# INSULAR AQUATIC ECOSYSTEMS: HAWAII

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Abstract: Extensive field studies by the Hawaii Cooperative Fishery Research Unit provided a basis for a provisional, functional classification of all Hawaiian surface waters exclusive of the marine ecological system. Traditional physicochemical features and characteristic biota are employed in the designation of 14 ecosystem types comprising 4 flowing water types, 3 lacustrine types, 4 palustrine (wetland) types, 2 estuarine types, and a unique mixohaline coastal ecosystem in recent lava fields--anchialine pools. Eight of the types are freshwater, and 6 are mixohaline; 11 of them are natural and 3 are manmade. Abundance of each type, mostly estimated, is given. Appendix information includes descriptive summaries of environmental features and biota of each ecosystem, and their distributions are shown on maps of the five largest islands.

## INTRODUCTION

The Hawaiian Archipelago is an isolated and diverse group of oceanic islands ranging from coral atolls to a glaciated volcanic high island. Its aquatic ecosystems, with particular reference to inland waters, are equally diverse. Recent geographic classifications of natural living resources recognized the Hawaiian Archipelago as a distinct locality. It has been identified by the International Union for the Conservation of Nature (IUCN 1974) as Biotic Province 6. 12. 23., a Mixed Island Systems biome of the Australian Biogeographic Region. Another international scheme relating to marine and coastal classification (Ray 1975) designated Hawaii zoogeographically as I. A. 3., one of several Indo-West Pacific Subprovinces of the Tropical Warm Water Shelf Province. In aquatic classification of national scope, Cowardin et al. (1976) listed Hawaii as one of 10 biogeographical provinces, the Pacific Insular Province.

Ecological resource classification is independent of geography in broad concept, but distinguishable regional variations or differences in ecosystems occur, as recognized by Cowardin et al. (1976). However, the aquatic classification scheme presented by those authors does not apply well to Hawaii because its perspective is continental and largely botanical. A detailed ecological classification for archipelagos of the South Pacific Commission by Dahl (1976) includes aquatic ecosystems, but Dahl's categories for inland waters, also botanically based, are not all mutually exclusive (some are minor components of ecosystems) and therefore are useful descriptively but not operationally.

A resume of prominent natural Hawaiian inland water ecosystems has been published (Maciolek 1975). The present effort is more detailed; proposed here is a comprehensive, applied classification of all ecologically significant inland surface waters (defined as waters not primarily marine or directly part of marine ecosystems). Comprehensiveness refers to the inclusion of all permanent and intermittent waters (natural, artificial, or culturally modified),

and also to estimates of numbers of ecosystem types and their geographical distributions. This classification originated as a contribution to a multi-agency committee effort to revise State water quality standards on an ecosystem basis. Its potential application includes various other agencies, as well as individuals who have use for an insular regional classification of aquatic ecosystems. Descriptive information and geographical distributions were obtained in part from references listed and in part from unpublished data of the Hawaii Cooperative Fishery Research Unit.

## TERMINOLOGY AND CRITERIA

Terminology presents a persistent problem in classification schemes. Different classifiers appear to employ some key ecological terms (e.g., "habitat") in different contexts, and often discuss such terms without providing the needed operational or pragmatic definitions. Much of the problem revolves about the different interdisciplinary connotation of ecological terms, such as between terrestrial and aquatic ecologists (see discussion in Hutchinson 1967, Chapter 19). Indeed, individual biologists in the same field may not agree completely on the meaning of all frequently used ecological expressions. Perhaps different terminology, or at least different definitions, should be applied to separate discipline elements of a broad ecological classification scheme. For the present, it remains incumbent on each classifier to attempt to provide operational definitions of important terms, even though they may not be fully acceptable to the entire audience.

The following definitions apply to the present classification of Hawaiian inland waters. The aquatic ecosystem is the principal coherent subunit of the aquatic biosphere, consisting of a watermass continuum with relatively sharp, delineable boundaries (ecotones), enclosing integral resident organisms and physiochemical features. Examples of common aquatic ecosystems are lakes, marshes, streams, and estuaries. Two basic components of an ecosystem are the biota (biocoenosis) or totality of living matter[1], and the environment which is here restricted to the nonliving (physicochemical) components of the ecosystem, including spatial dimensions. Habitat is used strictly in an autecological sense to designate all ecosystem requirements of a species, including space. Thus, habitats are not spatially exclusive subdivisions of an ecosystem, as are zones, strata, reaches, etc.

Various types of aquatic ecosystems are assigned to major divisions or classes which are the "Ecological Systems" of Cowardin et al. (1976) with three exceptions: (1) the "Marine" Ecological System is excluded from this classification; (2) Anchialine, a unique ecosystem class (discussed later), is introduced; and (3) Lotic is substituted for "Riverine", a word which connotes large ecosystems of specific type and also is etymologically aberrant with the classical derivations of other class names. "Lotic" fully covers the diversity of flowing water ecosystems (discussed later) recognized herein but not by Cowardin et al. (1976).

[1] In this context, communities are subunits openly definable as assemblages of organisms (such as plankton, nekton, and benthos) sharing common space or special features, and sometimes divided as major taxons.

Implicit here is that ecosystem designation must be based on descriptions of both characteristic biota and environmental features. Ideally, ecosystem categories should be mutually exclusive, each readily discernible by observation and measurements that do not require a protracted time interval to accomplish. Criteria used to distinguish ecosystems classes are hydrological regime, water depth, salinity, and characteristic major taxons of biota (usually, the fauna is more distinctive than the flora). Ecosystem types are defined by criteria that include altitude, topography, water character (temperature, pH, turbidity), cultural influences (environmental and biological), and individual genera or species. After reviewing chemical data, I concluded that oxygen content and pH usually cannot be applied at the ecosystem level. In many waters, particularly those of low ionic content and abundant flora, strong phytosynthesis and respiration diurnally change the levels of such characteristics significantly (pH sometimes more than two units). Criteria are defined further in Appendix A.

