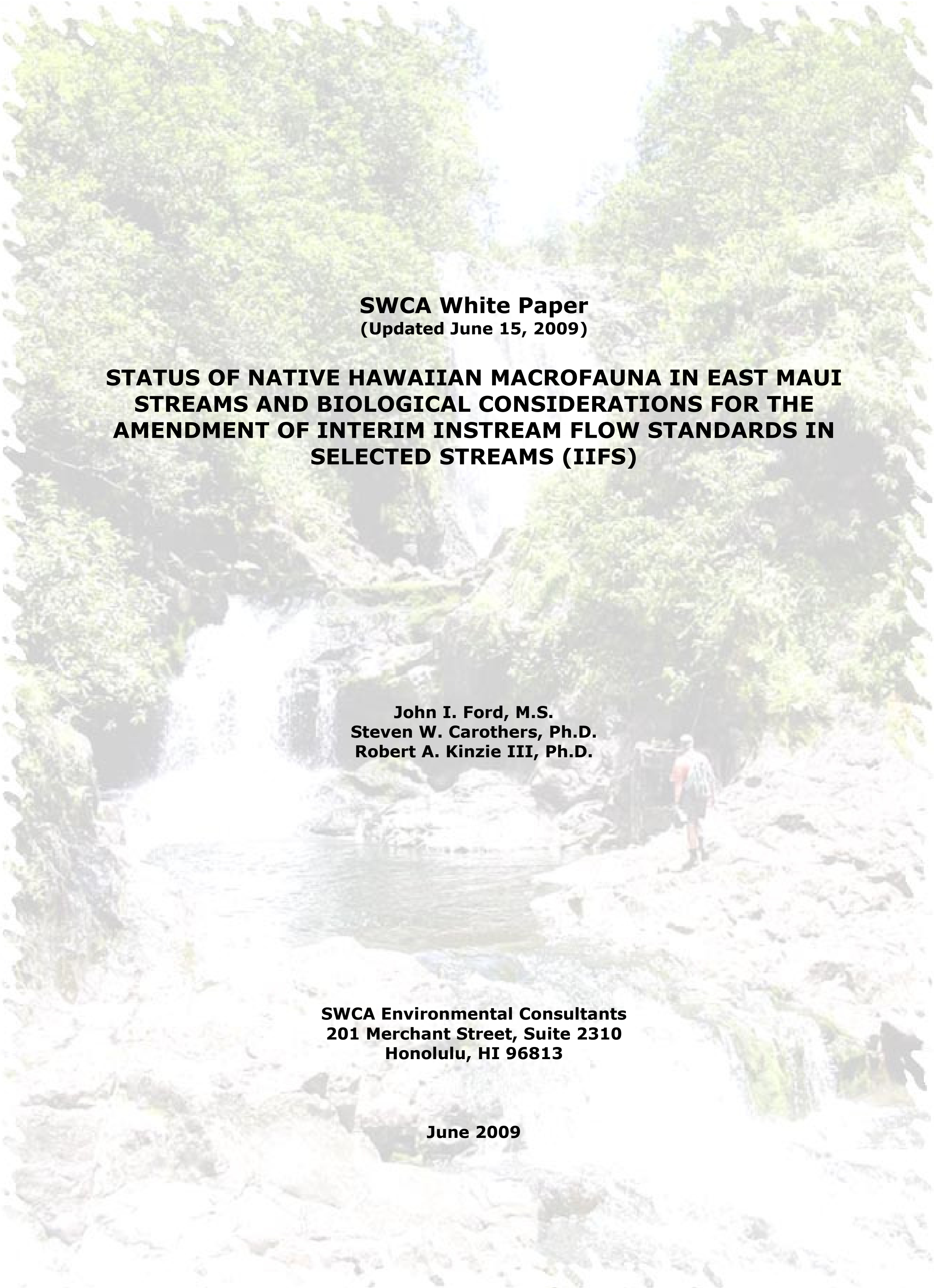

SWCA White Paper

(Updated June 15, 2009)

STATUS OF NATIVE HAWAIIAN MACROFAUNA IN EAST MAUI STREAMS AND BIOLOGICAL CONSIDERATIONS FOR THE AMENDMENT OF INTERIM INSTREAM FLOW STANDARDS IN SELECTED STREAMS (IIFS)

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EXECUTIVE SUMMARY

> *Little is known about the relationship between stream flows and the ecological systems of streams. Too many extraneous factors have been introduced to enable a one-to-one causal relationship between flow and stream viability. Watersheds have radically changed with the introduction of non-indigenous trees shrubs and grasses, altering the absorption characteristics of the watersheds' soil and the amounts and patterns of water released into the streams… some streams that have been severely degraded through reduced base flows, changes in their watersheds, and introduced aquatic species still support viable and thriving native species, while other comparable or even less degraded streams are nearly devoid of native life. (Miike 2004)*

The 1,600-year history of human habitation within the Hawaiian Islands has resulted in the loss and/or endangerment of an unusually high proportion of the archipelago's indigenous plant and animal species. By the time Captain James Cook visited the islands in 1778 the coastal areas and low lying forests of most islands had already been cleared and heavily settled (Kirch 1982, Cuddihy and Stone 1990, Burney et al. 2001, Athens et al. 2002, Burney and Flannery 2005). Most of the natural Hawaiian ecosystems, including streams, were transformed by humans and the invasion of exotic species centuries before the present. The combination of habitat loss, introductions of non-native competitive and predacious species and diseases have resulted in remarkably high numbers of extinct and threatened and endangered species throughout the Hawaiian Islands. In fact, the Hawaiian Islands are widely known as the endangered species capital of the world, and federal and state agencies and NGOs spend millions of dollars every year in attempts to eliminate non-native species and restore native flora and fauna.

One group of animals that shares a unique lifestyle, specifically several species of native freshwater macrofauna characteristic of Hawaiian streams, have survived the steady onslaught of ecological change and continue to thrive. They persist today in streams throughout the main Hawaiian Islands, including those streams that have been substantially modified for over a century of water diversions for taro and sugar cane irrigation as well as other human uses. The native stream species of concern discussed in this paper include four native Hawaiian gobies, or ʻoʻopu (*Lentipes concolor*, *Sicyopterus stimpsoni, Awaous guamensis, and Stenogobius hawaiiensis*), an eleotrid (*Eleotris sandwicensis*); two gastropod mollusks, including hīhīwai (*Neritina granosa*) and hapawai (*Neritina vespertina*); a prawn (*Macrobrachium grandimanus*); and a shrimp, or ʻopae kalaʻole (*Atyoida bisulcata*). These animals have been selected for assessment because of their importance in traditional and customary Hawaiian gathering and subsistence fishing. These nine species share a common life history strategy called *amphidromy* that involves migration from the freshwater streams to the ocean for larval development and return. There is ample anecdotal evidence to indicate that decades ago many of these species were more abundant than they are today (Titcomb 1972, Pukui 1983, Bell 1999). Contrary to what was once believed; however, there are no data available to suggest that any of these native species are at risk of either endangerment and/or extinction in East Maui streams or elsewhere throughout the Hawaiian Islands (Parham et al. 2008). In fact, East Maui streams are recognized among the most important habitats for native Hawaiian stream animals in the State under current diverted conditions (National Park Service Nationwide Rivers Inventory 1982, Hawaiʻi National Park Cooperative Studies Unit 1990).

The objective of this paper is to present biological information that can be utilized in determining equitable, reasonable, and beneficial in-stream and off-stream uses of the limited surface water resources of northeast Maui. By analyzing the current status of the native stream species we believe that missing critical information can be made available to decision makers, and an equitable distribution of the limited amount of water can be based on biological facts rather than perceptions. We summarize the scientific literature on Hawaiian stream ecosystems, the overall status of native amphidromous species, and the presence or absence of biological factors indicating the need for flow restoration to enhance these species' ecological survival. We offer insight regarding the persistence of the native amphidromous species in the region following 120 years of water development in East Maui and a millennium of human impacts to the landscape. The findings offered in this report are based upon stream research conducted by SWCA Environmental Consultants in East Maui and throughout the state, and an assessment of the published research by the United States Geological Survey, Hawaiʻi Division of Aquatic Resources, and other investigators.

It had generally been assumed that over a century of water diversion from East Maui streams has resulted in irreparable ecological damage to some elements of native Hawaiian flora and fauna. Some also postulate that a suspension of water diversions will effectively restore stream ecosystems to the benefit of native stream species, especially those with the amphidromous lifestyle. While we believe opportunities do exist to enhance some of the stream systems to benefit native wildlife, our findings do not support acceptance of the blanket assertion that the amphidromous species of the region are currently declining in numbers, and that suspension of water diversions in East Maui is needed to sustain healthy populations of these species.

Our review illustrates how hardy amphidromous species are despite historical stream modifications, including significant areas of intermittent dewaterment. Existing flow levels in streams with a long history of water diversions continue to provide habitat and ecological connectivity[1] sufficient to sustain native aquatic life, as recognized by Miike (2004) and as documented elsewhere on Maui (SWCA 2004, 2005, 2007, 2008; Parham et al. 2008). Of the total 106 linear kilometers (66 mi) of stream channels within the study area (as defined by Gingerich and Wolff 2005), SWCA has calculated that 57 percent of the total stream length has retained 75-100 percent of aquatic habitat at base flow relative to the estimated undiverted conditions.

The longitudinal distribution of native fishes, crustaceans, and mollusks in diverted East Maui streams generally mirrors the normal patterns of these species in unaltered streams. Moreover, our findings indicate that in the East Maui streams for which distributional data are available, most have known populations of amphidromous species both above and below diversion structures, and amphidromous species are well represented with self-sustaining populations throughout the entire East Maui Region and the State. In fact, 17 of 18 East Maui streams for which data exist have amphidromous species reported from their upper reaches. This confirms that ecological connectivity occurs under existing diverted conditions. Even though there are reliable distributional data for these East Maui streams, there are few or no quantitative data on population size or density.

Amphidromous species worldwide have evolved reproductive patterns adapted to the extremely variable and unpredictable flow conditions characteristic of ephemeral streams and are perfectly adapted to naturally ephemeral torrential flash floods and subsequent periods of decreasing flow (McDowall 1993). Larval hatching, downstream drift to the sea, and later migration into upstream habitats where they can survive, even in standing water pools, under conditions of base flow are strongly correlated to periods of torrential flow (Lindstrom 1998). This is an evolutionary strategy that has allowed these native species to endure while so many other native species have faced extirpation. The system of water diversions in East Maui, while clearly exacerbating the dry end of the wet-dry daily cycle of stream ecology, has not been demonstrated to preclude suitable habitat conditions for sustaining populations of the amphidromous species.

1.0 INTRODUCTION

1.1 Background

Since the Hawai'i Supreme Court handed down its substantive interpretation of the State Water Code in *Waiahole Ditch Combined Contested Case Hearing* in September 2000, the Commission on Water Resources Management (CWRM, or Water Commission) has been under increasing pressure to fulfill its responsibilities in establishing instream flow standards. In its Waiahole decision, the court directed the Water Commission to establish permanent instream flow standards for windward streams "with utmost haste and purpose."

The Waiahole issue demonstrated the increasing public interest and concern over the status of Hawaiian stream ecosystems. However, following testimony by numerous scientists, including Dr. Anne Brasher, Dr. John Maciolek, Dr. Mike Fitzsimons, Dr. Ken Bovee, Mr. Bill Devick, Mr. Mark

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[1] Dams, diversions, lakes, impoundments, and similar man-made structures can disturb longitudinal or linear connectivity of habitats within a stream ecosystem. With respect to Hawaiian stream ecosystems, we use 'ecological connectivity' to describe the interconnected nature of aquatic habitats that support populations of native amphidromous (migratory) stream macrofauna throughout their normal ranges within a given watershed. Hence, ecological connectivity exists if stream flows of sufficient volume and frequency allow the normal distribution of native amphidromous species within a given watershed.

Hodges, and Mr. Ron Englund, the Court concluded that information on Hawaiian stream biology and stream flow requirements of native Hawaiian species was incomplete and inconsistent. Within the past decade, over 20 petitions have been filed with the CWRM calling for flow restoration in the East Maui streams that have been diverted for off-stream uses over the past 120 years. In 2002, the CWRM commissioned the United States Geological Survey (USGS) Water Resources Division in Honolulu to evaluate the biological impacts of the East Maui Irrigation Company (EMI) ditch system on East Maui streams to assist CWRM in establishing amended Interim Instream Flow Standards (IIFS) for those streams. The USGS (Gingerich 2005, Gingerich and Wolff 2005) applied the PHABSIM model (Bovee 1982, Bovee et al. 1998) to estimate the amount of aquatic habitat available for the amphidromous species, and develop habitat duration statistics that provide estimates of the amount of increased habitat that would accrue with streamflow restoration (cessation or reduction of withdrawals). State funding support for USGS studies in East Maui streams continues today.

