensive stream habitat for native species and contributing to their replacement by hardy, useless exotics.

Mitigation should include (1) minimizing channelization projects, (2) maintaining the natural length of channels, (3) maintaining (replanting)

the vegetative canopy, (4) maintaining natural bottom material wherever possible, (5) using intermittent sections of natural bottom between minimum sections where lined channel is unavoidable, (6) building a narrow, low-flow notch into the bottom of flat lined channels, (7) installing minimum length culverts in ways that will avoid downstream elevations above stream level (waterfalls).

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ABBREVIATIONS

g	grams
km	kilometers
LD_{50}	lethal temperature at time of 50% sample mortality during a gradual heating test
m	meters
m^3/s	cubic meters per second
mg/ℓ	milligrams per liter
NTU	nephelometric turbidity units
μmhos	micromhos

SYMBOLS

°C	degrees, Celsius

ENTS

Table

1

plied by Carl Couret, Lawrence
ichael Nishimoto. The Honolulu office
.S. Geological Survey provided data and
ogy and water quality measurements.
c. shared relevant data on water quality.
ping and Susan Takemoto prepared the figure.

INTRODUCTION

The Hawaiian stream environment is like nothing in mainland America. The inhabited islands are all of recent volcanic origin, with small land area, dominated by steep slopes of porous, igneous rock, and lacking extensive coastal plains. Climate is dominated by prevailing oceanic trade winds that shed rainfall mostly between elevations of a few hundred and about 2500 meters on the windward sides of the high islands. This results in great local variability in climate and stream locations, with a strong concentration of streams on windward slopes. Streams tend to have steep gradients, rocky channels, heavy vegetative canopy cover, and great temporal variability in discharge. A natural result is frequent and considerable flooding of the narrow plains in the lower reaches. These plains are the locations of extremely rapid recent residential and commercial development brought about by the State's explosive growth in population and tourism. Extensive stream channelization has resulted over a very short period of time (Most has been performed within the last 2 decades).

Before this study, the extent and nature of these modifications were poorly known, and their environmental effects on the unique Hawaiian stream ecosystems had not been studied. The hydrological uniqueness of the streams made it hard to predict environmental changes. The uniqueness of the poorly studied native fauna made it hard to predict biological results. Many of the State's streams were poorly characterized on a geographical/hydrological basis.

The present study was conceived to provide a start at addressing all these major information needs. It consists of (1) a physical inventory of all perennial streams in the State (None existed previously!) and an inventory of channel modification types and locations and associated fauna, (2) a set of measurements designed to show the effects of channel modification on environmental parameters, and (3) an assessment of biological results both by controlled manipulation of individual parameters in the laboratory and by comparison of natural communities in the field. The results as reported herein and in the companion reports (FWS/OBS-78/16, -78/17 and -78/18) provide a valuable basis for intelligent planning concerning channel modification in Hawaii. They should also be directly applicable to the high tropical islands of Puerto Rico, the U.S. Virgin Islands, and the U.S. Trust Territory, and tropical oceanic high islands generally.

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BACKGROUND: ECOLOGY OF NATIVE SPECIES

The native Hawaiian freshwater fauna is very limited and highly specialized, the result of evolutionary processes on small, geographically young, strongly isolated land masses. Of the 5 truly freshwater native fish species (all gobies), 4 are endemic; both native decapods are endemic (see Table 2, p. 8). Thus, aside from any other importance, native species have intrinsic biological value, and any threat to their limited insular habitat must be weighed against the requirements for survival of a species on earth. The endemic goby, *Lentipes concolor*, has been proposed for endangered status, and other native species have been mentioned for consideration of special protective concern (Miller 1972). Some of the native species had important positions in traditional diet and culture (Titcomb 1972). At least 4 native species - *Awaous stamineus*, *Macrobrachium grandimanus*, *Atya bisulcata*, and *Neritina granosa* - are still taken as food and/or bait.