## ECOSYSTEM CLASSIFICATION

Fourteen types of inland aquatic ecosystems, occurring almost exclusively on the major high islands of the Hawaiian Archipelago, are listed and qualified in Table 1. These ecosystems (underscored below) are grouped into five ecosystem classes: Lotic, Lacustrine, Palustrine, Estuarine, and Anchialine. Brief descriptions follow. Defining features are given in Appendix B and general map locations in Appendix C.

The Lotic Ecological System contains four types of flowing waters. Perennial Streams forms the largest (by area) and most widely distributed type of ecosystem in Hawaii. In a nearly completed statewide inventory, Timbol and Maciolek (1976) listed 334 streams. Several more have been added recently to the inventory and the final tally is expected to be near 360. These streams are distinguished by three endemic diadromous gobies and a mollusk that live as adults in no other ecosystem. Intermittent Streams differ environmentally in flow regime, and biologically in lacking diadromous fauna, but contain abundant small invertebrates such as ostracods that elsewhere are rare. Rheocrenes are numerous, ubiquitous small seepages ("leaks" from elevated aquifers) without channels that provide habitat for endemic lymnaeid snails and other invertebrates (e.g., damselfly naiads). Ditches and Flumes are artificial streams in which some animals are native but most are exotic. Some ditches were built by ancient Hawaiians for taro irrigation; most were constructed during the past century for sugar cane irrigation. They occur on all major islands but have not been inventoried.

The Lacustrine Ecological System is represented by a few natural and many artificial deepwater basins. Only four freshwater Natural Lakes are known, their occurrence limited by substratum permeability (Maciolek 1969). Each is distinctive in location, environmental features, and native invertebrate fauna. Reservoirs (impoundments) are the most abundant lacustrine ecosystem; more than 400 are shown on quadrangle maps of the U.S. Geological Survey. They are artificial ecosystems, not only in basin origin and structure but also in biota, which is dominated by introduced macrofauna. Two Saline/Haline Lakes constitute a rare ecosystem type in Hawaii, one being a high-island shoreline feature and the other a flat-island closed lagoon. They are mutually distinct and could be classified as separate ecosystem types.

Table 1. Hawaiian Inland Water Ecosystems: Distribution, Abundance, and Fauna

| Ecosystem Class | Location (Island)[a] | Elevation (m; SL = Sea level) | Approximate Number | Characteristic Fauna (N = native, I = introduced) |
|---|---|---|---|---|
| 1. LOTIC (RIVERINE) | | | | |
| 1a. Perennial Streams | All | <2000 | 360 | N: diadromous fishes, invertebrates |
| 1b. Intermittent Streams | All | Various | >100 | N: ostracods, beetles |
| 1c. Rheocrenes | All | <1000 | >1000 | N: snails, damselflies |
| 1d. Ditches and Flumes | K,Ma,O | < 500 | >200 | N/I: dipterous larvae, fishes |
| 2. LACUSTRINE | | | | |
| 2.1 Limnetic (fresh) | | | | |
| 2.1a Natural Lakes | -- | Various | 4 | N/I: small invertebrates |
| 2.1b Reservoirs | K,Ma,O | < 1000 | 400 | I: fishes, crayfish |
| 2.2 Saline/Haline | -- | SL | 2 | N: various |
| 3. PALUSTRINE | | | | |
| 3.1 Elevated Wetlands | | | | |
| 3.1a Montane Bogs | All[b] | 600-2000 | 8 areas | N: odonates, beetles |
| 3.1b Ponds and Marshes | K,H | 100-1200 | 5 areas | N: odonates, beetles, cladocerans |
| 3.2 Low Wetlands | | | | |
| 3.2a Limnetic Wetlands | K,Ma,O | SL | >10 areas | I: topminnows, crayfish, tadpoles |
| 3.2b Saline Wetlands | All | SL | 25 areas | I/N: snails, insects, tilapia |
| 4. ESTUARINE | | | | |
| 4a. Natural Estuaries | K,H | SL | 20 | N/I: euryhaline fishes, crustaceans |
| 4b. Developed Estuaries | H,Mo,O | SL | 10 | I/N: fishes, crustaceans, worms |
| 5. ANCHIALINE (Pools) | H,Ma | SL | 30 areas | N: snails, hypogeal shrimps |

[a] Islands were most abundant: H = Hawaii, K = Kauai, Ma = Maui, Mo = Molokai, O = Oahu
[b] Also Playa "Lakes," Island of Niihau.

The Palustrine Ecological System includes various wetlands initially subdivided into interior-elevated and coastal-lowland ecosystems, each with two types. Elevated wetlands, located in remote areas, are mainly natural ecosystems in which native biota dominates; low wetlands have been modified severely by man although they still constitute the primary habitat for most native waterbirds. Montaine Bogs occur in limited sites on all high islands and are distinguished by strongly acid waters and impoverished invertebrate fauna. Elevated Ponds and Marshes appear more productive than bogs and have greater faunal diversity. Further study might show that these two types form a graded series classifiable as a single ecosystem type. Introduced biota predominates in Limnetic Low Wetlands, a complexity of similar ecosystems ranging from flooded taro fields to natural marsh basins. Saline Low Wetlands are shoreline salt marshes and ponds that originated artificially (abandoned Hawaiian fishponds, recently constructed waterbird refuges) or naturally (perennial and seasonal wetlands, Maciolek 1971). Salt-dependent pickleweed (Batis maritima) is a common emergent plant; fauna includes introduced euryhaline fishes and invertebrates co-occurring with native snails and isopods. Present day aquaculture ponds can be fitted into either of the above types of coastal-lowland ecosystems.