Gingerich and Wolff (2005) found that aquatic habitat values in East Maui streams today average 58 to 60 percent of natural, undiverted conditions. What this essentially means is that the withdrawal system has been taking, on average, for well over a century, approximately 40 percent of the base stream flow. USGS was not tasked with an evaluation of the current status of the target species within the streams so this important information is still unknown. Recent longitudinal surveys conducted by Hawaiʽi Division of Aquatic Resources (DAR) biologists in five East Maui streams (including two within the USGS study area) attribute reduced native aquatic insect diversity to dewaterment of the middle reaches of these streams (DAR testimony before CWRM, September 2, 2008).

On 24 September 2008 the CWRM voted to return an average total of approximately 12 million gallons per day (mgd) of diverted water in 8 of the 27 East Maui streams that were subjects of the citizens' petitions. CWRM staff indicated that the selected instream flow standards are based largely on the USGS's hydrology and habitat availability studies (Dawson 2006). While some of the returned water was provided for the benefit of downstream taro farmers, it was stated that the releases were also to benefit other elements of traditional gathering practices and to restore natural habitats.

The streams affected by the CWRM's decision are Waiokamilo, Palauhulu, Honopou, Wailuanui, Hanehoi and Huelo. Subsequent flow monitoring by CWRM staff has revealed that flow restoration has not met the desired intent in at least two of these streams. In Waiokamilo Stream, restored flow disappears into the streambed above Dam 3 and has yet to be shown to benefit to either taro growers or the stream ecology (CWRM Field Investigation Report FI2009021005, 10 February 2009). In the Palauhulu tributary of Piʽinaʽau Stream some flow may be lost to the streambed between 800 ft and 300 ft elevation (Gingerich 2005). This unfortunate outcome demonstrates the importance of thorough pre-implementation studies and the value of post-implementation monitoring as part of the adaptive management approach.

The Hearing Officer's Proposed Finding of Facts, Conclusions of Law, and Decision and Order in the Nā Wai ʽEhā contested case hearing (Case No. CCH-MA06-01) provides guidance for physical and biological studies that could be conducted to validate and/or refine the proposed IIFS. As stated on page 179 of the document, the Hearing Officer "chose a relatively small range of flows, from the minimum recorded flows up to the Q90 flows." His reasoning appears to be based on an assumption that some percentage of natural low flows is the minimum that could be considered as an IIFS, even though he acknowledges that the first amounts of water returned to a dry channel have the most benefit. Secondarily, the Hearing Officer argues that a continuously wetted channel from mauka to makai "provides the best conditions for re-establishing the ecological and biological health of the waters of the Nā Wai ʽEhā" (page 172).

In relying solely on a percentage of natural flow, the recommendations did not address either how much benefit is provided by the recommended flows in the Nā Wai ʽEhā stream channels or how the recommended flows relate to achieving a continuously wetted channel (except for the Waikapu where it is not expected in any case). Answering these questions was integral to the recommendations of both experts for the Hawaiian Commercial & Sugar Company (HC&S), Tom Payne and John Ford. Tom Payne suggested using the demonstration flow assessment to evaluate the physical effects of various releases, and John Ford suggested releasing smaller but sequentially increasing amounts of water to evaluate the corresponding biological effects. It is not known whether or not the flow recommendations are efficient at achieving their stated objectives. Based on the steep, cobbleboulder character of the Nā Wai ‘Ehā stream channels (that wet quickly with small amounts of water), it is likely that the recommended flows would provide more water than actually needed to have continuous flow mauka to makai. Addressing these data gaps both in Nā Wai ‘Ehā and East Maui streams is likely to benefit both the decision making process of the CWRM and the flow diversion needs of offstream users by measuring the efficiency of water releases in achieving the primary objectives of the recommendations.

1.2 Objective

The objective of this paper is to present biological information that can be utilized in determining equitable, reasonable and beneficial in-stream and off-stream uses of the limited surface water resources of northeast Maui. We offer insight regarding the persistence of the native amphidromous species in the region following 120-years of water development in East Maui and a millennium of human impacts to the landscape. By analyzing the current status of the native stream species we believe that missing critical information can be made available to decision makers, and an equitable distribution of a limited amount of water can be based on biological facts rather than perceptions. We also summarize the scientific literature on Hawaiian stream ecosystems, the overall status of native amphidromous species, and the presence or absence of biological factors indicating the need for flow restoration to enhance these species' ecological survival. The findings offered in this report are based upon stream research conducted by SWCA in East Maui and throughout the state, and our assessment of the published research of USGS, DAR, and other investigators.

1.3 Significance in Hawaiian Culture

Spiritual, cultural and natural resources are one and the same to the Hawaiian people. Wai‘ola, living waters, are recognized as the source of life and have a strong spiritual connotation (Pukui 1983). In pre-western contact Hawai‘i prior to the reign of Kamehameha, inalienable titles to water rights did not exist (Handy and Handy 1972). High chiefs (*ali‘i*) held in trust all lands, waters, fisheries, and other natural resources extending from the mountain tops to the depths of the ocean (Maly and Maly 2001a). The *ahupua'a*, or principal political subdivisions of lands, helped ensure that native planters had access to a share of subsistence resources, including ability to harvest ‘o‘opu, ‘ōpae, and hīhīwai from streams. The right to use these resources was given to the native tenants at the prerogative of the *ali'i* and their representatives or *konohiki* (Maly and Maly 2001a). The breakdown of the traditional Hawaiian method of sharing flowing water, beginning with western influences upon Kamehameha through modern case law, has left a confusing and controversial legacy (Miike 2004).

Native oral traditions indicate a close relationship between Hawaiian and amphidromous species; for example, most of the nine amphidromous species addressed in this report were an important part of the native food base, traditions that continue today in East Maui (Titcomb 1972, 1978; Group 70 et al 1995: Maly and Maly 2001a and 2001b). Many Hawaiian proverbs, oral traditions, and nuances of language involve these species (see Pukui 1983, Maly and Maly 2001a and 2001b, Miike 2004). Hawaiian oral tradition is replete with accounts of concentrations of theses species during "hinana runs" where the post-larval fish were so numerous that they could be caught by hand (Titcomb 1972): "*ka i‘a mili i ka poho o ka lima*" (the fish fondled by the palm of the hand) (Pukui 1983).

Many other *‘ōlelo no‘eau*, or proverbs, clearly demonstrate that the Hawaiians understood aspects of the ecology of amphidromous species: "*Ka i‘a a ka wai nui i lawe mai ai*" (the fish borne along by the flood); "*ka ia hāhā i kahawai*" (the fish groped for in the streams); "*ka i‘a ho‘opumehana i ka weuweu*" (mountain ‘ōpae, cling to weeds and grasses along the banks of streams when cloudbursts occur in the uplands); "*ka i‘a huli wale i ka pohaku*" (the fish that turns over the stones, referring to the necessity of rolling over cobbles to catch hīhīwai); "‘*a‘ohe loea i ka wai ‘ōpae"* (it is no feat to catch shrimp during a freshet) (all from Pukui 1983).

The Hawaiians also recognized the interdependencies of their physical environment: "*huli ka lau o ka ‘ama‘u i uka, nui ka wai o kahawai*" (when the winds blow the leaves of the ‘ama‘u fern inland, floods will follow); *‘o ka makani ke ala o ka ‘ino*" (wind drives rain clouds that bring torrential floods); "*ka wai makamaka‘ole*" (the water with no friends, referring to the danger of floods) (Pukui 1983). Group 70 et al (1995) and Maly and Maly (2001a) provided interesting narratives of resident kupuna within the East Maui study area, who share stories of their relationship to the land, streams, and ocean. Maly and Maly (2001a and 2001b) report a general perception of area residents that there is less water flowing in East Maui streams today than flowed several decades ago (cf. Oki 2004), and that this has resulted in fewer ʻoʻopu, ʻopae, and hīhīwai. However, individual kūpuna suggest that traditional gathering continues in East Maui streams. This practice is said to be most successful for residents who know where to find these resources.

1.4 Brief Overview of the Literature

Few scientific papers about Hawaiian stream life, other than original species descriptions, were published prior to 1939. Classical scientific studies on these aquatic resources began in the first decade after statehood. At that time the then Hawaiʻi Division of Fish and Game conducted statewide stream surveys primarily to assess the feasibility of introducing non-native game fishes. Many of these surveys, supported with Federal Dingle-Johnson Act program funds, were conducted by pioneering aquatic biologists Stan Shima and Kenji Ego.

What follows is a general summary of the major research directions in Hawaiian stream ecology since 1960. It is not meant to be a comprehensive bibliography. In the late 1960s and throughout the 1970s, John Maciolek and his students at the University of Hawaiʻi Cooperative Fishery Research Unit initiated studies on life histories and distribution of native aquatic species, and began cataloging the extent of human alterations to streams throughout the state. Through the 1970s and 1980s, research led by Maciolek and Kinzie and their students focused on life history and population biology of amphidromous species, contaminants in fish tissues, and the applicability of methods to assess fish habitat utilization and preference (Ford and Kinzie 1982, Kinzie et al. 1988, Kinzie 1991). During this period the United States Fish and Wildlife Service (USFWS) (Dodd et al. 1985) listed ʻoʻopu hiʻukole (*Lentipes concolor*) as a Candidate Endangered Species, based on limited distribution and abundance data. Two other species, *Awaous guamensis* (ʻoʻopu nākea) and *Sicyopterus stimpsoni* (ʻoʻopu nopili) were also listed along with *L. concolor* by both the American Fisheries Society (Deacon et al. 1979) and the IUCN Red List of Threatened and Endangered Species™. Both *Lentipes* and *Awaous* were listed on the 2003 IUCN Red List of Threatened Species™ as being Data Deficient, and *S. stimpsoni* was listed as lower risk but close to qualifying for threatened status.

The past two decades of research and discovery has provided a new understanding of Hawaiian stream ecosystems. Bill Devick and Robert Nishimoto of DAR and Mike Fitzsimons of Louisiana State University began collaborating in the early 1990s to conduct comprehensive statewide inventories of stream fauna, and expanded their studies on the ecology of amphidromous species in relation to stream flow. The methods pioneered by DAR biologists during the statewide surveys are still being used and refined today. Following an initial round of study, Fitzsimons (1990) advised the USFWS that *Lentipes concolor* "represent healthy, actively breeding populations in no apparent need of special protection." Devick et al. (1992) stated that populations of *L. concolor* "appear to be stable or increasing as direct impacts of agriculture and urban development have eased." Subsequently, the USFWS delisted *L. concolor* as candidate endangered species in 1996 in response to statewide stream surveys. Yet just four years later, in his testimony during the Waiahole stream hearings in 1996, Devick stated that populations of the five characteristic species of native Hawaiian stream animals had "…declined dramatically throughout the islands as a direct result of diversion of stream waters."

There has been no statewide effort to monitor the abundance or population trends of any of the amphidromous stream animals since that time (Polhemus, DAR, personal communication), and no efforts have been undertaken by any resource agency to consider any of the amphidromous species for threatened or endangered species status or for specific measures to ensure their continued survival.

Beginning in the early 1990s, Anne Brasher, Steven Anthony, and Reuben Wolff of USGS conducted quantitative research into the impacts of human activities on Hawaiian stream ecosystems for the USGS Water Resources Office in Honolulu. Mike Fitzsimons, Robert Nishimoto, and Mike Kido gave us an insight on the recovery of amphidromous species in streams following floods and landslides associated with Hurricane Iniki (Fitzsimons and Nishimoto 1995, Kido 1996a, 1997a). Scott Larned, Scott Santos, Robert Kinzie and others expanded our understanding of stream energetics and the response of stream communities to diversion and flow restoration (Larned 2000, Larned and Santos 2000, Larned et al. 2001, Kinzie et al. 2006).

Robert Zink and A.C. Chubb have given us a new perspective on patterns of evolution and population genetics among the native gobies (Zink 1990, Zink et al. 1996, Chubb et al. 1998). Dan Lindstrom, Robert Nishimoto and Daryl Kuamo'o studied the timing of reproduction and larval drift, and post larval recruitment in Hawaiian amphidromous fishes (Lindstrom 1998, 1999; Nishimoto and Kuamo'o 1997; Chong 1999). Mike Yamamoto and Annette Tagawa (2000) published a popular guidebook for identification of native and alien freshwater species in Hawaiʻi. Richard Radtke and Robert Kinzie collaborated to clarify the larval life span of amphidromous gobies (Radtke et al.1988, Radtke and Kinzie 1996, Radtke et al. 2001). Basic research studies have also addressed biological organization at the community and ecosystem levels (Larned 2000, McIntosh et al. 2002, and Kinzie et al. 2006). Jim Parham created a GIS-based model to predict the distribution of amphidromous fishes in Hawaiian streams (Parham 2002).