All the truly freshwater fish and decapod species are of marine derivation, and all have diadromous life histories, i.e. they reside in streams as adults, but their larvae must reach the sea to develop and later migrate upstream as post-larvae. The extent of adult up- and downstream movement is poorly known and certainly varies among species. However, at some stage of their lives, some species such as *A. stamineus* migrate many kilometers up to elevations of over 500 m. Thus, almost all actual and potential locations for channel modifications lie within the obligatory migration path of several native species. If impacts are severe enough due to disturbance at any channel section in the stream, the life cycle of the species in the stream cannot be completed, even though acceptable adult habitat remains above the alteration.

The native macroinvertebrates are, of course, benthic animals, and the native fishes are demersal to the point of being almost of the benthos as well. The 4 gobiid fishes have fused pelvic fins with which they cling to the substrate; the eleotrid is also strongly demersal. All are more or less cryptic, and make considerable use of rocks and other stream bottom cover for protection. Most species appear to browse benthic algae as an important part of the diet. As is often the case with endemics that have evolved isolated from vigorous competition, the native species appear to be poorly equipped to compete successfully with some of the many hardy species recently introduced to the State's streams.

PHYSICAL INVENTORY

The physical inventory revealed 366 perennial streams in the 5 major islands of the State (Table 1). Fifty-nine percent of these streams are continuous (i.e. containing water in their channels continuously from the highest point to the mouth). Fifteen percent of all streams have been channelized (Table 1); 56% of all altered streams are on Oahu, the most populous island in the State.

Six types of channel modifications have been indentified: (1) channel realigned and/or vegetation removed, (2) channel walls revetted, (3) channel directed through an elevated culvert, (4) channel bottom and sides lined, usually with concrete, (5) extended culvert (a longer version of (3) above), and (6) channel blocked or filled in. A total length of 151 km of these modifications was found statewide, 89% on Oahu. Twenty-eight percent of the total was realigned/cleared, 24% revetment, 3% elevated culvert (mostly road crossings), 40% lined channel, <1% extended culvert, and 5% blocked channel. Timbol & Maciolek (1978) provide a fuller description of channel alteration types, detailed island-based breakdown of channelization statistics, a complete tabular list of all State streams with some basic physical data and ecological quality ratings on them, maps of all channelized streams showing watershed limits, stream channels, longitudinal gradient of main stream, and approximate locations of the various types of channel alterations. For most channelized streams, results of field collections of macrofauna are shown, giving some indication of the nature of living stream communities.

Table 1. Inventory Data Summary on Hawaiian Streams and Stream Channel Modifications (Data from Timbol and Maciolek 1978)

Island	Oahu	Maui	Molokai	Hawaii	Kauai	Total
Perennial streams						
Total number	54	96	37	123	56	366
Continuous	53%	58%	43%	57%	77%	59%
Water diverted	58%	59%	12%	60%	45%	53%
Physically pristine[a]	0	1%	49%	11%	32%	14%
Pristine-Preservation ecological quality[b]	0	34%	81%	21%	20%	27%
Channelized	31 (57%)	7 (7%)	1 (3%)	4 (3%)	12 (21%)	55 (15%)
Modified channel						
Total modified length (km)	134	5	0.1	4	8	151
Types (% of total modified length)						
Cleared/realigned	27	54	0	31	51	28
Revetment	23	34	0	23	35	24
Elevated culvert	< 1	4	3	2	14	3
Lined channel	43	8	0	44	0	40
Extended culvert	< 1	0	0	0	0	<1
Blocked/filled	6	0	0	0	0	5

[a]Channel not altered, water not diverted, no road crossings (except foot trails).

[b]Highest ecological quality status in the system devised by the State Department of Health (Timbol and Maciolek 1978).

ENVIRONMENTAL CHANGES AND ENVIRONMENTAL TOLERANCES

Hawaiian streams have a unique combination of physical/chemical properties. The largest mean discharge is only 9.7 m^3/sec (maximum instantaneous discharge, 271 m^3/sec). Huge temporal flow variations occur; even among a group of the 3 largest streams of each island, the ratio of mean to minimum discharge is over 1000 in 2 cases. Discharge of many streams (53% statewide) is greatly reduced by the diversion of water for irrigation and domestic uses (Table 1). In a good many cases, dry reaches of channel result during most of the year, and diadromous migration is impeded. The range of temperatures measured in this complete study in unaltered streams, over the full range of elevation, season and time of day, was 19.5 to 26.8°C. Island average pH values ranged from 6.2 on Hawaii to 7.5 on Maui (7.2 on Oahu). Conductivity ranged from 43 µmhos on Hawaii to 180 µmhos on Oahu. Corresponding dissolved solids values were 31.0 mg/ℓ to 112.2 mg/ℓ.