The Estuarine Ecological System is restricted to mixohaline tidal waters in distinct basins that have sufficient surface connection to the ocean for frequent or periodic migration of euryhaline marine fauna. Natural Estuaries, most of which occur on Kauai, serve as nurseries for mullet and kuhliid fishes and harbor various other native fishes, mollusks, and crustaceans. Common introduced animals include Scylla crabs and tilapia. Two subtypes, drowned river mouths and estuarine limnocrenes are similar in environmental conditions and resident fauna, but drowned river mouths receive stream runoff and thus are important as migratory routes for diadromous fauna. Developed Estuaries include basins that are manmade (e.g., dredged or channelized stream mouths) or developed from a natural state. Fauna is similar to that in Natural Estuaries but is usually less diverse, except in some Hawaiian fishponds (structure described in Kikuchi 1976) that biologically resemble estuarine limnocrenes.

The Anchialine Ecological System consists of a single type, Anchialine Pools. The name (from Greek Anchialos, "near the sea") was suggested by Holthuis (1973) to define "pools with no surface connection with the sea, containing salt or brackish water, which fluctuates with the tides." Ecosystem definition should note further that distinctive biota includes invertebrate species not found elsewhere. Anchialine Pools occur in various insular and continental locations but within the United States they appear to be uniquely Hawaiian. Most are in recent coastal lava fields on Maui and Hawaii islands. Kona Coast sites containing anchialine pools and other ecosystem types were inventoried and described by Maciolek and Brock (1974). Most pools are small, 90 percent being less than 100 $m^2$ in area. Surfaces are inland extensions of the oceanic water table. Mixohalinity, usually less than 10 percent, results from dilution by seaward percolating groundwater. Mat- and crust-forming algal communities occur in rocky pools, and widgeongrass (Ruppia maritima) is characteristic in sedimented basins. The fauna, which includes many endemic species, consists mostly of invertebrates of marine origin that invaded through subterranean interstices. Characteristic taxons are snails, amphipods, and shrimps; fishes are absent or rare.

## CLASSIFICATION DEFICIENCIES AND ENIGMAS

Any comprehensive classification scheme, designed for practical application and encompassing diverse ecosystems that are sometimes transitional, is fundamentally provisional. Its completeness and utility are relative, reflecting the accuracy, extensiveness, and recency of data on which it is based. Relevant data are never fully adequate. Thus, each ecosystem described can be rated on the "strength" of its informational base. Perennial Streams are best qualified in the present classification as a result of extensive biological surveys, and data on flow and water quality generated from the continuing monitoring program of the U.S. Geological Survey (e.g., USGS 1976). Data bases for Anchialine Pools and Natural Lakes are good, but further information on them is desirable. Additional data would materially improve descriptions on the other ecosystem types. Least well qualified in this classification are artificial and culturally modified ecosystems such as Reservoirs, Ditches, and Developed Estuaries.

Assuming that natural quality of the ecosystem is important in a classification scheme, Hawaii has a serious problem in the growing influence of human culture on both the environment and biota. Stream channelization and water diversion, for example, degrade part of the native ecosystem physically and biologically. More than half of Oahu's 54 streams have channel alterations. Approximately 60 percent of all Hawaiian streams have diversions or channel alterations. How extensively must a given stream be channelized or diverted before it is classified as an artificial ecosystem? Furthermore, man has caused establishment of foreign species to the extent that they outnumber native species among the freshwater macrofauna. Recent biological surveys indicate that all lowland limnetic ecosystems on Oahu are dominated in species numbers and biomass, by exotics. Some exotics spread so slowly that it will be many years before biota equilibrium is approached statewide, even if further introductions could somehow be halted. Should we treat these situations as successional phenomena or should we design two classification schemes, drawing a line between natural and artificial ecosystems in all categories?

The Hawaii Department of Health, in a proposed revision of water quality standards based on ecosystem types, recognizes five "status-use" categories with differing levels of certain water quality parameters into which all surface waters are assigned. Relative natural quality is one of the factors used in assigning a given ecosystem into a category. Such an approach involves considerable subjective judgment and requires periodic reevaluation of many ecosystems that in time could degrade or improve in natural quality.

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# APPENDIX A

## DEFINITIONS OF TERMS AND UNITS

1. Dimensions.

°/₀₀ = parts per thousand, measure of salinity.
% gradient = relative slope measured as unit elevational change per 100 horizontal units (as m/100 m).
μmhos = reciprocal megohms, measure of water conductivity.
Also: distances, areas, volumes, etc. given in metric system; temperatures in ° Celsius.

2. Water Regimes.

Lentic = standing or still water as in ponds, reservoirs, etc.
Lotic = flowing water as in streams, springs, etc. Refers to unidirectional gravitational flow, thereby excluding waters moving with wind currents, waves, and tides.

3. Dissolved Minerals.

a. Qualitative aspects.
Haline (halinity) = brackish or salty water condition wherein dissolved ions are derived from seawater.
Saline (salinity) = general term for water with noticeable salt content; ions from various sources.

b. Quantitative aspects.
Limnetic = freshwater, salt content <0.5 °/₀₀.

Mixohaline = brackish water, salt content 0.5 to 30 °/₀₀.

Euhaline = seawater, salt content 30-40 °/₀₀.

Hyperhaline = brine-like water, salt content >40 °/₀₀.

c. Concentration vs. time.
Homoiohaline = salt concentration stable or fluctuating over narrow range.
Poikilohaline = salt concentration fluctuating widely.

d. Biological response.
Euryhaline = tolerates wide range of salt concentration.
Stenohaline = tolerance limited to narrrow range of salt concentration.

4. Faunal Life History.

Diadromous = two migrations; refers to an aquatic animal that obligately spends parts of its life in different ecosystems (eg. a Hawaiian stream dweller that undergoes larval development in the ocean).

# HAWAIIAN INLAND WATERS: DESCRIPTIVE FEATURES AND CHARACTERISTIC BIOTA.

## 1. LOTIC (RIVERINE) ECOLOGICAL SYSTEMS.

Limnetic surface waters flowing unidirectionally down altitudinal gradients.