Vis et al. (1994), LaPerriere (1995), Larned and Santos (2000), and Sherwood (2004a and 2004b) shed light on the identity and productivity of Hawaiian stream algae.

Dan Polhemus and Ron Englund of the Bishop Museum focused their attention on the important but understudied communities of aquatic insects (Polhemus 1994, 1995; and numerous publications of the Bishop Museum). These and related studies on insects revealed extensive patterns of speciation that parallel the terrestrial insects and flora of Hawaiʻi. Both Englund and Polhemus, along with Eric Benbow, have suggested that endemic aquatic insects may be a more sensitive bellwether of stream health than presence/absence of amphidromous species (Benbow et al. 1997). Kido et al. (1993), Polhemus and Asquith (1996), Eldridge and Miller (1997), and Kondratieff et al. (1997) also provided new insight on the ecology of native Hawaiian aquatic insects.

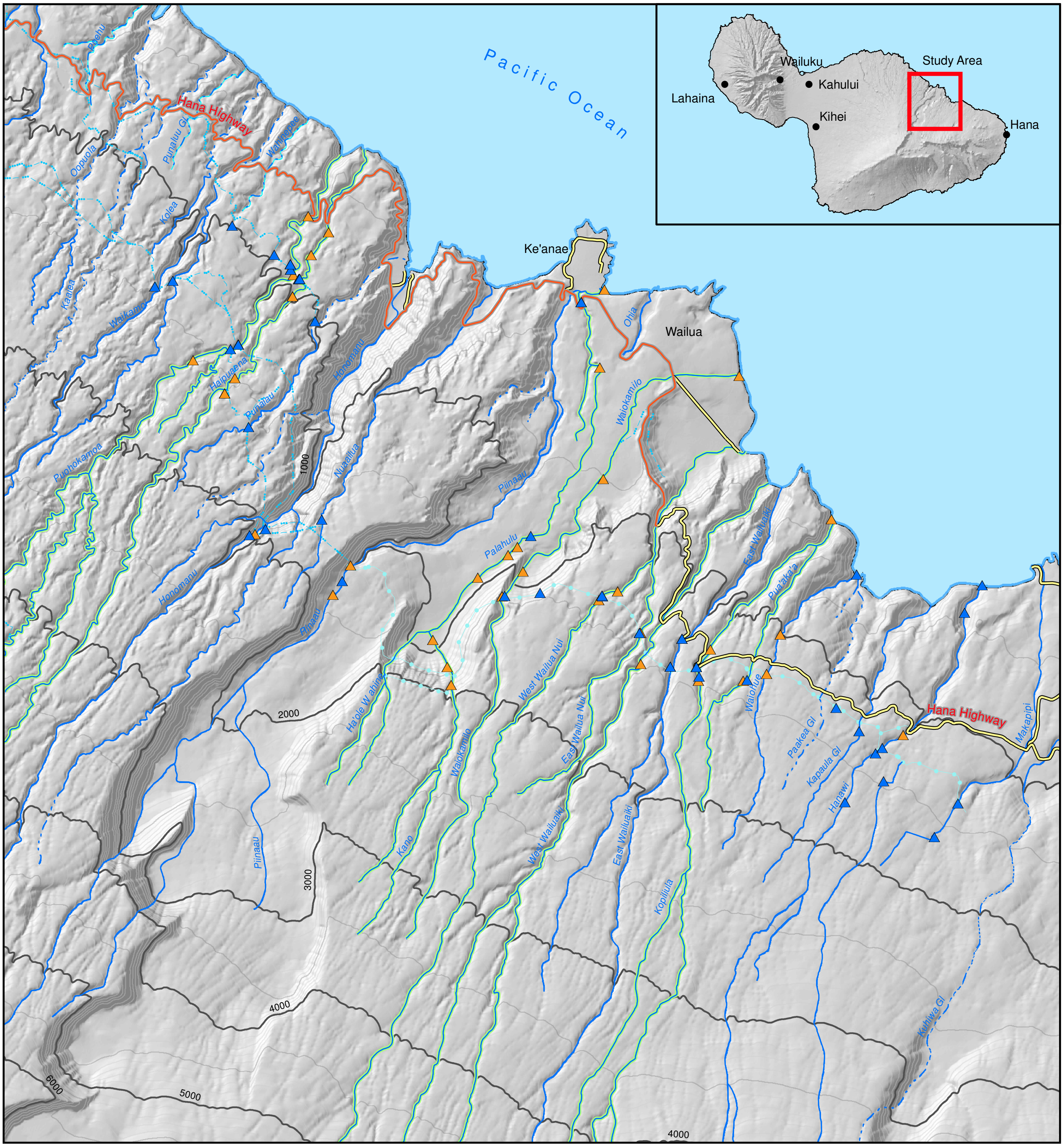
More recent studies include the reproductive ecology of *Eleotris sandwicensis* in urban and forested streams (Sim 2006); assessment of ecological sinks and sources (McRae 2007); aquatic insect taxa as indicators of habitat disturbance (Englund et al. 2003); production and dispersal of larval gobiids (Murphy and Cowan 2007); and tracing nutrient sources in adult and larval gobiids (Hobson et al. 2007). In addition to recent research in Hawai'i, scientists have found striking similarities between the ecology of Hawaiian amphidromous species and those of Oceania, the Indo-West Pacific, Caribbean, and Atlantic high islands (Erdman 1961, Hunte 1978, Bright 1982, Maciolek and Ford 1987, Covich 1988, Resh et al. 1990, Ryan 1991, Resh et al. 1992, Resh et al. 1995, Nelson et al. 1997, Holmquist et al. 1998, Resh et al. 1992, Myers et al. 2000, Buden and Lynch 2001, Fitzsimons et al. 2002, Keith 2003, McDowall 2003, March et al. 2003, Pyron and Covich 2003, McDowall 2007, Fukushima et al. 2007).

As Murphy and Cowan (2007) state, "…what is known about the biology of other species of amphidromous gobies should be transferable to the Hawaiian ʻoʻopu, with consideration of species-specific differences and the degree of geographical isolation that are unique to the Hawaiian Islands."

1.5 Setting

The Hawaiian Islands are among the youngest major archipelagos, forming over a 'hot spot' for at least the last 70 million years. The archipelago consists of linear chains of islands or seamounts produced as the Pacific Plate moves in a northwesterly direction. The former high islands in the extreme northwestern portion of the archipelago (now seamounts) are perhaps 60 to 90 million years old. Kauaʻi is roughly 5.5 million years old, and volcanism is still building the Island of Hawaiʻi today at Kīlauea (Juvik and Juvik 1998).

The area studied by Gingerich and Wolff (2005) and SWCA encompassed 21 streams along the northeastern slopes of Mt. Haleakala in East Maui (Figure 1). Among the main Hawaiian Islands, East Maui is intermediate in age, and notably has both broad deeply incised valleys (e.g. Keʻanae) as well as much smaller watersheds (e.g. Waiohue and ʻOhia) (Figure 2). Except on the oldest islands or in the broadest valleys, streams in Hawaiʻi are typically steep with step-like profiles consisting of alternating falls/pools and shallow riffle areas. The substratum ranges from bedrock to boulders, cobbles and gravel in pools and slower runs. Because of the step-like nature of the channels, pools can retain water even when flow is low or nonexistent. These pools serve as important refugia for aquatic animals in times of low flow. Geologically older streams such as those on Kauaʻi and Oʻahu fall precipitously into deeply incised valleys, then flow into broad terminal estuaries. Many smaller streams on geologically younger Maui and Hawaiʻi flow directly into the sea over terminal waterfalls.



Legend

- 🔺 SWCA Sample Sites
- 🔺 SWCA Prevous Sample Sites
- ═ SWCA Study Streams

USGS Gauging Stations

- ▲ Active Stream Gauge

Transportation

- ═ Secondary Routes
- ═ Road or Street

USGS Mapped Streams

- — Perennial
- – - Intermittent; Non-Perennial

USGS Ditch Type

- ·· – Ditch
- ●— Aqueduct
- — Dam
- ═ Flume

Elevation Contours (feet)

- — 1000' contour
- — 500' contour
- — 100' contour

Figure 1 - East Maui Streams Study Area
SWCA Study Streams and
Sampling Locations

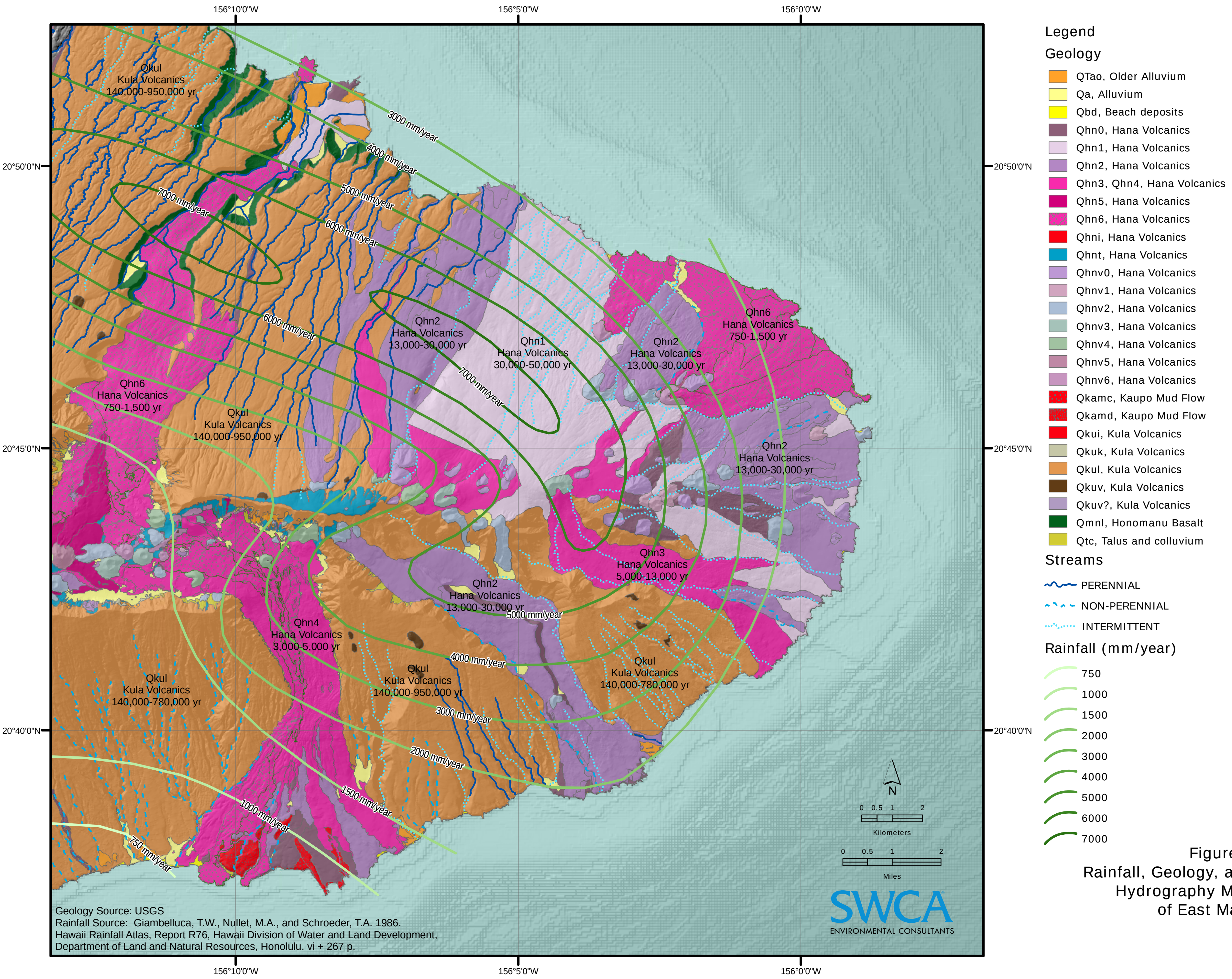
N

0 0.5 1 2 Mi

0 0.5 1 2 Km

SWCA ENVIRONMENTAL CONSULTANTS

Source:
Elevation contours provided by the School of Ocean and Earth Science and Technology, University of Hawai'i Streams, Ditches, and other watercourses provided by USGS



Geology Source: USGS
Rainfall Source: Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A. 1986.
Hawaii Rainfall Atlas, Report R76, Hawaii Division of Water and Land Development,
Department of Land and Natural Resources, Honolulu. vi + 267 p.