Alteration of the natural channel condition produced significant (sometimes dramatic) changes in physical/chemical parameter values. These changes in field values and the results of laboratory experiments on the effects upon stream animals of parameter values in and near this range are reported by Hathaway (1978). His measurement of field parameters was concentrated in 3 streams on Oahu, containing conditions ranging from natural channels through several major types of channelization. Stream sampling statewide confirmed the general trend of response of the environmental parameters to the channel alterations.

For the intensively studied streams over a year's sampling, the full range of temperatures in channelized sections was 17.8-36.2°C. Fig. 1 is representative of the strong diurnal heating and large diel variation in temperature that occur in a concrete lined channel (the most common alteration in urban areas) compared to a natural channel. Similar trends were consistently recorded in pH, conductivity and dissolved oxygen. The temporal cycle of the latter 3 parameters (like that of temperature) seems largely dependent on insolation; pH, oxygen, and probably conductivity respond positively to the resulting photosynthesis of the lush algal growth commonly attached to concrete channel surfaces. Levels of pH measured in several lined channel stations frequently exceeded levels generally considered suitable for most aquatic animal species and far exceeded the maximum limit of 8.0 in Hawaii Department of Health water quality standards. Mean mid-afternoon values over a year's time ranged for 5 lined channel stations from 7.5 to 9.9. Peak values were as high as 10.4.