### 1a. Perennial Streams.

Waters draining land surfaces in discrete channels and flowing year-round. Upper altitudinal limit. ca. 2,000 m, fixed by orographic rainfall regime. Turbidity low except during freshets; dissolved oxygen normally near saturation throughout watercourse. Flora mainly mosses, filamentous algae, and epilithic diatoms. Native macrofauna (fishes, shrimps, mollusk) diadromous, with marine larval development. Prominent altitudinal zonation of environmental conditions and biota.

Headwater Reach. Elevation >800 m or gradient >30%, or both. Substratum mainly bedrock. Water: temperature <18° (usually 12-15°); conductivity <50 μmhos (dissolved solids <40 mg/l); pH usually <5.5. Fauna primarily native: aquatic insects (Coleoptera, Diptera, Odonata) and lower invertebrates; no decapod crustaceans or native fishes.

Midreach. Intermediate in environmental conditions between Headwater and Terminal Reaches (see below). Substratum predominantly boulders. Native fauna: atyid shrimp, riffle midges, lymnaeid and neritid snails, true gobies (especially Lentipes and Sicydium); no eleotrid or itinerant marine fishes. Introduced fauna: caddisfly, Tahitian prawn, crayfish, and several fishes (especially tilapia, topminnows, loach).

Terminal Reach. Watercourse below sharp gradient that bars upstream migration of itinerant marine fishes--elevation generally <50 m and gradient <5%. Substratum: rock, gravel, and sediment. Water, except during freshets: temperature >18° (mainly 19-22°); conductivity >80 μmhos (mainly 100-150 μmhos); dissolved solids 60-100 mg/l; pH 6.5-7.8. Native fauna: midge and cranefly larvae, snails (Melania, Neritina), prawn, gobioid and itinerant marine fishes (Eleotris, Kuhlia, and Mugil). Introduced fauna: crayfish, Tahitian prawn, topminnows, tilapia, and clariid catfish.

Remarks: More than 360 perennial streams identified, all major islands (localities, Appendix C); largest = Wailuku River, Hawaii--35 km long, 350 $km^2$ drainage area, 8 $m^3/s$ (285 cfs) mean discharge. Most streams originally discharged continuously to ocean; some small interrupted streams discharge only seasonally but flow perennially in upper reaches. Most streams diverted for agricultural and domestic purposes; total normal flow diverted from many streams (Oahu, Maui), rendering them artificially interrupted. Channel alteration (16% of all streams) modifies or eliminates native ecosystem character, particularly in Honolulu area. Oahu's streams dominated by introduced fauna. Few relatively pristine streams remain in archipelago, mainly on the remote windward slopes of Kauai, Molokai, and Hawaii (Kohala District) Islands.

1b. Intermittent Streams. Seasonally flowing waters draining land surfaces in discrete channels (gulches or wadis). Water quality variable. Characteristic biota appearing where water persists for at least a few weeks (usually as diminishing flow): filamentous algae, oligochaete worms, Ancylus limpets, ostracods, beetles, backswimmers. No diadromous fauna. Occur on dry (leeward) slopes of all islands and porous wet slopes (recent lava, e.g., Hualalai and Mauna Loa, Hawaii). Some occur at elevations above 2,000 m (eg. Pohakuloa Gulch, Mauna Kea; Pulehu Gulch, Haleakala).

1c. Rheocrenes. "Flowing spring." Perennial seeps and springs flowing short distances over rock surfaces or in indistinct channels. Found typically along banks of deeply incised streams or coastal rock faces (especially windward coasts of Kauai, Molokai, East Maui). Variable water quality, sometimes iron-rich as evidenced by bacterial precipitation of ferric hydroxide. Characteristic biota: gelatinous (blue-green) algae, mosses, maidenhair fern, detritivorous leeches, (Diptera, Odonata), lymnaeid snails.

1d. Ditches and Flumes. Water flowing continuously in artificial channels. Environmental character and biota vary with location and degree of use. Primary Ditches/Flumes carry diverted stream water to reservoirs or use areas. Generally high-quality water like that in stream at diversion point (most located 100-500 m elevation, comparable to midreach stream water). Lack of shelter and slack water results in low faunal diversity; most prominent are aquatic fly larvae, snails, and sometimes atyid shrimp. Fishes scarce. Primary ditches abundant on Kauai, Oahu, Maui, and Hawaii (Kohala District) Islands. Secondary (or effluent) Ditches carry water from reservoirs, agricultural sites, and use facilities. Moderate to low water quality, sometimes polysaprobic. Macrofauna, when present, consists mainly of introduced fishes and tolerant invertebrates. Mostly at elevations below 50 m.

2. LACUSTRINE ECOLOGICAL SYSTEMS.
Lentic water in definite basins with predominant open water and depth exceeding 2 m.

2.1. Limnetic water, salinity <0.5 °/oo

2.1a. Natural Lakes. Uncommon in Hawaii. Four small lakes known: Waiau and Green, Hawaii; Waiele'ele, Maui; and Meyer, Molokai (Appendix C). Range in elevation from 3,969 m to near sea level. Individually distinctive environmental character and biota. Native fauna: small invertebrates (no fishes, shrimps). Exotic fishes introduced into two lakes.

2.1b. Reservoirs. Artificial water bodies constructed for irrigation and other socioeconomic purposes. Low to intermediate altitudes (<1,000 m) principally on Kauai, Oahu, Maui, and Hawaii (Appendix C). Surface area <1 to 104 ha (Waita, Kauai). Not inhabited by native fauna. Environmental quality and biota vary with reservoir type.

Primary Storage Reservoirs. Primarily for agricultural and domestic water supply. Water bodies near source streams in remote upland sites. Relatively stable surface levels and good water quality. Some with submersed and floating water flora. Fauna: crayfish, sport fishes (especially largemouth bass, bluegill, catfish), topminnows, tilapia, insects.