Figure 2
Rainfall, Geology, and
Hydrography Map
of East Maui

Depending on the current state of the channel/valley system and the degree of erosion, Hawaiian streams can be roughly divided into those that enter the sea as high terminal waterfalls (e.g. Waiokamilo and Haipuaʽena) or across a beach, often composed of boulders which can sometimes close off the stream from the sea such as Hanawī and Puohokamoa (Maciolek 1977, McRae 2007).

2.0 INTRODUCTION TO HAWAIIAN STREAM ECOLOGY

2.1 Origins of the Characteristic Macrofauna

Located some 5,000 km (3,000 mi) southwest of the nearest continental landmass, the Hawaiian Islands are among the most isolated and youngest islands in the world. The former high islands in the extreme northwestern portion of the archipelago (now seamounts) are perhaps 60 - 90 million years old; Kauaʽi is roughly 5.5 million years old; and volcanism is still building the Island of Hawaiʽi today.

All of Hawaiʽi's native biota originated from sources outside the archipelago (Ziegler 2002). Representatives of various taxonomic groups arrived infrequently from diverse regions throughout the Pacific Rim. As a result, the biota is considered disharmonic; that is, it lacks many groups of organisms represented on continental landmasses. This is also true of Hawaiʽi's freshwater fauna (Ford and Kinzie 1982, Kinzie 1997, McDowall 2003). Scientists have recognized for years that certain freshwater fishes, crustaceans, and mollusks do not demonstrate the same pattern of speciation and adaptive radiation characterized by many Hawaiian terrestrial plants, insects, and birds. The reason why this is so is linked to the unique amphidromous life cycle of these animals (Myers 1958, Ford and Kinzie 1982, McDowall 1988).

Characteristic macrofauna of Hawaiian streams (Table 1) include five species of goby fishes: *Awaous guamensis* (oʽopu nakea), *Sicyopterus stimpsoni* (oʽopu nopili), *Lentipes concolor* (oʽopu alamoʽo); and the eleotrids *Eleotris sandwicensis* (oʽopu akupa) and *Stenogobius hawaiiensis* (oʽopu naniha). Two gastropods, *Neritina granosa* (hīhīwai) and the estuarine *Neritina vespertina* (hapawai), are common in many East Maui, Hawaiʽi, Molokaʽi and Kauaʽi streams. The shrimp *Atyoida bisulcata* ('ōpae kalaole) inhabits the middle and upper reaches of pristine mountain streams statewide and is locally abundant in plunge pools and irrigation ditches.

Table 1. *Amphidromous species known to inhabit East Maui streams and their generalized distribution within natural undiverted streams (shaded area).*

Scientific Name / Hawaiian Name	Biogeographic Status	Lower Reach	Middle Reach	Upper Reach
MOLLUSKS				
Neritina vespertina / hapawai	Endemic	▨		
Neritina granosa / hīhīwai	Endemic	▨	▨	
CRUSTACEANS				
Macrobrachium grandimanus / ʽŌpae ʽoehaʽa	Endemic	▨		
*Macrobrachium lar / Tahitian prawn**	Introduced	▨	▨	
Atyoida bisulcata / ʽŌpae kalaʽole	Endemic	▨	▨	▨
FISHES				
Stenogobius hawaiiensis / ʽOʽopu naniha	Endemic	▨		
Eleotris sandwicensis / ʽOʽopu akupa	Endemic	▨	▨	
Awaous guamensis / ʽOʽopu nakea	Indigenous	▨	▨	
Sicyopterus stimpsoni / ʽOʽopu nopili	Endemic	▨	▨	
Lentipes concolor / ʽOʽopu alamoʽo	Endemic	▨	▨	▨

NOTE: The Tahitian prawn, while a non-native amphidromous species, in included here as it is often an important element of the stream fauna.

The Hawaiian prawn *Macrobrachium grandimanus* ('ōpae 'oeha'a) inhabits estuaries and the terminal reaches of streams. Original descriptions of these species first begin to appear in scientific literature in the 19th century. Between 1900 and 1955, several authors revised these early catalogues of fishes and invertebrates. Early literature specific to the life history aspects of Hawaiian stream fauna appeared in Edmondson (1929), Mainland (1939), and Ego (1956). Lindstrom (1998) presents a cogent review of early scientific evidence on amphidromous fishes.

All of these species share the same life history strategy referred to as *amphidromy*. Larvae of these amphidromous species hatch from demersal eggs and are swept into nearshore marine waters where they develop for periods up to 150 days as zooplankton before re-entering freshwater streams as post-larvae (Radtke et al. 1988, 2001).

Once they re-enter a stream mouth, post-larvae migrate upstream rapidly where they grow and reproduce as adults (Maciolek 1977; Ford and Kinzie 1982; Radtke and Kinzie 1991; Nishimoto and Kuamo'o 1996, 1997; Keith 2003). Lindstrom (1999) developed a method to identify newly hatched larvae of all Hawaiian freshwater gobies and provided a key for their identification, and Tate et al. (1992) developed a key for the identification of post-larval Hawaiian freshwater gobies. Unlike diadromous salmon, amphidromous species in Hawaii show no definitive evidence of returning to their natal stream.

In addition to the amphidromous macrofauna, some other native marine species are important in Hawaiian stream ecology. Fishes commonly found in the terminal and lower reaches of small Hawaiian streams also include the endemic predatory flagtails *Kuhlia xenura* and *K. sandvicensis* (ʻāholehole). ʻĀholehole are not amphidromous but may be considered an itinerant marine species. Adults live and breed in nearshore coastal reefs, but juveniles commonly invade stream mouths in large schools presumably to avoid predation and to utilize post-larval and juvenile gobioids as a food source. Many other itinerant marine species may undergo juvenile development in estuaries of large streams.

ʻĀholehole are known to attack nests of goby eggs (Ha and Kinzie 1996) and may also consume returning post-larval gobies. Many other itinerant marine species may undergo juvenile development in streams; however, since non-amphidromous species do not have the ability to climb terminal waterfalls, these species may only occur in streams with low gradient terminal reaches or estuaries. Additionally, numerous alien stream animals, both amphidromous (e.g. *Macrobrachium lar*) and those restricted to freshwater, are impacting native Hawaiian species including fishes, amphibians and crustaceans (Yamamoto and Tagawa 2000).

Myers (1949) used the term *amphidromous* to describe fishes that undergo regular, obligatory migration between freshwaters and the sea "at some stage in their life cycle other than the breeding period"*.* McDowall (1988) described two different forms of amphidromy. All the Hawaiian amphidromous species exhibit 'freshwater amphidromy' where spawning takes place in freshwater, and the newly hatched larvae are swept into the sea by stream currents. While in the marine environment, the larvae undergo development as zooplankton before returning to freshwater to grow to maturity. The length of time they spend in marine plankton is unknown for most species.

An important ecological characteristic of the amphidromous fauna is the ability (in varying degrees among species) to move upstream, surmounting riffles and small falls, and for some species even very high waterfalls (Ford and Kinzie 1982, Radtke and Kinzie 1996). Amphidromous species occur throughout the world's tropical and subtropical freshwater streams, especially high islands. The native Hawaiian species are descendents from amphidromous species elsewhere and did not develop this life style after their arrival in Hawaiʻi (Myers 1949, Kinzie 1991, McDowall 2003). This means that the life history characteristics and ecological requirements of these species reflect a pattern common to amphidromous species throughout the world, not one specific to the Hawaiian Islands.

The non-amphidromous native stream fauna has, until fairly recently, received less attention than the amphidromous species. However the native insects, snails, and other invertebrates are important for their diversity, endemism, and their contribution to the freshwater ecosystem dynamics. Currently the USFWS has listed six damselfly species in the endemic genus *Megalagrion* as Candidate Endangered Species, two of which have been recently observed by SWCA and DAR biologists in East Maui streams: the Flying earwig Hawaiian damselfly (*Megalagrion nesiotes*) and the Pacific Hawaiian damselfly (*Megalagrion pacificum*) (Polhemus and Asquith 1996). A listed endangered gastropod mollusk (*Erinna newcombi*) can also be found confined to streams and seeps in central Kauaʻi. Many factors in addition to dewaterment may contribute to the demise of these unique species including predation by both native and non-native insects, birds, and aquatic species. Other native damselflies including *M. nigrohamatum nigrohamatum* are still common today in East Maui streams. Scientists are continually describing new species of endemic aquatic insects as their field studies take them farther into the headwaters of Hawaiian streams (e.g. Englund et al. 2003).

In the recent past, aquatic biologists in Hawaiʻi considered the presence of all the native amphidromous species described above as an indicator of outstanding environmental quality. Conversely, the total absence of these species in streams between sea level and 1,500 ft elevation was considered a possible indicator of environmental degradation (Hawaii Cooperative National Park Studies Unit 1990). However, community structure in a given Hawaiian stream may change frequently due to random processes affecting reproduction, recruitment of post-larvae, migration, predation and competition, and survival (Kinzie and Ford 1982, Kinzie 1988). Therefore, the absence of a given species at any reach and time must not be interpreted as a negative indicator of stream quality (Parham at al. 2008).

Most prior research on Hawaiian freshwater ecology has dealt with individual species and populations of the characteristic macrofauna. Little is known about Hawaiian stream ecosystem response to changes in stream flow (Covich 1988; Chong et al. 2000; Larned 2000; Larned et al. 2003; Kido 1996a, 1996b, 1996c; and Kinzie et al. 2006). Research over the past decade on the genetics of stream fishes suggests that each of the Hawaiian freshwater gobies is a member of a statewide metapopulation (Fitzsimons et al. 1990; Zink et al. 1996; Chubb et al. 1998; Lindstrom, personal communication). A metapopulation consists of a group of spatially separated populations of the same species in which gene flow occurs with sufficient frequency to prevent isolation and subsequent speciation. Simply put, the native Hawaiian amphidromous fishes, shrimp, and mollusks found in East Maui streams are from the same metapopulations as those found in ʻOahu, Molokaʻi, Kauaʻi, and Hawaiʻi Island streams. In the case of native amphidromous species, these spatially separated (by island and stream) populations are able to exchange individuals via their oceanic larval pool and recolonize sites from which the species has recently been extirpated. As the evidence of recent genetic studies has illustrated (Zink et al. 1996, Chubb et al. 1998), there is no evidence of within-archipelago diversification or speciation of the Hawaiian stream fishes, indicating among-island gene flow attributable to amphidromy.

Species with extended ocean larval life spans and those capable of delaying metamorphosis are able to achieve greater dispersal among island streams. Radtke et al. (1988), Radtke and Kinzie (1991), and Radtke et al. (2001) provide excellent data on the length of larval life (LLL) in four species of amphidromous gobies from Hawaiian Island streams. The mean LLL for the endemic *Lentipes concolor* was 84 days (n=236), while the mean LLL for the indigenous *Awaous guamensis* was found to be 161 days (n=8) (Radtke et al. 2001).

One characteristic of freshwater amphidromy is spawning and egg-laying in freshwater (McDowall 1988). When larvae hatch, they are swept into the sea by stream currents and temporarily undergo development as marine zooplankton before returning to freshwater as 10 - 16mm long post-larvae to migrate upstream and continue their growth to maturity. Recruitment of post-larvae from the oceanic pool, characteristic of amphidromy, allows rapid recolonization of streams after catastrophic events such as landslides, floods, hurricanes, and droughts (Ford and Yuen 1986; Fitzsimons and Nishimoto 1995; Kido 1996a, 1996b, 1996c; Kinzie 1988; Chubb et al. 1998; Way et al. 1998; McIntosh et al. 2002; Keith 2003; and McDowall 1993, 1995, 2003), and prevents genetic isolation of populations. Holmquist et al. (1998) noted that ʻoʻopu will recruit to any freshwater source regardless of the suitability of the habitat from which it flows.

2.2 Adaptive Advantages of Amphidromy

McDowall (1997) suggested that amphidromy is an "ancient, widespread, successful, and evolutionarily stable life history strategy that has evolved in many fish groups (at least 10 families and perhaps more than once in some of these)." Zink (1990) concluded that *L. concolor* "does not yet show effects of population reduction and 'genetic peril' (if any), and that the planktonic larval pool may well form a sort of natural insurance that will allow colonization of streams in areas influenced by prevailing ocean currents." Based upon the results of their studies of population genetics of Hawaiian stream fishes, Fitzsimons et al. (1990) suggested that the common marine planktonic pool offers a "natural insurance against extinction." They also speculated that once instream conditions become favorable for native fishes, "restocking from other streams will likely occur automatically." By "other streams", he is referring to larvae contributed to the ocean larval pool from other streams.