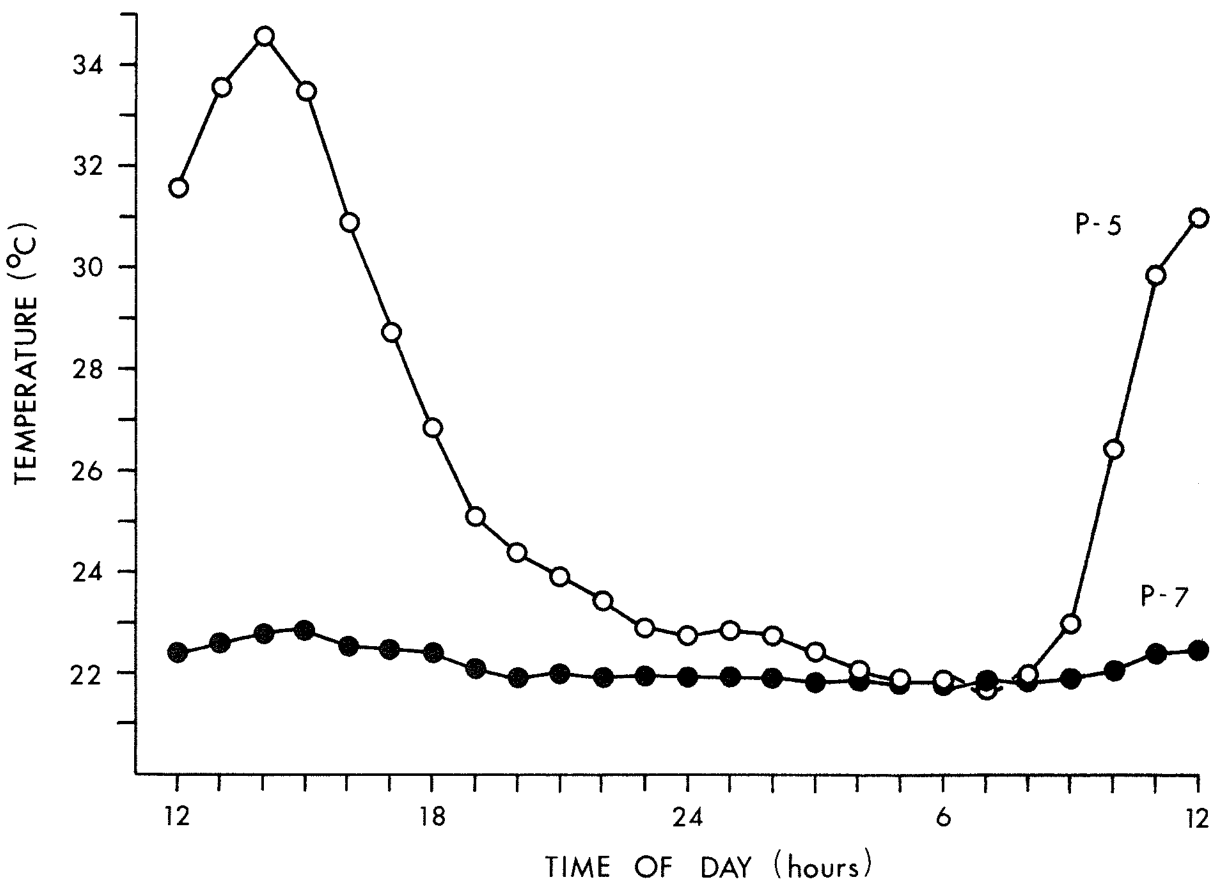

Figure 1. Diel cycle of water temperature (1) in a natural section of stream channel (•), and (2) after flowing through 2400 m of concrete lined channel (o). (From Hathaway 1978).

Peak daily temperatures averaged over a year's time were raised as much as 7.8°C in the process of flowing a distance of 2400m through a lined channel. Elevations as great as 9.1°C above the temperature in the natural channel, and absolute values of 36.2°C, were recorded at times. The persistence of water temperatures well above normal was demonstrated for hundreds of meters downstream of the end of a channelized section. Highest temperatures cross-stream were measured near the edge of the channel (as much as 4.5°C higher than mid-stream values, such as all those reported above). At the channel edge, water speed was lowest, and presumably moving upstream would be hydrodynamically easiest for stream animals. These effects would make it especially difficult for post-larvae to complete a normal migration upstream from the sea.

Upper lethal temperature limits for adults of 9 native and 2 exotic stream species were tested in the laboratory (Table 2). In the actual field situation, mortality would normally occur at somewhat lower temperatures, and successful spawning would be restricted to lower temperatures yet. For some of the now scarce native fish species (e.g. Sicydium stimpsoni and L. concolor) and both the native crustaceans, the laboratory lethal temperatures fall within the measured range of peak daily water temperatures in lined channels. The 2 exotic fishes have by far the highest lethal temperatures, and these are well above the highest water temperatures encountered in lined channels. Interestingly, the statewide field studies showed that these 2 species are very abundant in lined channel sections; Poecilia mexicana is often the dominant animal. Tests on post-larval fish of several of the species indicated acute stress at lower temperatures than for the adults, but higher upper lethal temperatures. Individuals collected from more degraded stream sections showed no different thermal tolerance from individuals collected from natural stream sections.

Laboratory growth tests indicated increased growth rate and increased variance in growth rate with increasing temperature above natural stream values up to about 30-32°C. Growth rate was reduced at still higher temperatures (still several degrees below lethal limits in 3 goby species). The physiological consequences of unnaturally rapid growth are unknown. In animals evolutionarily adapted to warm tropical temperatures, this may constitute a chronic physiological stress.

Table 2. Upper Lethal Temperature Limits of Native and Selected Exotic Species (Data from Hathaway 1978)

Group Species	Lethal Range (°C)	LD_{50} (°C)
Fish		
Awaous genivittatus (indigenous)	39.2-39.7	39.7
Awaous stamineus (endemic)	37.2-38.8	38.2
Eleotris sandwicensis (endemic)	39.2-39.6	39.3
Sicydium stimpsoni (endemic)	35.4-35.8	35.6
Lentipes concolor (endemic)	35.9-36.3	36.1
Poecilia mexicana (exotic)	41.2-41.4	41.3
Sarotherodon (=Tilapia) sp. (exotic)	42.7-43.1	42.9
Mollusks		
Neritina granosa (endemic)	38.4-40.1	38.8
Melania sp. (indigenous)	36.7-38.6	37.5
Crustaceans		
Atya bisulcata (endemic)	34.0-34.5	34.2
Macrobrachium grandimanus (endemic)	36.4-37.3	36.8