Distributional Reservoirs. Water bodies mainly on agricultural lands or in populated areas, mostly for temporary water storage and redistribution. Fluctuating surface levels. Water quality moderate to poor, usually turbid. Fauna: crayfish, tilapia, topminnows, tadpoles.

Effluent Reservoirs. Receiving waters for effluent ditches. Low-quality water, very turbid, often anaerobic. Fauna mainly tolerant invertebrates.

2.2. Saline or Haline Waters. Category not further subdivided. Includes single lacustrine ecosystems not classifiable elsewhere. Examples: euhaline Nomilo Pond, Kauai (6.2 ha; maximum depth 20 m) with marine algae, invertebrates, and fishes; poikilohaline Laysan Lagoon, Leeward Archipelago, fluctuating area and depth (maximum area, 70 ha; maximum depth 5 m) with brine flies, Artemia, amphipods.

3. PALUSTRINE ECOLOGICAL SYSTEMS.
Lentic waters <2 m deep (usually <1 m). Sometimes in irregular or poorly defined basins.

3.1. Elevated Wetlands. Natural limnetic water bodies located at elevations >100 m. Fauna predominantly native, no fishes or shrimps.

3.1a. Montane Bogs. Small bodies of acid, open water on elevated 600-2,000 m) flat topography in areas of high persistent rainfall (>500 cm/yr), all islands (Appendix C). Organic and hydromorphic soil substratum. Water clear, cool (<16°), very low in dissolved minerals (conductivity <30 mhos) and yellow to brownish with humic solutes (pH <5.5). Bordered by acidophilic flora (mosses, lichens, dwarf shrubs). Fauna low in abundance and diversity and consists primarily of insects (Odonata, Coleoptera, Diptera).

3.1b. Ponds and Marshes. Perennial to seasonally intermittent wetlands in upland areas (100-1,200 m) of moderate to high rainfall, better drained than boglands (Appendix C). Water clear, sometimes yellowish, low to moderate dissolved mineral content (conductivity 30-80 μmhos), and circumneutral (pH 5.5-7.5). Emergent aquatic plants (sedges, grasses) often abundant. Fauna similar to but more abundant and diverse than that of bogs.

3.2. Low Wetlands. Altered or artificial shallow ecosystems located coastally or in valley flats. Variable environmental character. Fauna mainly introduced species; emergent flora predominant.

3.2a. Limnetic Wetlands. Perennial freshwater marshes and ponds not immediately adjacent to coastline. Variable water quality: salinity <0.5 °/°° (conductivity 100-300 mhos), pH 6-7.5. Includes natural basins such as Kawainui Marsh, Oahu, and artificial basins such as taro fields. Sedges, bullrush, or California grass predominates in wild areas; Colocasia esculenta in taro fields. Introduced fauna: crayfish, topminnows, tilapia, Bufo tadpoles.

3.2b. Saline Wetlands. Seasonal or permanent coastal ponds and marshes of variable salinity resulting from intrusion of haline groundwater or inundation from large waves. No definite or periodic surface connection to ocean. Water warm (20-30°), usually mixohaline and poikilohaline (evaporation may cause seasonal ponds to becomes hyperhaline), pH 6.5-8. Flora: blue-green algae, bullrushes, and sedges (low salinity waters), pickleweed (Batis maritima) and mangrove. Fauna: euryhaline fishes (tilapia, sailfin molly) and insects (hydrophilid beetles, Trichocorixa water boatman), Ligia isopods, Melania and Assiminea snails. Examples include open ponds (Kealia and Kanaha on Maui), salt marshes (Ewa plain, Oahu), man-made waterbird refuge ponds (Pearl Harbor, Oahu), playa "lakes" (Niihau Island).

4. ESTUARINE ECOLOGICAL SYSTEMS.

Mixohaline water in delineable basins with continuous or periodic surface connection to the ocean, allowing entry of euryhaline marine fauna (excludes waters inhabited by stenohaline marine inshore animals such as corals, urchins, etc.). Tidal fluctuation of surface level.

4a. Natural Estuaries. Waters in natural basins individually ranging from limnetic to nearly euhaline. Pronounced stratification of halinity, temperature, and usually oxygen concentration. Diverse native euryhaline fauna including: neritid snails (Theodoxus); barnacles, paleamonid shrimps, and grapsid and portunid crabs; gobioid, serrate swimming crab, tilapia, topminnows. Two distinct subtypes of estuaries based on freshwater input and relevance to diadromous fauna.

True Estuaries. Drowned river (stream) mouths. Limnetic water from perennial surface runoff. Inland extent determined by measurable tidal fluctuation and topography. Subtype extremes: vertically stratified estuaries with freshwater inflow volume low relative to basin volume (Huleia and Kilauea, Kauai); horizontally stratified with relatively large freshwater inflow (Hanalei, Kauai). Poikilohalinity in both subtypes results from wide seasonal fluctuations in stream discharge. Important as migratory pathway for larval and juvenile diadromous stream animals. Most occur on Kauai.

Estuarine Limnocrenes. Nearshore basins with subterranean limnetic water sources (springs). Homoiohaline. Biota similar to True Estuaries but lacks transient diadromous (stream) fauna and has submerged vascular plants. Hawaii Island only (eg. Waiakea and Lokoaka Ponds, Hilo).

4b. Developed Estuaries. Estuarine systems constructed recently to prehistorically, or highly modified from natural state. Mixohalinity resulting from groundwater seepage or surface runoff. Water quality variable. Native biota similar to that found in Natural Estuaries, but often dominated by exotic plants (mangrove) or animals (tilapia). Includes walled Hawaiian fishponds (Hawaii, Molokai, Oahu), altered stream mouths (Ala Wai Canal), and biologically modified systems (Heeia Mangrove Swamp and Pearl Harbor sites, Oahu).

5. ANCHIALINE ECOLOGICAL SYSTEM.
Mixohaline lentic waters occurring in recent coastal lava fields or elevated fossil reef rock. No surface connection to ocean but with tidal fluctuations. Unique faunal and algal communities. Ecosystem not subdivided.