It is no wonder that the native amphidromous species of fishes, shrimps, and mollusks in Hawaii represent families that inhabit high-island tropical and subtropical streams. Amphidromous gobies "have evolved reproductive patterns adapted to the extremely variable and unpredictable habitat conditions characteristic of Hawaiian streams" (Way et al. 1998). They are adapted to the naturally ephemeral hydrologic torrential flash floods (Keith 2003). Nishimoto (2005) recognized that "…animals in these streams survive, not in spite of episodic floods, but actually because of them."

Fitzsimons and Nishimoto (1995) evaluated the recovery of Kaua'i streams following their devastation by Hurricane Iniki and concluded that the Hawaiian stream fishes showed "remarkable resilience." They noted that amphidromy "provides the potential for repopulating a stream with a full complement of its formerly predominant vertebrate and invertebrate species". In his written direct testimony in the Waiahole Stream case, Devick noted that, "The flashy nature of Hawaiian windward streams, with their sudden peaks and long troughs in flow rates is an integral component for maintenance of biotic stability in the streams. The peak flows help to flush debris from the streambed and provide triggers for migration and spawning by aquatic organisms. *Periodic drying that naturally occurs in the lower reaches of streams may help maintain genetic variability in amphidromous species that would be advantageous for survival over the long term in response to temporal shifts in weather patterns. Native species, particularly amphidromous species, have evolved to fit these conditions*" (emphasis ours).

Hobson et al. (2007) provide recent biochemical evidence that the larvae of amphidromous species may congregate in nutrient-rich freshwater plumes offshore of stream mouths prior to their recruitment. But it is not yet known whether these larvae spend their entire planktonic existence in freshwater nutrient plumes close to natal streams or 'stage' at river mouths after a period of drifting offshore (Hobson et al. 2007). Murphy and Cowan (2007) note that seasonal post-larval recruitment of 'o'opu to Hawaiian shores corresponds to the return of drift bottles deployed in surface current experiments conducted by Barkley et al. (1964). The lack of genetic isolation among 'o'opu among islands described by Fitzsimons et al. (1990), Zink et al. (1996), and Chubb et al. (1998) could be explained by as few as one recruit per generation per species drifting between streams (Hobson et al. 2007; Kinzie, personal communication). To date there is no evidence of within-archipelago isolation or insipient speciation of this unique group of Hawaiian aquatic animals, indicating among-island and between-stream gene flow attributable to their amphidromous life-cycle.

Aquatic biologists now speculate that some streams may be greater sources of larvae than others. Some streams may in fact be "sinks" where larvae cannot reach the sea and/or where recruits may not survive to reproduce. McRae (2007) speculated that sinks might include larger, longer second- and third-order streams with terminal estuaries that harbor many potential predators, and source streams might include shorter first-order streams with terminal falls where itinerant marine predators are excluded. Sinks might also include irrigation ditches connected to streams where breeding populations of amphidromous species inhabit waters upstream of intake structures. The ditch systems are also known to provide habitat for amphidromous species and may act as a conduit for movement of adults between streams but this has not be studied to date.

To fully appreciate how successful a life strategy amphidromy is, one must consider the nature of disturbance in the stream ecosystems in which these species evolved. Cataclysmic influences discussed above include flood, drought, landslides, and volcanism. Longer-term influences must have included periodic changes in rainfall patterns, stream piracy, gaining and losing reaches, predation, competition for resources, and shifting patterns of ocean currents. Reproduction and recruitment of the native amphidromous species appear to respond to stochastic influences. This flexibility allows rapid recolonization of disturbed areas from the oceanic larval pool. The fact that this group of aquatic animals has not demonstrated the adaptive radiation seen in Hawaiian terrestrial fauna and flora suggests that oceanic mixing and transport of larvae sufficiently prevent genetic isolation (McDowall 2003).

3.0 ENVIRONMENTAL INFLUENCES ON HAWAIIAN STREAMS

3.1 Influence of Stream Geomorphology, Discharge, and Periodicity on Species Distribution

Biologists have learned that the geomorphologic profile of tropical insular streams strongly influences the distribution of amphidromous species within a given stream due to the differences in climbing ability, territorial behavior, dietary preferences, and interspecific interactions among the amphidromous species*.* Overlaps in species distribution and other exceptions to the pattern of distribution (Table 1) are common. Based upon oral histories and written records (e.g., Titcomb 1972; Pukui 1983; and Maly 2001a,) it is likely that this was also understood to some extent by pre-contact native Hawaiians.

Maciolek (1977) coined the phrase "*Lentipes* streams" to describe those streams in which ʻoʻopu alamoʻo was the dominant or only native amphidromous fish present. Usually, these were small to mid-size streams having a terminal waterfall or cascade that prevented colonization by other amphidromous fishes. Kinzie and Ford (1975, 1982, and 1986) also described trends in longitudinal distribution of amphidromous species that could be attributed to stream morphology. Parham (2002) on Guam, Buden et al. (2003) on Pohnpei, and Cook (2004) on Taʻu described similar patterns. Recently, Parham (2002) used this observed pattern as the basis for a computer model based on geographic information systems (GIS) technology, which he hopes will predict the distribution of amphidromous species within island streams. Geomorphology too has influenced patterns of distribution and local endemism in several families of aquatic insects (Polhemus 2005). This issue is significant to the establishment of IIFS insofar as it helps to pinpoint reaches where we would expect to find significant populations of amphidromous species and where others might be naturally excluded.

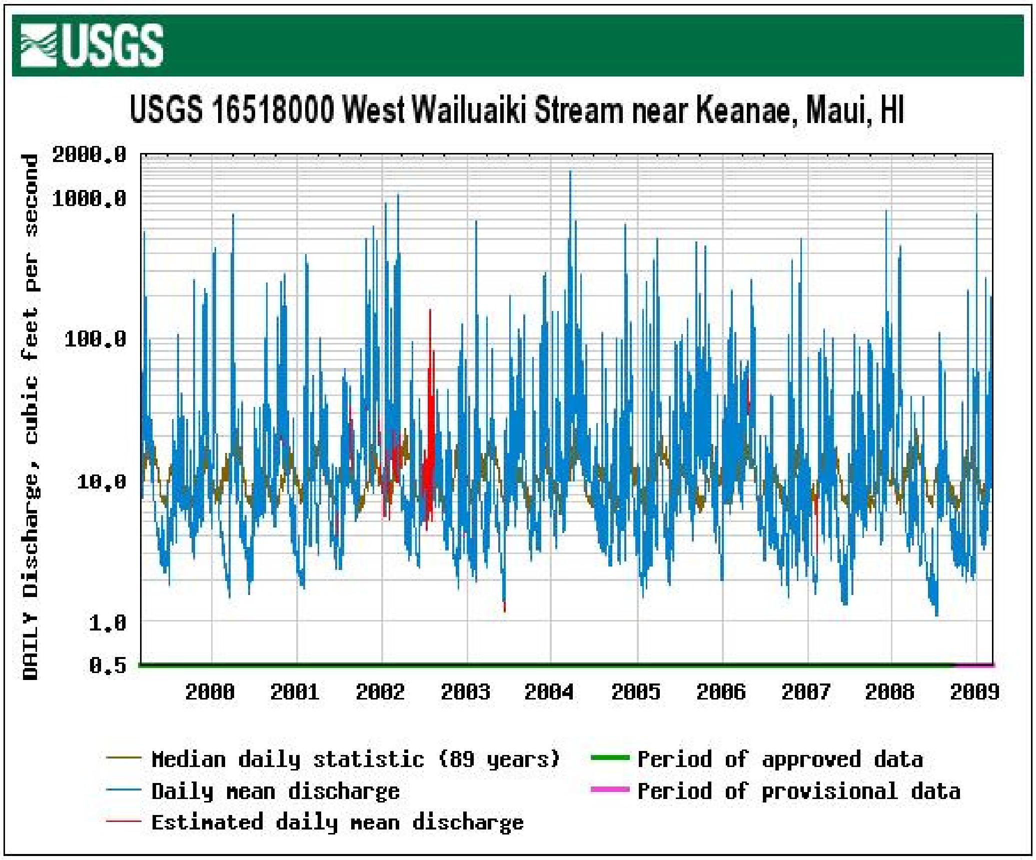
The relationship between the morphology of the stream channel and hydrology is direct and well understood (Macdonald et al. 1983, Morisawa 1968); there is also a strong influence of the channel conditions on the distribution and abundance of the stream biota. The importance of the longitudinal profile of streams to the location of aquatic species in tropical insular streams was known to Hawaiians of the past (Titcomb 1972) as well as today (Maly and Maly 2001a, 2001b).

The climate of the archipelago is dominated by northeasterly trade winds, especially in the summer months (Juvik and Juvik 1998). Storms with accompanying high rainfall are most common in the winter but can occur in any month. High flows occurring at irregular and unpredictable intervals are an integral part of Hawaiian surface water hydrology. Local weather conditions are strongly influenced by the interactions of prevailing winds and landforms producing patterns of orographic rainfall, typically heaviest on the windward (northeast) sides of the high islands. Precipitation at higher elevations leads to erosion of stream channels especially along windward slopes. Headward valley erosion produces the typical amphitheater-headed valleys, and stream piracy results in the older islands having a few very large valleys (Stearns 1966).

Precipitation, ground cover, soils, geology, and the structure of underlying lavas influence stream flows. Heavy rainfall between 2,000 and 3,000 ft elevations (Figure 2) and fog drip form the most significant contributions to streamflow and groundwater in East Maui (Scholl et al. 2002). Rainfall in the region averages more than 350 inches per year at the 2,500-ft elevation on the slopes of Haleakala to about 120 to 160 in/yr on the coast (Giambelluca et al. 1986). While the effects of terrain on storm rainfall are not as pervasive as on trade wind showers, large differences in rainfall do occur over small distances because of topography and location of the rain clouds. The heaviest rains come with winter storms between October and April, though storms and freshets can and do occur at any time of year. The nature of the rainfall patterns and underlying rock of the windward slopes of Haleakala dictate that discharge in East Maui stream channels fluctuates over several orders of magnitude from base flow to peak flood flow in a day (see Miike 2004), and sometimes hourly, from stream-to-stream throughout the year.

Flow regimes in Hawaiian streams are affected by both weather and geology. Perhaps the most characteristic feature of Hawaiian streams is their 'flashy' pattern of flood and base flow that reflects a direct relationship to patterns of rainfall. Figure 3 illustrates the natural daily streamflow data and statistics for West Wailuaiki Stream (above the diversion) over a recent nine-year period. Throughout each year there are several periods of high and low flows.

Figure 3. *USGS daily stream flow data and statistics for West Wailuaiki Stream, East Maui, over nine years (1999-2008) illustrating the frequency of flash floods or freshets typical of Hawaiian streams. All flows over 20mgd (31 cfs) pass below the diversion dam, so it is clear to see just how often these ‘freshet’ flows are available, even on a diverted stream, to serve as passage for amphidromous species’ downstream larval drift and upstream migration of post-larvae. Source: USGS.*



While many larger perennial streams possess naturally continuous surface waters (Polhemus et al. 1992) from the headwaters to the sea, smaller streams and tributaries of large streams can be naturally intermittent with losing reaches going dry in periods of low rainfall and reduced base flow (Stearns and Macdonald 1942, Macdonald et al. 1983). On East Maui, perennial continuous streams are concentrated on older lava flows within the USGS study area and Kipahulu Valley (Figure 2). Many streams in Hawai‘i are naturally interrupted due to their geological structure, and sometimes run dry as water is ‘lost’ through the streambed. Examples of naturally interrupted streams in East Maui include Waiokamilo, Pi‘ina‘au, and the Palikea tributary of Ohe‘o Gulch in Kipahulu Valley. Streams east of Makapipi from Kuhiwa Gulch eastward past Hana toward Kipahulu cross younger lava flows and are naturally intermittent. Timbol and Maciolek (1978) recognized 96 perennial streams on Maui. Fifty-eight percent (58%) of these were continuous, the rest naturally interrupted, and the remainder are naturally interrupted streams or intermittent.

Use of surface water in Hawai‘i, whether by the native stream fauna and flora, or by humans, cannot avoid these features of the natural system, and whether by evolution or engineering, the systems in place today reflect these hydrological realities.

Hawaiian streams are also subjected to a number of natural cataclysmic events including torrential flooding, drought, and landslides. All three processes can locally exterminate stream fauna in affected reaches. Ford and Yuen (1986) observed dramatic evidence of this immediately following a cataclysmic landslide in Pelekunu Valley, Moloka‘i. These events can occur at any time. Yet despite wide fluctuations in stream flow under natural conditions, both interrupted and intermittent streams can provide habitat for amphidromous species, as a decade of extensive stream surveys by State of Hawaii Division of Aquatic Resources staff have demonstrated.