BIOLOGICAL RESULTS

Twenty-five species of fish and decapod crustaceans were collected in the statewide stream inventory (Table 3). Seventeen of these species are exotic. As a general trend, exotic species tend to be more dominant on more heavily developed islands, and this trend appears clearly in comparing areas within an island. Table 4 indicates the dominance of exotic species in channelized compared to unaltered streams in Oahu. A number of native species, particularly the gobies, S. stimpsoni and L. concolor, were dramatically more abundant in less developed areas. L. concolor, originally described from Oahu, where the bulk of channelization has occurred, was not found there in the entire survey and apparently is extinct there. The data on occurrence and abundance of S. stimpsoni, together with what is known of its habitat requirements, suggest using any decline or disappearance of its population as an indication of serious stream degradation. Several introduced species (primarily poeciliids) were prominent in most channelized streams; the introduced guppy, Poecilia reticulata, was the most widely distributed and abundant of all fish species. Further details on a statewide basis appear in Timbol & Maciolek (1978).

Table 3. Occurrence of Macrofaunal Species in Statewide Stream Inventory (Data from Timbol and Maciolek 1978)

Island	Oahu	Maui	Molokai	Hawaii	Kauai	Total
No. native fish species	5	6	6	6	6	6
No. exotic fish species	14	3	0	3	7	15
Total no. fish and decapod crustaceans	23	13	9	12	17	25
% of native species in the macrofauna	30	62	89	67	47	32

Table 4. Comparisons of Numbers and Weights Per 20 m X 1 m Station of Different Groups of Macrofauna in 17 Altered and 6 Unaltered Streams on Oahu. Native Species are Associated Mostly with Unaltered Streams, While Exotic Species Predominate in Altered Streams (From Timbol and Maciolek 1978)

Stream Fauna-Grouped	Unaltered % No. (No.)	Unaltered % Wt. (Wt., g)	Altered % No. (No.)	Altered % Wt. (Wt., g)
Native Crustaceans	53 (177)	13 (186.0)	7 (293)	2 (242.4)
Native Fishes	19 (64)	47 (646.8)	7 (262)	11 (1759.9)
Exotic Crustaceans	10 (32)	31 (424.5)	11 (434)	21 (3110.2)
Exotic Fishes	18 (62)	9 (126.2)	75 (2923)	66 (10094.1)

A more intensive study of entire communities in natural versus altered channels was conducted in 3 Oahu streams over a period of about 2 years. Several of the stations were also used for the above mentioned intensive environmental measurements (Hathaway 1978). The results are reported in detail in Norton et al. (1978). Exotic fishes were dominant in both artificial and natural bottom channel sections in altered streams (Table 5). The two poeciliids, P. mexicana and P. reticulata, were most abundant. These species were regularly present in abundance in lined sections of the channels, whereas no native species was ever found in lined channel sections, and native decapods appeared to avoid this substrate also. Thus, diversity was lower in lined channel sections. Biomass was also significantly lower, but numbers were greater due to the abundance of small poeciliids. As in many Hawaiian streams, the introduced crayfish, Procambarus clarkii, and the introduced prawn, Macrobrachium lar, were prominent. The latter is probably present in every stream in the State, and based on the statewide survey, appears to be displacing the endemic M. grandimanus. The intensive study results are consistent with those of the statewide inventory in which Timbol and Maciolek (1978) found that exotics comprised 97% by number and 92% by weight of all fishes and decapods in artificial bottom channel sections.