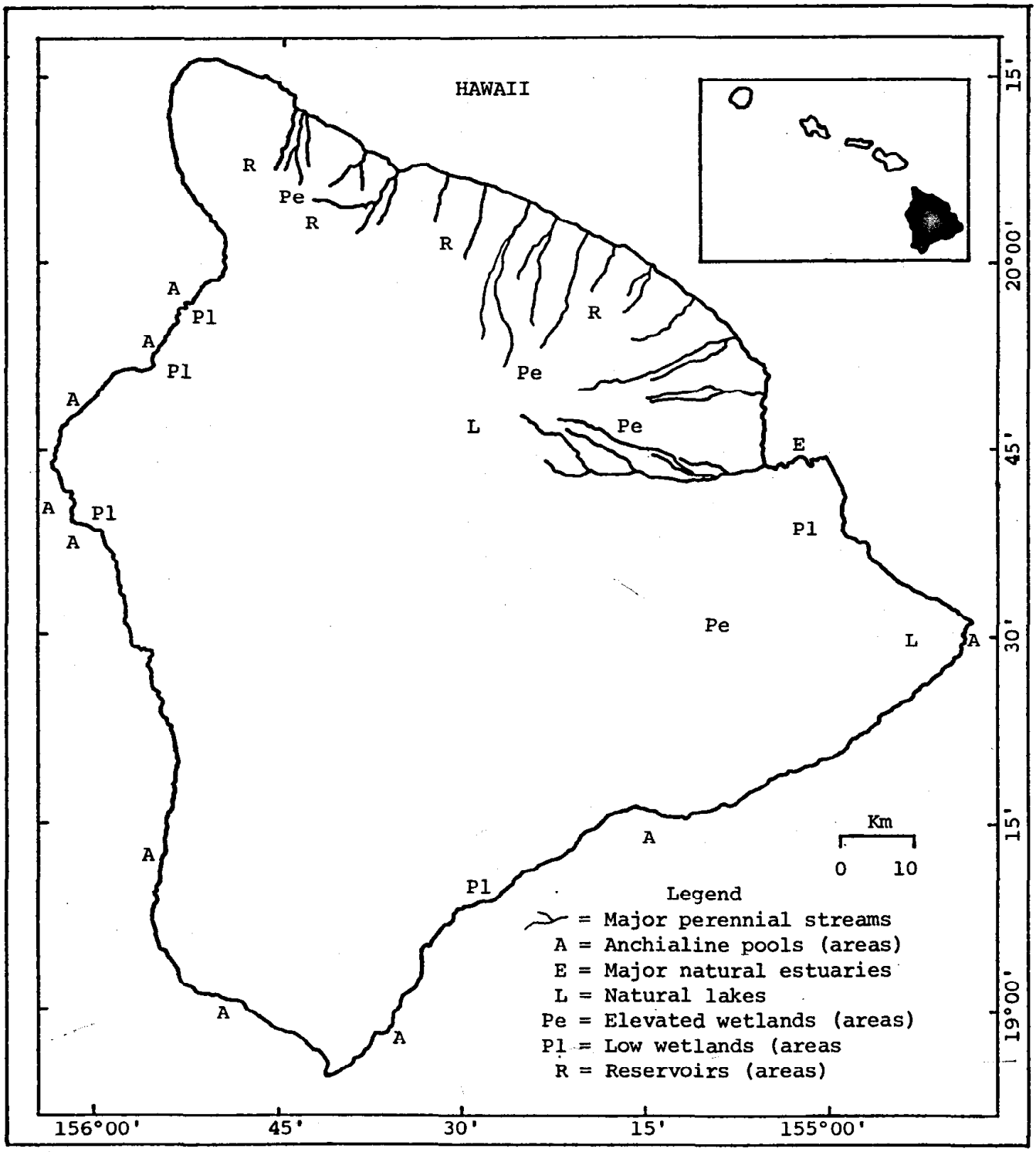
Anchialine Pools. Mostly small, irregular water exposures in barren lava, with or without sediments. Surface level is inland extension of marine water table. Mixohaline water results from dilution of intruding ocean water with seaward-percolating limnetic groundwater. Homoiohaline, but sharp, stable, vertical, salinity stratification is evident in deep pools. Salinity of surface water usually 1-10 °/°° but occasionally approaches euhaline levels. Depth varies with tide; some very shallow pools appear only at high tide. Water usually clear, circumneutral, temperature 22-30°.

Biota distinctive, some faunal species (shrimps) not found elsewhere. Flora: filamentous chlorophytes; mat and crust communities dominated by cyanophytes (Lyngbya, Scytonema); epilithic rhodophytes (Hildenbrandtia); widgeongrass (Ruppia maritima) where soft sediments occur. Fauna predominantly shrimps (10 spp.), amphipods and snails (3 spp.); fishes absent or rare. Most characteristic is a small (1 cm) red atyid shrimp, Halocaridina rubra; most unusual are sightless hippolytid and procaridid shrimps (only in water >10 °/°°). Introduction of fishes degrades or eliminates crustacean community, changing ecosystem to Haline Low Wetland (type 3.2b).