Unlike streams in temperate continental ecosystems where seasonal cues (e.g. day length, deciduous shade, wide temperature changes, and spring snow melt) strongly influence the biology and behavior of animals, stochastic, or chance, processes are more important to the biology of tropical insular streams (Kinzie and Ford 1982, Lake 2000). A review of the literature demonstrates that most amphidromous species have broad periods of reproductive activity and relatively weak seasonal trends. Lindstrom (1999) found this to be the case during his study of larval gobioid drift in the Wainiha River on Kauai. In their study of fish populations in small Hawaiian streams, Kinzie and Ford (1982) found that reproduction, recruitment, and hence community structure at any given time were the result of stochastic phenomena. They found that reproductive periodicity in native stream fishes was so broadly spread over time that it appeared unlikely that a strong correlation with seasonal cues had evolved. They also found that the timing of recruitment was also widely variable and prolonged. Other detailed life history studies (Couret 1976, Ford 1979b, Ha and Kinzie 1996, Kinzie 1988, Way et al. 1998, and Lindstrom 1998) discovered similar evidence with regard to the timing of reproduction and recruitment.

Recent studies of larval drift by Lindstrom (1999) in the Wainiha River on Kaua'i suggest that 'o'opu reproduction occurs year-round and appears to be strongly influenced by freshets. Nishimoto and Kuamo'o (1997) also found that post-larval recruitment of gobies into streams occurs year-round, and appears to be most common immediately after freshets and periods of heavy rain. Hence, populations of the same species in different streams appeared to be acting independently with regard to breeding and recruitment (Kinzie and Ford 1982), and may be strongly influenced by instream and offshore conditions. Equally important is the invasion of stream mouths by post-larval amphidromous species. Research by several authors suggests that this may occur at different times for different species. Given the stochastic processes influencing current patterns, streamflow, and planktonic larval survival one would expect that these patterns might be subject to considerable temporal and geographic variation. Common in all areas is the necessity for terminal discharge of sufficient duration and volume to attract and accommodate upstream migration of post-larval fishes, mollusks, and crustaceans.

McRae (2007) suggested that during wet periods, small streams might be more significant as contributors of larvae to the oceanic larval pool. In dry periods, large streams may provide more eggs. Hence, they argue that representative streams of all types must be protected in order to ensure the continued survival of amphidromous species in Hawai'i.

4.0 HUMAN IMPACTS

Since the arrival of humans in the archipelago some 1600 years ago there have been alterations to the islands' landscapes, streams, and watersheds (Kirch 1982, 2000; Burney et al. 2001; Athens et al. 2002). Understanding and formulating management plans today requires understanding of these events in the past.

4.1 Pre-Captain Cook Human Influences on Hawaiian Streams

While restoration to a pre-Captain Cook state (Miike 2004) might be an idealistic goal for stream restoration, so much post-contact modification has occurred that the combined impacts of cumulative perturbations to Hawaiian streams prevent us from knowing what a stream with pre-Captain Cook characteristics looked like or how it might have functioned (Kinzie 1993). Zimmerman (1963), Kirsch (1982), Wagner et al. (1985), Stone (1985), Cuddihy and Stone (1990), Athens et al. (2002), and Ziegler (2002) summarize the impacts to forested watersheds in Hawai'i caused by activities of prehistoric Polynesians beginning about 1,600 years ago. Activities most likely to adversely impact stream ecosystems included the extensive lower watershed deforestation by clearing and burning, agriculture (especially the modification of stream flow for wetland crops), introduction of alien species, and fishing.

Following and after the arrival of the first and second waves of Polynesian immigrants, the Hawaiians refined the ahupua'a concept of resource allocation and engineered diversions ('auwai) to irrigate taro fields (lo'i) (Kirch 1982, Gingerich et al. 2007). Sometimes quite extensive in nature, these 'auwai carried water to irrigate taro lo'i throughout the middle and lower reaches of many valleys on the five major Hawaiian Islands (Handy and Handy 1972). Widespread impacts of these pre-historic activities and deforestation caused by the introduced Polynesian rat included decrease in watershed soil moisture, permeability, and surface water retention; rapid run-off; sedimentation of streams and nearshore waters; lowered water tables; altered-microclimates; and drought (Newman 1969, Spriggs 1985). Hawaiians directly influenced the stream fauna by fishing and collecting returning post-larvae (hinana) (Titcomb 1972); however, this impact may have been small compared to the alterations in the landscapes (Athens et al. 2002).

4.2 Post-Captain Cook Human Influences on Hawaiian Stream Ecosystems

By the time comprehensive descriptions of the Hawaiian landscape began appearing in western literature in the late 1700s, feral ungulates and non-native plants had already begun to dramatically change the nature of Hawaiian watershed structure and function. The restriction (kapu) placed upon killing introduced cattle permitted the unchecked growth of large herds, which along with introduced sheep beginning in 1793, decimated native lowland forests. This was accompanied by the introduction of non-native plants that forever changed the nature of Hawaiian watersheds. These cumulative effects of human activities led to the permanent and irreversible modification of Hawaiian watersheds and their streams. The effects include but are not limited to the following, in rough chronological order:

- Changes to watershed vegetation, soils, and water budgets by introduced species
- Destruction of watershed vegetation and soil erosion caused by feral ungulates
- Surface water diversions, groundwater, and well development
- Soil erosion from sugar cane and pineapple cultivation
- Discharge of bagasse at stream mouths (late 1800s to 1972)
- Aquatic alien plant and animal introductions
- Introduced diseases and parasites of aquatic animals
- Urbanization and industrialization with subsequent impacts upon water budgets and quality
- Widespread stream channel modifications for flood control
- Modern consumptive practices (e.g., fishing with illegal electroshocking and traps)

4.3 Water Development

The history of surface water development in Hawai'i was summarized by Wilcox (1996). She documented the tremendous engineering feats involved in bringing water, often from long distances over rough terrain, to centers of large-scale agriculture. The plantation system this water development supported laid the groundwork for the economic development of the Hawaiian Islands beginning in the late 1800s. While we know the history and current state of the movement of water through these systems, we know much less about how diversion impacts Hawaiian stream ecosystems. Kido (1997b) noted that the "rapidly changing terrestrial landscape in Hawaiian watersheds coupled with the escalating rates of alien species introductions are altering natural functioning of these [stream] ecosystems."

In one of the few published studies that directly examined the effects of stream dewaterment in Hawai'i, Kinzie et al. (2006) found that stream diversion reduced available habitat for benthic (bottom-dwelling) invertebrates in reaches below a hydropower dam on the Wainiha River, Kaua'i. Benthic primary and secondary production were lowest at sampling sites below the diversion dam with the lowest flows. Complex and sometimes subtle biotic and abiotic effects associated with diversions were also discovered that are yet difficult to explain. Invertebrate drift was strongly influenced by the dam suggesting entrainment of drift into the diversion ditch (Kinzie et al. 2006).

Maciolek (1978) stated that *Neritina granosa* (hīhīwai) can occupy continuous streams up to 400 meters in elevation; however, it is uncommon to find hīhīwai at that elevation. Ford (1979b) and Brasher (1997a) found that hīhīwai were limited to about 185 meters and 223 meters in the lower reaches of Waiohue and Waikolu Streams, respectively. Both investigators suggested that this was due to the effects of dewaterment on habitat availability. Way et al. (1998) noted altered patterns in reproductive out put among *Lentipes concolor* ('o'opu alamo'o) from continuous Makamaka'ole Stream on Maui and diverted Waikolu Stream on Molokai.

Benbow (1997) concluded that a Maui diversion dramatically reduced habitat for benthic invertebrates. A major unanswered question is whether these impacts threaten populations of native amphidromous species. This question is central to the crafting of instream flow standards, but has yet to be properly answered.

Native Hawaiian amphidromous species are able to surmount many low dams and weirs as we have discovered in our field studies of East Maui, Nā Wai ʽEhā (SWCA 2008), and other West Maui streams (SWCA 2004, 2007). This was reported by both USGS (Gingerich and Wolff 2005) and DAR (Parham et al. 2008). Under existing diverted conditions, flow volume and frequency is sufficient to allow upstream migration by ʽoʽopu nākea, ʽoʽopu alamoʽo, ʽopae kalaʽole and by the non-native amphidromous Tahitian prawn to inhabit elevations where they would normally be found. Fukushima et al. (2007) discovered that upstream migration by gobies was unaffected by dams in Hokkaido streams. Holmquist et al. (1998) noted that the native Antillean goby *Sicydium plumieri* was able to negotiate high dams with spillway releases, albeit in reduced numbers, in Puerto Rican rivers.

Diversion structures in many East Maui streams are located at or above the uppermost elevations that ʽoʽopu alamoʽo and ʽōpae kalaʽole normally inhabit under natural undiverted conditions. In such cases the structures would not represent ʽbottlenecks' to upstream migration. However, as Gingerich and Wolff (2005) noted, dry stream reaches (e.g. below diversion structures) can function as ʽbottlenecks' for the migration of any species. In Hawaiian streams, dry reaches in diverted, naturally intermittent, and interrupted perennial streams are temporary and are periodically wetted by freshets. The presence of amphidromous species above dry reaches throughout the State (Parham et al. 2008) demonstrates that ecological connectivity is restored during these events allowing migration to occur. Large waterfalls may prevent upstream migration of all amphidromous species except ʽoʽopu alamoʽo and ʽōpae kalaʽole (Gingerich and Wolff 2005). This is true under both natural and diverted conditions. This is significant in the evaluation of IIFS for native stream life. Changes in aquatic habitat caused by diversions in upstream reaches are not relevant to those species that do not normally inhabit reaches above natural bottlenecks or cannot migrate upstream to inhabit these reaches (Gingerich and Wolff 2005).

4.4 Summary of Human Impacts on Hawaiian Streams

SWCA believes that there are no ʽpre-Captain Cook' streams (sensu Miike 2004) in Hawaiʽi today, and there can never be such streams again due to the complex synergistic effects of watershed alteration by a millennium of human alteration of the environment throughout the archipelago. There are, however, streams with minimal levels of alteration that continue to harbor healthy populations of native amphidromous species. These streams are commonly referred to today as being ʽpristine', ʽunaltered', or ʽnatural' (Hawaiʽi Cooperative National Park Studies Unit 1990).

Despite the history of disturbances in island watersheds that began with the Polynesian immigrants the amphidromous fauna of Hawaiʽi persists, although not in the numbers once described in literature and lore. The characteristic species may still be found in many streams on all five major islands, and often in abundance. East Maui streams continue to be recognized among the most important habitats for native Hawaiian stream animals in the State (Hawaiʽi Cooperative National Park Studies Unit 1990, Gingerich and Wolff 2005). No specific evidence is available to suggest that any of the amphidromous species is presently at risk of extinction. However, the synergistic effects of human alterations have led to a decline in the populations of native freshwater species statewide. Surprisingly, no studies have been conducted on the long-term population trends for Hawaiian amphidromous species, and there is nothing in the scientific literature on this topic.

A pattern that is not yet widely acknowledged is that the amphidromous native macrofauna are extraordinarily resilient to changing conditions within streams, and they continue to persist within the Hawaiian Islands in apparently stable metapopulations. Evidence of this has been cited by others, including Dr. Lawrence Miike of the CWRM (see his quotation in the Executive Summary on page 3 of this report), yet its significance is perhaps not recognized:

> *While continuous stream flow from the source in the mountains to the mouth at the ocean ("connectivity from mauka to makai") is perhaps a necessary condition for most of Hawaii's perennial streams to sustain reproducing amphidromous populations at pre-diversion levels, …there are streams that are naturally interrupted with healthy populations; i.e., with*

> *ecological instead of physical connectivity, or stream flows of sufficient volume and frequency to allow the normal distribution of native amphidromous species within a given watershed, F0F 557…* (Hearing Officer's Proposed Finding of Fact, Conclusions of Law, and Decision and Order, Case Number CCH-MA06-01, April 2009).
>
> *These [Statewide Monitoring and Survey Program] surveys have already yielded valuable and unexpected results. For example healthy 'o'opu populations have been discovered in intermittent leeward streams, previously thought to be incapable of supporting native fishes.* (Dr. Robert Nishimoto, Aquatic Biologist, as quoted in "Hawaiian Waters - the Mauka Makai Lifeline" video published by the Education Program, Department of Aquatic Resources, DLNR.)

5.0 THE EAST MAUI IRRIGATION COMPANY (EMI) DITCH SYSTEM

Built between 1876 and 1923, the East Maui ditch system is operated by the East Maui Irrigation Company (EMI), a subsidiary of Alexander and Baldwin. It is an engineering marvel consisting of at least 388 intakes, 24 miles of ditches, 50 miles of tunnels, 12 inverted siphons, and hundreds of small secondary intakes with a total capacity of about 445 mgd (Wilcox 1996). She estimated the replacement cost to be $200 million, and states that it is the "largest privately owned water company in the United States, perhaps in the world."