Table 5. Relative Abundances of Native and Exotic Faunal Groups in Different Channel Types, Collected from Three Study Streams (From Norton et al. 1978)

Faunal Group	Altered Streams: Concrete Lined % No.	Altered Streams: Concrete Lined % Wt.	Altered Streams: Natural Bottom % No.	Altered Streams: Natural Bottom %Wt.	Unaltered Stream: Natural Bottom % No.	Unaltered Stream: Natural Bottom % Wt.
Native Fishes	0	0	4	8	1	6
Exotic Fishes	99	92	79	50	46	37
Native Crustaceans	0	0	1	1	50	32
Exotic Crustaceans	1	8	16	41	3	25

In the unaltered stream, both exotic fishes and native crustaceans were prominent (Table 5). Native fishes were present throughout the stream, but they were nowhere abundant in any stream in this intensive study. Because of the predominance of exotics in the altered streams, one of them (Manoa) had more total macrofaunal species than the unaltered stream. All evidence in this study accords with casual observations over the last several years indicating that the hardier exotics are progressively displacing native stream species, especially in areas of greater human activity. This study strongly suggests that channelization practices, particularly long lined channel sections, are aiding this takeover by exotics.

EFFECTS OF CHANNELIZATION AND MITIGATION

Virtually every channel modification project begins with destroying some or all of the streamside vegetation and digging into channel surfaces. This activity alone causes short-term destruction of habitat and creates very high short-term levels of turbidity. A "worst case" example may be that of Kamooalii tributary of Kaneohe Stream, Oahu, where extensive earth moving work has resulted in repeated turbidity measurements of 220 NTU or greater and readings as high as 530 NTU (personal communication, Environmental Consultants, Inc.). These levels are orders of magnitude above the usual 2 to 6 NTU for natural Hawaiian streams at moderate discharges. But records indicate that occasional storm freshets can increase the turbidity in a natural stream by a factor of 100 or more. Although native species must have developed some tolerance for very short-term high levels of turbidity, prolonged high levels during and for some period after channel modification probably displace them from portions of the stream and discourage migration in the channel downstream of the work site. Where the stream surroundings are simply cleared and the channel widened and/or realigned, long-term turbidity levels can be mitigated by allowing or encouraging revegetation of stream banks.

In channel projects where the cleared and dug channel is left with "natural" soil/rock surfaces (not revetted or lined), the most harmful effects are probably excessive illumination and warming due to removal of streamside vegetation. Laboratory and field studies indicated that native species avoid both excessive illumination and heat and seek sheltered habitat. In the long term, the quality of the natural community in these channels seems to depend largely on the degree of shading. Much of the damage done by realignment could be mitigated by intelligently replanting streamside canopy vegetation.

Revetment of stream banks is the next step away from the natural situation. It can reduce turbidity caused by bank erosion, although the long-term effect is probably minor. It may complicate the problem of replanting streamside vegetation. In theory, some increase in water temperature might be expected beyond the natural bank situation. Where other factors are equal, revetted streams with natural bottoms appear to have communities much like realigned streams with channels of natural materials.

The lined channel appears to offer considerably more serious environmental problems. In addition to short-term construction problems, habitat destroyed during construction is never recovered. Channel surfaces are usually relatively smooth concrete. Even where constructed of mortared stone, they provide essentially no shelter for native animals. The often long and totally bare expanses of concrete offer substrate that is in no way natural or suitable for demersal native stream species, all of which orient strongly to the natural substrate. Since lined channels are sized for freshet flows (and thus have large cross-section), the common flat-bottom geometry results in very shallow water depths across the entire flowing stream during most of the year, when flows are hundreds or thousands of times less than peak flow. The result is a very unnatural and inhospitable habitat to stream species accustomed to frequenting pools as well as riffles. An additional problem is the common practice of clearing the channels of sediment periodically by running a bulldozer through the channels, greatly increasing turbidity and disturbing habitat.

Illumination levels in exposed lined channels are extremely high, typically 70 times as high as in a natural stream channel beneath its normal tree canopy. Where occasional lined channels were found that had partial canopy shading from "volunteer" secondary growth, illumination levels were 3 to 10 times higher than those under a natural stream channel canopy. Lined channels cause the most rapid water heating of any type of modification. Water passing through a lined channel is heated more than water in a natural channel even when shading by vegetative canopy is comparable (either heavy or absent). This appears to be due to the shallow depth maintained by flat channel bottoms, high solar heat transfer by the concrete/masonry material, and probably by a focusing effect of solar energy caused by the usual rectangular lined channel cross-section.