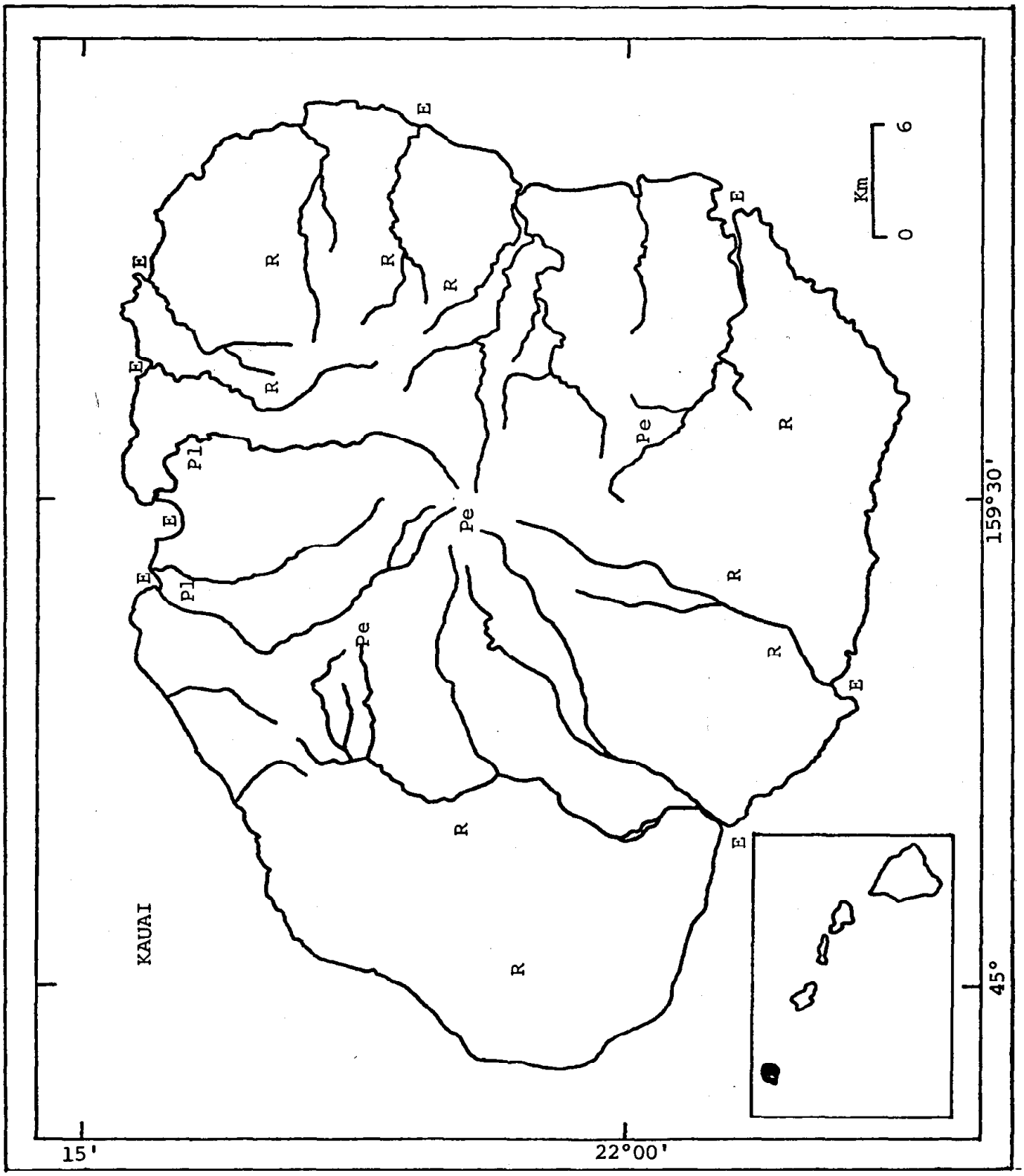
Anchialine pools occur singly and in groups (areas) with subterranean interconnections. Mostly on post-Pleistocene lavas of Hawaii and East Maui Islands (Appendix C). Unusual examples: Waianapanapa Caves, Maui (lava tube); L. Kauhako, Molokai (volcanic vent); Popoia Islet, Oahu (sinkhole in fossil reef).