Today the ditch system conveys 62 billion gallons of water per year (over 20.2 million acre feet) to Central Maui to irrigate 30,000 acres of sugar; and up to one billion gallons per year (over 326,000 acre feet) for domestic use by the County of Maui. The American Society of Civil Engineering designated the EMI ditch system as a National Historic Civil Engineering Landmark in February 2003. Within the USGS East Maui study area, six ditch/tunnel systems intercept stream flows from 21 streams at elevations as high as 1,950 ft. The County of Maui collects water from some East Maui streams at even higher elevations. EMI records document 58 major structural intakes and 119 minor diversions within the study area (Table 2).

Major structures generally consist of concrete and/or stone diversion dams or fixed-crest weirs built across the stream channel. Water is diverted into ditches and flumes through debris gratings or drainage galleries adjacent to and immediately upstream of the dams. The volume of water entering the ditch systems can be adjusted at each stream by manually operated head gates. None of the diversion structures currently have bypass systems (e.g. fish ladders or fish-ways) built specifically to enhance upstream or downstream fish passage. Many of the dams have some seepage through the face or toe of the structure and through head gates.

Table 2. *Registered diversion structures within the East Maui study area (Source: East Maui Irrigation Company, Ltd.)*

Ditch Name	Major Diversions	Minor Diversions
Ko'olau	33	83
Wailoa	4	3
Spreckels	10	22
New Hamakua	3	0
Manuel Luis	5	10
Center	3	1
Total diversions	**58**	**119**

Secondary diversions structures consist of small water development tunnels, weirs, check dams, and PVC pipes fitted to capture seepage below dam faces and runoff from small gullies and swales. Several streams in the western portion of the study area are diverted at several elevations by different ditch systems.

During periods of prolonged drought in East Maui, flow in the ditch system is reduced to 10 mgd. This is the volume of water that is available to provide the County of Maui to supply domestic water needs for upcountry towns including Pukalani, Kula, and Makawao.

The ditch system itself supports both native and non-native aquatic life, yet we are unaware of any scientific study of its biological function. Local residents know well that portions of the ditch system are the best places to collect mountain ʽōpae for subsistence. The ditch serves as a means of lateral dispersal across watersheds for *both* native and non-native aquatic species. It may also serve as a sink for newly hatched larvae of amphidromous species inhabiting the upper reaches of East Maui streams.

6.0 AMPHIDROMOUS SPECIES IN EAST MAUI STREAMS

6.1 Recent Studies

Gingerich (1999) studied the relationship between and availability of groundwater and surface water in East Maui as potential future sources for domestic water supply. Following the submittal of a petition to set Instream Flow Standards (IFS) in 27 East Maui streams in 2002 by concerned citizens, the geographic extent of the East Maui study area was limited to the region between Kolea Stream and Makapipi Stream (Gingerich 2004). In his study of median- and low-flow characteristics under natural and diverted conditions, Gingerich (2004) developed a system to estimate flow characteristics (base flow and total flow) for ungaged East Maui streams. Building on this, he further identified the location of gaining and losing reaches and significant springs in stream valleys in the East Maui study area. Gingerich and Wolff (2005) attempted to estimate habitat for native stream macrofauna and to model how the amount of this habitat might respond to changes in flow.

SWCA biologists conducted biological surveys and collected flow measurements above and below diversions throughout the study area. Kinzie et al. (2006) had found that reaches affected most by water removal are those located between ditch intakes and influent tributaries, springs, or seeps that contribute to flow at lower elevations. This pattern was also apparent within the East Maui study area as well as in Honokohau Stream on West Maui (SWCA 2004, 2005). The location and type of diversion structures and stream crossings strongly influence the ability of amphidromous species to surmount the structure to inhabit upstream reaches (March et al. 2003a, Resh 2004, SWCA 2004, 2005).

Seven of the 21 East Maui study streams within the project area have terminal waterfalls or cascades. The East Maui streams with high terminal falls are: Kolea, Waikamoi, Wahinepeʽe, Haipuaʽena, Waiokamilo, and Paʽakea. Paʽakea has a freshwater plunge pool just above the mouth of the stream; however, the falls above it restricts other amphidromous fishes from inhabiting the stream above the terminal pool. *Lentipes* and *Atyoida* were observed together in most of the streams studied by USGS, SWCA, and DAR. A summary of amphidromous species presence within the study area streams in found in Table 3.

The atyid ʽōpae kalaʽole was the most conspicuous species found above the diversions during our study. Dragonfly and damselfly naiads, Japanese wrinkled frog tadpoles, and lymnaeid snails were common. ʽŌpae were also observed above every intake with the exception of Punalau Stream. Insufficient data are available to assess amphidromous species populations in Wahinepeʽe, ʽOhia, Waiaʽaka and Makapipi streams. Direct visual surveys of upper Uluini tributary and Nuaʽailua streams were not possible due to excessive turbidity. The source of suspended sediments in these areas appeared to be from disturbance of watershed soils by feral pigs (Hew, personal communication; Voorhees, personal communication).

In 2008, at the request of the CWRM, DAR biologists conducted comprehensive longitudinal sampling in five East Maui stream systems, including Honopou, Hanehoi, Piʽinaʽau, Waiokamilo, and Wailuanui. Their results, which were published online in the Hawaii Watershed Atlas (www.hawaiiwatershedatlas.com), included data for amphidromous species listed in Table 3. DAR biologists also surveyed native freshwater insects in each of the five stream systems and found a greater diversity of native insects in the upper reaches of streams above the highest diversion structure. Insect diversity in the lower reaches of streams affected by diversions was reduced.

At least one species of endemic damselfly, *Megalagrion pacificum*, a candidate endangered species, was found in the upper reaches of Honopou, Hanehoi, and Piʽinaʽau Streams. DAR concluded that diversion of surface waters converted the normally perennial mid-reaches of these five systems into the equivalent of intermittent streams. The few remnant pools were colonized by alien invasive species. They also concluded that upstream dispersal of invasive species was inhibited by numerous

Table 3. Known distribution of amphidromous species in streams of the East Maui study area (data summarized from SWCA, USGS, and DAR sources). X = present; ND = no data. Streams have not been surveyed equally throughout all reaches and over time, so the lack of an observation of a given species from a given stream must not be interpreted as absolute evidence of that species’ absence from that watershed. East Maui streams with the greatest number of amphidromous species reported have been the most intensively studied and surveyed repeatedly over a period of may years (e.g. Hanawī, Waiohue, and Palauhulu/Pi’ina’au).

East Maui Streams (T) = terminal falls	*Kuhlia spp.*	*Eleotris* sandwicensis	*Stenogobius hawaiiensis*	*Awaous guamensis*	*Sicyopterus stimpsoni*	*Lentipes concolor*	*Neritina granosa*	*Neritina vespertinus*	*Macrobrachium lar (Alien amphidromous)*	*Macrobrachium grandimanus*	*Atyoida bisulcata*
Honopou		**X**		**X**	**X**	**X**			**X**	**X**	**X**
Hanehoi											**X**
Kolea (T)	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**
Waikamoi (T)									**X**		**X**
Wahinepe‘e (T)	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**	**ND**
Haipua‘ena (T)						**X**			**X**		**X**
Puohokamoa				**X**		**X**			**X**		**X**
Punalau				**X**	**X**	**X**			**X**		
Honomanū											**X**
Nua‘ailua				**X**	**X**	**X**	**X**	**X**	**X**		**X**
Palauhulu/Pi’ina’au	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
‘Ohia							**X**				
Waiokamilo (T)				**X**					**X**		**X**
Wailua Nui	**X**	**X**		**X**		**X**			**X**		**X**
W. Wailua Iki	**X**			**X**		**X**	**X**		**X**		**X**
E. Wailua Iki	**X**	**X**		**X**		**X**	**X**		**X**		**X**
Kopiliula	**X**	**X**		**X**	**X**	**X**	**X**		**X**		**X**
Waiohue	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Pa‘akea (T)				**X**		**X**	**X**		**X**		**X**
Kapaula											**X**
Hanawī	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**		**X**
Makapipi	**X**	**X**		**X**	**X**	**X**			**X**		**X**

waterfalls in each stream. They further suggested that the EMI ditch systems serve as lateral conduits for spread of invasive species, but failed to acknowledge the presence of native amphidromous species throughout the ditch and the significance of the ditch in the cross-watershed dispersal of native species.

DAR also suggested that the potential exists for recolonization by native species in all five streams, and they predicted that native fishes would recolonize from the terminal reaches up, and insects would recolonize from the headwater reaches down. Given the potentially deleterious impacts to the successful recolonization by the presence of non-native species, they recommended that flow restoration be released from stream flows, not ditch flows, to mitigate the spread of aquatic invasive species.

It is interesting to note that streams close to areas of habitation in East Maui have the largest number of non-native species. The State of Hawaiʽi Department of Health may have introduced non-native Poeciliid fishes (guppies and mosquitofish) to several East Maui streams during the 2002 outbreak of Dengue fever (Brock, pers. comm.). Local residents of Keanae and Wailua peninsulas have also introduced numerous species of potentially harmful non-native species which may represent a significant threat to native amphidromous species, if they are allowed to disperse throughout the stream systems. Potentially harmful species reported from East Maui streams include guppies, mosquitofish, swordtails, carp, oriental weatherfish (dojo), goldfish, Louisiana crayfish, apple snails, and Asian clam. The potentially detrimental effects of the non-native Tahitian prawn, also an amphidromous species introduced by the State of Hawaiʽi in the late 1960s, have never been determined.

6.2 Status of Amphidromous Species Distribution in East Maui Streams

Table 4 shows the number of amphidromous species known to occur in the 21 streams within the USGS East Maui Study Area (Gingerich and Wolff 2005, Parham et al. 2008, and this study). The information in Table 4 is graphically depicted in Figure 4. Of the 21 streams, data on amphidromous species are available for 18, and all of these streams have diversion structures. The interruption of flow by diversion ditches can create an sporadic impediment to downstream larval drift and upstream migration of post-larvae, but should not be interpreted as the sole cause of low numbers of native amphidromous species (Timbol and Maciolek 1978, Kirch 1982, Chan 1986, Cuddihy and Stone 1990, Devick 1991, Kido 1997, Englund 1999, Brasher and Wolff 2001, Richardson and Jowett 2002, Englund 2002, Brasher 2003, Resh 2005).

Table 4 also reflects the distribution of amphidromous species along longitudinal gradients within the streams, and includes species occurrence data from the newly available Hawaiian Watershed Atlas (Parham et al 2008). Although many of the records within the atlas are older (circa 1961-63), all reported observations are post-diversion (e.g. after 1900). In the table, each stream has been partitioned into lower, middle, and upper reaches. These are relative terms that are widely and loosely used in scientific literature. The lower reach generally refers to that length of stream channel from its mouth upstream to the head of its terminal estuary or to the base of the first significant high waterfall, or it may roughly encompass the lower third of the stream's total length. The middle reach encompasses the stream above the lower reach but below an elevation of about 1,000 to 1,500 ft. The upper reach generally refers to elevations above 1,500 ft, or the upper third of the total stream length, and represents the highest elevations inhabited by amphidromous species under natural, undiverted conditions. Of course the highest elevations inhabited by these species vary with local geomorphologic and hydrologic conditions.

Figure 5 summarizes the number of streams within the USGS East Maui study area (Gingerich and Wolff 2005) that harbor amphidromous species in their lower, middle, and upper reaches. It is significant to note that of the 18 East Maui streams for which we have data, 17 were found to have amphidromous species in their upper reaches. These individuals had to have migrated upstream past diversion structures to inhabit these reaches, confirming that ecological connectivity occurs under existing conditions. It is also possible that the EMI ditch system may also be a means of access to stream reaches above diversions.

The data also confirm that there is a substantial amount of suitable habitat in East Maui streams for all nine native amphidromous species (as well as the non-native amphidromous Tahitian prawn) under existing diverted conditions. Based upon Gingerich and Wolff (2005), SWCA calculated that there are roughly 106 linear kilometers (66 linear miles) of stream channels within the study area below an elevation of 2,000 ft (which is presumed to be the uppermost elevation inhabited by amphidromous species under natural, undiverted conditions). Figure 6 (Plate 1 of Gingerich and Wolff 2005) illustrates the amount of aquatic habitat availability in relation to undiverted conditions estimated by Gingerich and Wolff (2005). Figure 7 illustrates stream channel lengths, in linear meters, throughout the East Maui study area in which the aquatic habitat values were estimated by Gingerich and Wolff (2005) as a certain percentage of natural conditions at base flow.