Temperature and other physicochemical water parameters (e.g. pH, conductivity) do not change linearly with length of modified channel. Thus, water quality can be seriously affected by rather short lengths of artificial channel. However, prolonged channelized lengths increase the risk of exceeding the animals' temporal tolerance to elevated levels, with immediate or delayed lethal effects or interruption of the migration behavior necessary to maintain the populations. The harmful effects may operate within the channel or hundreds of meters downstream.

Mitigation may be provided by interrupting channelized sections with alternating sections of natural channel with vegetative canopy. This will give water quality periodic opportunity to recover and provide shaded areas of acceptable habitat for native species. These "rest stops" along the way are likely to permit migration in otherwise impassable altered reaches of streams. A simple form of mitigation that will reduce heating and improve habitat quality is addition of a narrow notch in the channel bottom to provide a narrower, deeper watercourse during low flows. The U.S. Army Corps of Engineers is currently constructing an imitation "natural" bottom in a lined channel in Iao Stream, Maui.

The effects of culverts are least well studied. All culverts replace natural substrate with artificial, while producing greatly reduced illumination and solar heating. Most are short, so that little habitat is lost, and there is no evidence from the study that short lengths of culvert at stream grade cause serious restriction to movements of native species. If

the downstream end is sufficiently elevated above downstream channel level, they may represent a barrier to upmigration of post-larvae, especially the poorer "climbers" such as Eleotris sandwicensis. The survey data spot checks on communities suggest in a few cases that such negative pressure on migration may be operating, but results are not definitive. Since all Hawaiian stream species have some facility for ascending stream gradients, mitigation is feasible through modified culvert design, e.g. a sloped culvert installation rather than a high, horizontal culvert that creates an artificial waterfall at the downstream end.

Extended culverts (≥60m long and usually of concrete box form) are much less common, and their distribution has made their effects difficult to isolate from other activities in the same streams. The total lack of illumination, in situ primary productivity (most native species browse algae) and natural substrate suggest that they are unsuitable habitat. The data do not clearly indicate whether great lengths of culvert are serious barriers to migration, but the habits of the native animal species suggest that they may be.

Blocking or filling in a channel results in destruction of the stream as habitat for native aquatic animals. Whatever disposition is made of the water flow, the downstream fluvial habitat and the migratory path are destroyed, which eliminates the native fauna.

SUMMARY AND CONCLUSIONS

The 5 major islands of Hawaii contain about 366 perennial streams. A considerable amount of physical and ecological field survey information on them has been collected and catalogued in Timbol and Maciolek (1978). Six types of channel alterations have been identified, affecting 151 km of channel in 15% of the State's streams. Oahu is most heavily channelized (57% of its streams, 134 km of alterations); 43% of the altered length is concrete lined channel - the most ecologically damaging type of alteration. Fifty-three percent of State streams have some form of water diversion; only 14% are physically pristine. Only about 27% could be placed in the highest ecological quality category; none of these is on Oahu.

Natural stream temperatures ranged from 19.5 to 26.8°C. Island average pH values were from 6.2 to 7.5, conductivity from 43 to 180 µmhos. Removal of vegetative canopy by channelization produced large diel fluctuations of all these parameters, involving more extreme values. The greatest extremes were produced in lined channels where there was high radiative/conductive substrate heat exchange and shallow, uniform sheet flow. There the temperature range increased to 17.8 - 36.2°C, and elevations as great as 9.1°C above natural channel temperatures occurred. Mid-afternoon annual average pH went as high as 9.9. Deterioration in these water quality parameters was detectable hundreds of meters downstream from lined channel sections.

Upper lethal temperature of native fishes (LD_{50}) ranged from 35.6 to 39.7°C; 2 species, and both species of native decapod crustaceans, had values within the measured range of altered channel temperatures. The 2 exotic fishes tested had much higher lethal temperatures. Laboratory tests of some native fish species showed first an increased growth rate with temperature, followed by decreased growth at higher temperatures.