GENERAL LOCATIONS OF PROMINENT INLAND WATER ECOSYSTEMS

MAP 1, ISLAND OF HAWAII



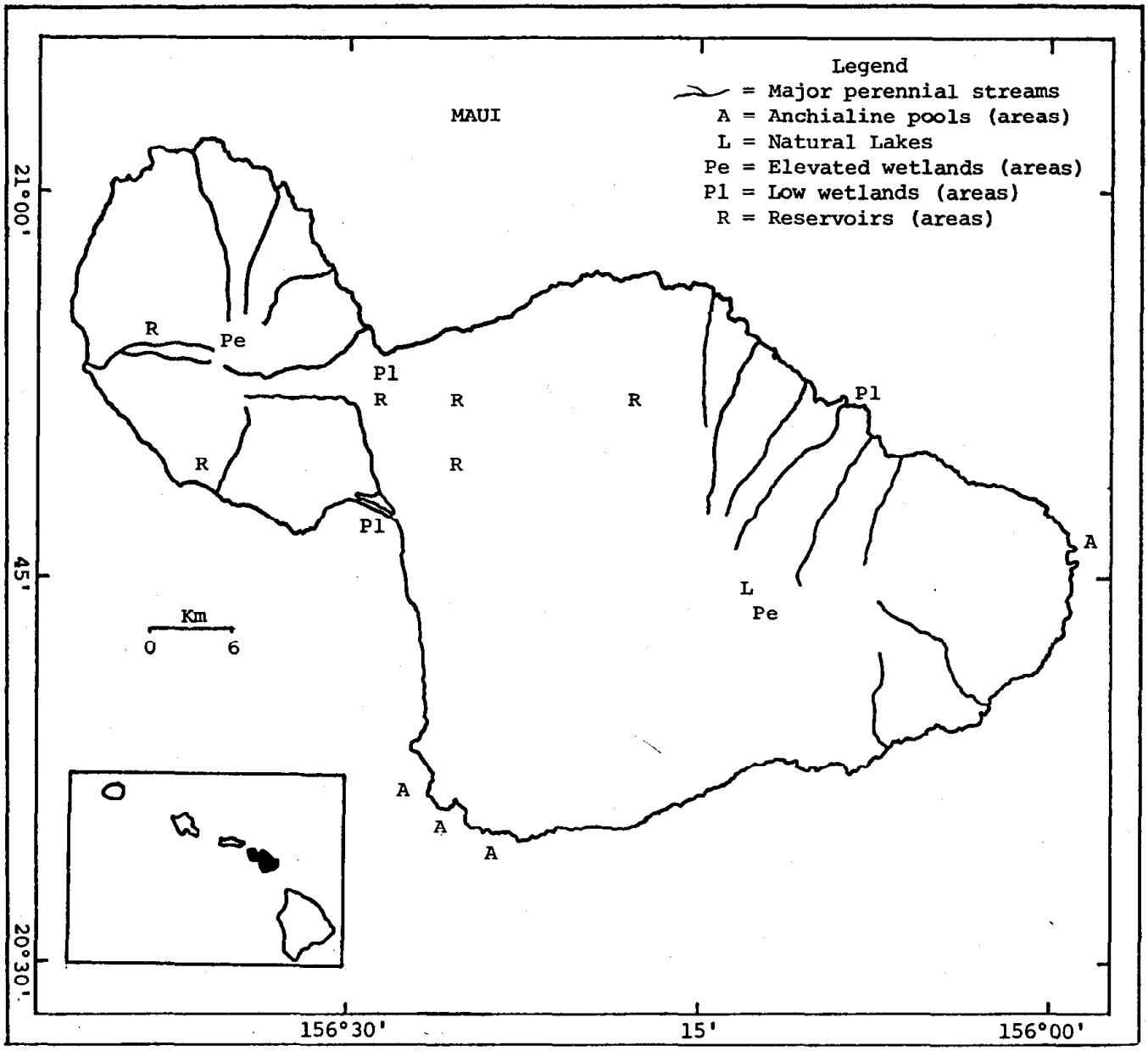
MAP 2, ISLAND OF KAUAI



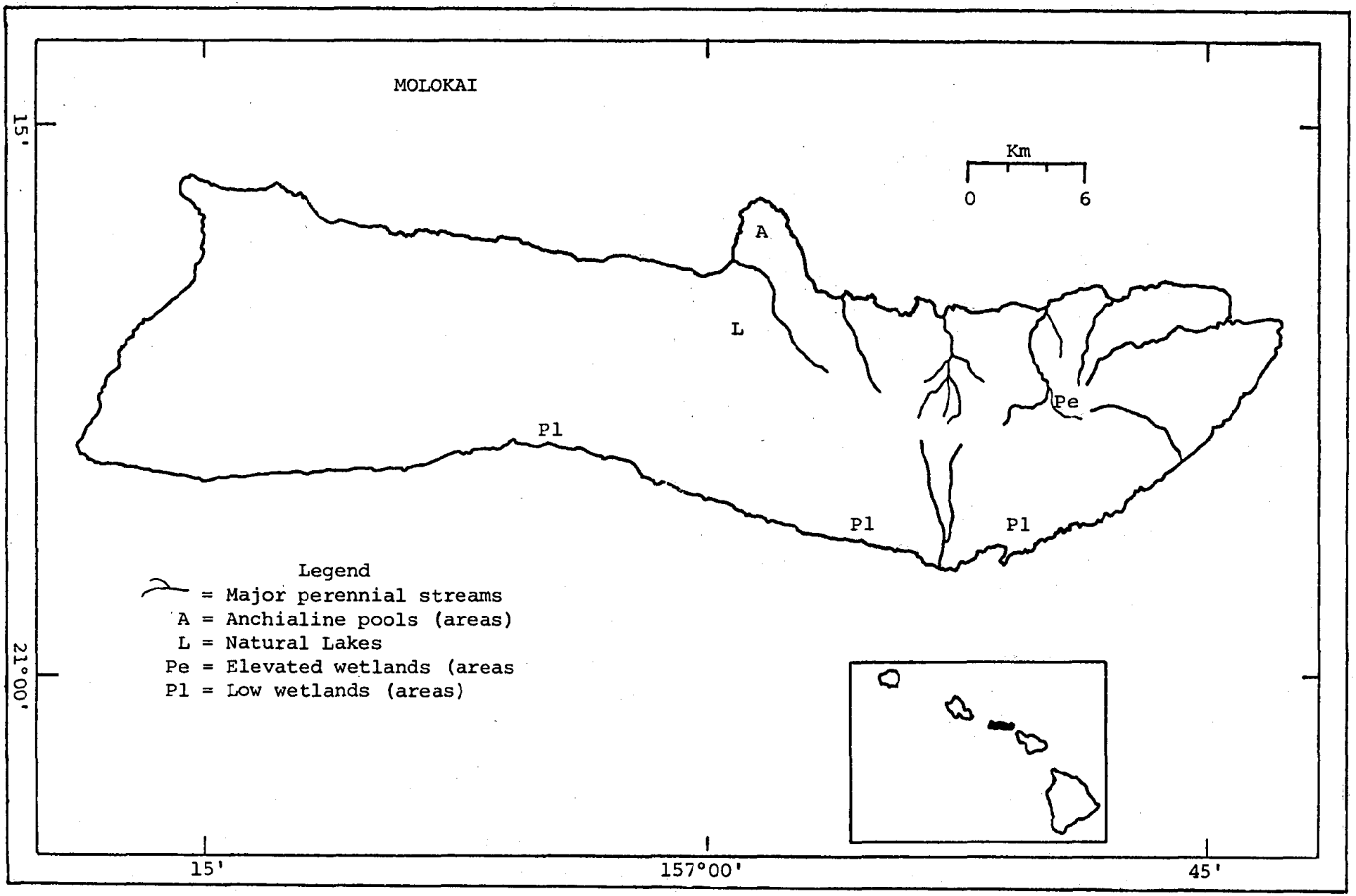

Legend

= Major perennial streams
E = Major natural estuaries
Pe = Elevated wetlands (areas)
Pl = Low wetlands (areas)
R = Reservoirs (areas)

MAP 3, ISLAND OF MAUI



MAP 4, ISLAND OF MOLOKAI



MAP 5, ISLAND OF OAHU