Of 25 macrofaunal species collected in the statewide inventory, only 8 were native. There was a trend to scarcity of native fish species and strong dominance by exotics in more developed areas of the State, and in particular, in heavily channelized streams. Some exotic species, especially certain poeciliid fishes, were abundant in concrete lined channel sections, whereas native species avoided these areas almost entirely. Two introduced decapods were prominent; the ubiquitous Macrobrachium lar seems to be displacing the endemic M. grandimanus. In general, channelization practices, particularly lined channels, seem to be contributing to the replacement of a fragile native (large endemic) stream macrofauna by useless exotic species.

Channelization results in initial high turbidity that may ultimately subside to moderate levels. The open channel forms cause undesirable (sometimes dangerous) extremes of illumination, temperature, pH and conductivity. Lined channels produce the most extreme effects of all open channel forms. All forms of channelization disturb important natural substrate habitat during construction. All culverts and lined channels result in permanent loss; with lined channels, the amount (length) of lost habitat may be significant to survival in a stream. The wide, shallow, unnatural water flow created by lined channels is especially inhospitable to native species. Culverts with the downstream end above stream grade (creating a waterfall) may interfere with upmigration of some species. Since all native species are obligately diadromous, their populatious cannot survive confined above modified channel sections. Sufficient deterioration of substrate or water quality at any one point in a channel may curtail the migration necessary for survival of the population.

It appears that channelization has had a considerable negative effect on native stream populations. Further alteration projects should be avoided where possible. Mitigation measures should include maintaining the approximate original channel length to retain natural water speed and avoid destructive erosion below channelized sections. It is especially important to maintain (replant as necessary) streamside vegetation that will provide a canopy to shade the stream. Where at all possible, the bottom should be of natural material. Where an artifically lined bottom is unavoidable, it should be used in minimum length sections alternated with natural bottom sections. A narrow notch should be built into any flat bottom lined channel to provide a narrower, deeper flow cross-section under low flow conditions. Culvert lengths should be kept to a minimum, and the downstream end should be at downstream channel grade (not elevated).

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15. Supplementary Notes

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16. Abstract (Limit: 200 words) A 3-year, statewide study was made of the occurrence and consequences of channelization in Hawaiian streams. The 366 perennial streams of the State were inventoried for the first time, and some basic information was catalogued on their physical characteristics, complete status of channel alteration, and macrofaunal communities. Fifteen percent of the State's streams have channels altered in at least 1 of 6 forms. Forty percent of the modified channel length is concrete lined-the form of alteration found to be most ecologically damaging. Field measurements showed that channel alterations commonly caused large changes in pH valuse, conductivity, dissolved oxygen and daily temperatures. The native species tested in the laboratory had less tolerance of high temperatures than exotics, and some natives had upper lethal temperature limits within the temperature range measured in channelized streams. Twenty-five species of fish and decapod crustaceans were collected statewide, of which only 8 were native. Native species were not abundant in most areas intensively surveyed; they appeared to thrive only in areas remote from development. Certain introduced species, notably poeciliid fishes were abundant in the most heavily channelized sections, whereas native species were almost entirely absent. Recommendations for mitigating the impact of channel modification are included.

17. Document Analysis a. Descriptors Ecology, Aquatic life, Aquatic populations, Biological communities, Biomass, Channel improvement, Channeling, Concrete-lined canals, Crustaceans, Distributions, Fish populations, Environmental Effects, Damages, Freshwater fish, Hawaii, Habitats, Land clearing, Riparian land, Riparian plants, Degradation (Stream), Stream, Watershed (Basins), Water Temperature, Hydrogen ion concentration, Electricl conductance

b. Identifiers/Open-Ended Terms
Hawaiian streams, Altered streams, Channelization project summary, Native Hawaiian stream fauna, Stream mangement, Mitigative measures, Hawaiian stream environment, Channelization effects, Relevance to high tropical islands, Ecology of native species, Stream inventory, Lethal temperatures, High turbidities, Excessive illumination.

c. COSATI Field/Group

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