Table 4*. Distribution of amphidromous species in lower, middle, and upper reaches of East Maui Streams within the USGS study area (summarized from SWCA, USGS, and DAR sources).*

STREAM	**Number of Amphidromous Species Reported**			**Terminal Waterfall**	**Number of Non-Native Species Reported**
	Lower	**Middle***	**Upper****		
Kolea	ND	ND	ND	√	ND
Waikamoi		1	2	√	5
Waikamoi – Alo***			1		
Wahinepe'e	ND	ND	ND	√	ND
Puohokamoa	4	3	2		1
Haipua‘ena	1	3	1	√	4
Punalau	2	1	1		2
Honomanu	1		1		
Nua'ailua	6	5	2		2
Pi'ina'au / Palauhulu	10	6	4		9
'Ōhi'a	1				
Waiokamilo		2	2	√	8
Wailuanui	10	6	5		5
West Wailuaiki	4	4	1		7
East Wailuaiki	5	2	1		1
Kopiliula / Puaka'a	4	7	6		3
Waiohue	10	5	4		2
Pa'akea	5	2	1	√	1
Waia'aka	ND	ND	ND		
Kapā'ula			1		
Hanawi	7	7	2		2
Makapipi	4	5	2		6

Key to Table:

ND = no data

* Above diversion structures in some reaches

** Above diversion structures

*** Waikamoi and its tributary Alo are counted as one stream.

Of the total 106 linear kilometers of stream channels within the study area, 57 percent of the total stream length retained 75 - 100 percent of aquatic habitat at base flow relative to the estimated undiverted conditions (Gingerich and Wolff 2005). An additional 27 percent of the total stream length retains between 25 - 75 percent of aquatic habitat at base flow relative to the estimated undiverted conditions, and 16 percent of the total stream length within the study area was dry at base flow.

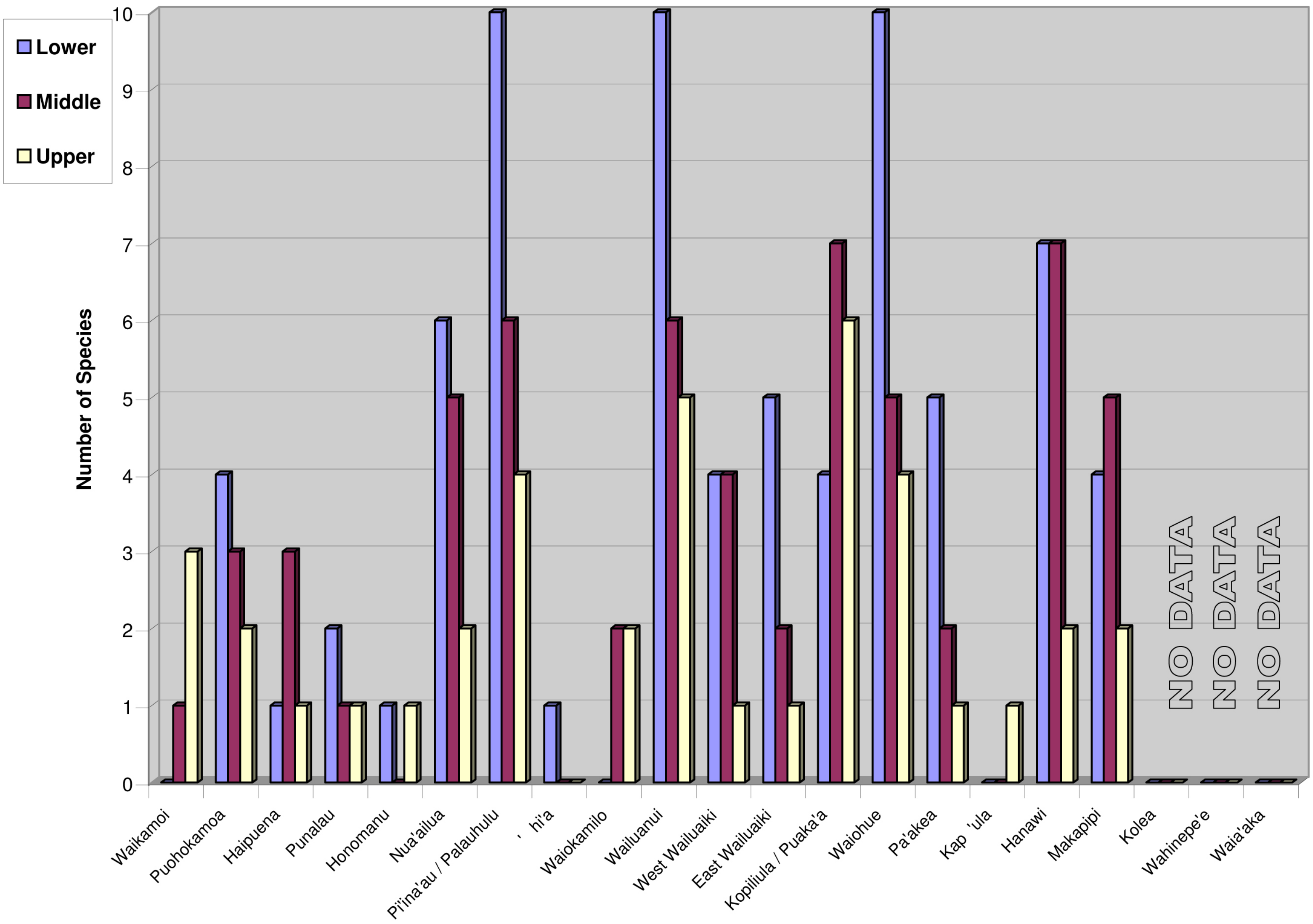
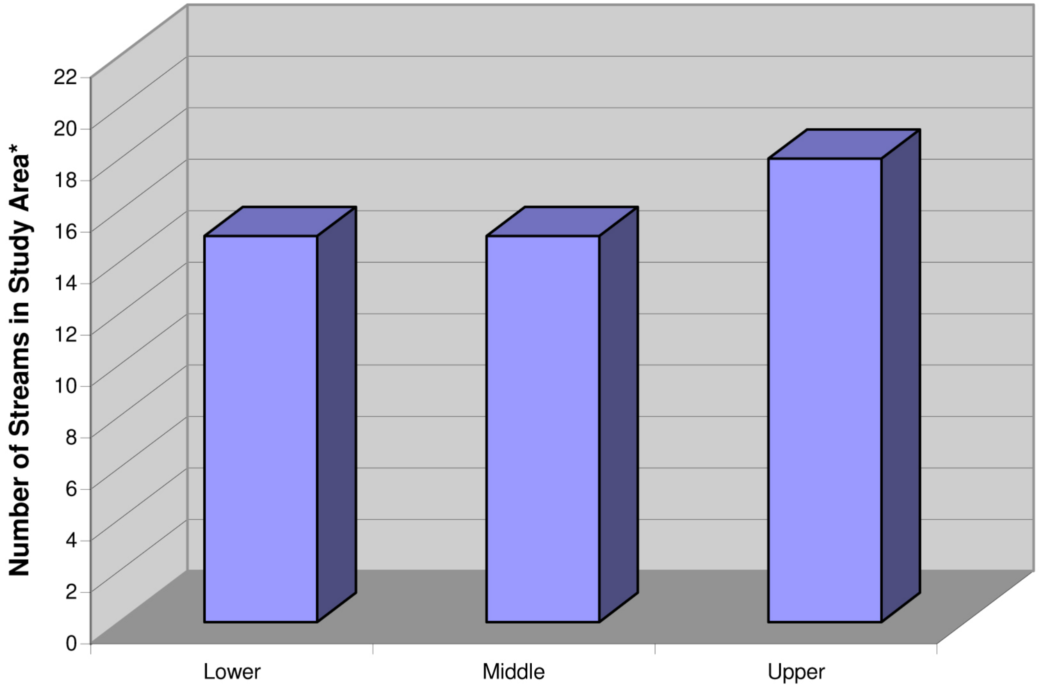


Figure 4. *Number of amphidromous species distributed within lower, middle, and upper reaches of East Maui study streams. Source data for this assessment include data from USGS (Gingerich and Wolff 2005), DAR (Hawaii Watershed Atlas (Parham et al. 2008), and SWCA field studies since 2003, and data obtained in numerous other surveys conducted by authors Kinzie and Ford since 1974.*



*Data available for 18 of 22 streams

***Figure 5**. Seventeen of 18 East Maui streams for which data are available were found to have amphidromous species within their upper reaches, demonstrating that ecological connectivity occurs under present diverted conditions. Source data for this assessment include data from USGS (Gingerich and Wolff 2005), DAR (Hawaii Watershed Atlas (Parham et al. 2008), and SWCA field studies since 2003, and data obtained in numerous other surveys conducted by authors Kinzie and Ford since 1974.*

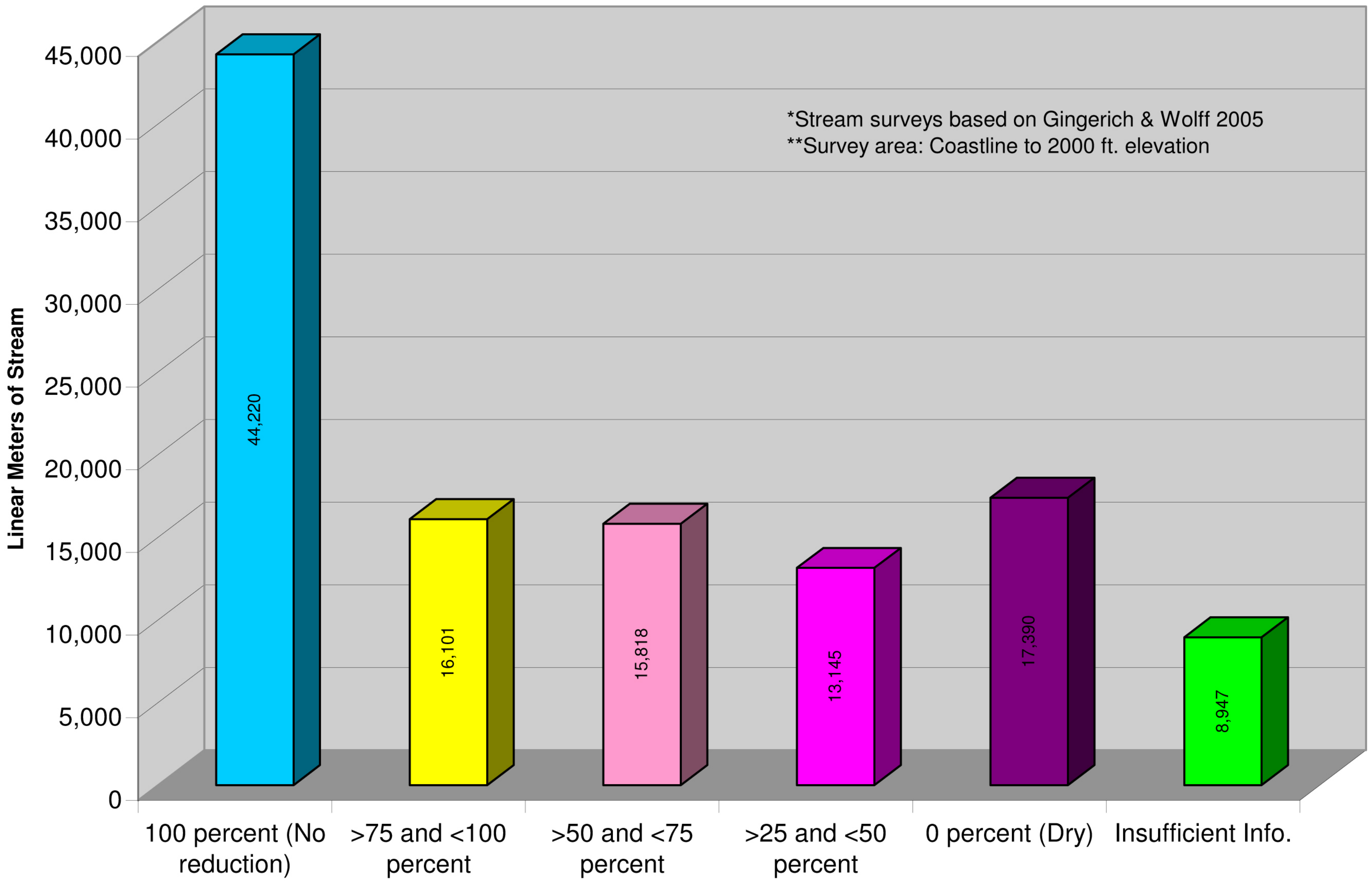


Figure 6. *Summary of estimated aquatic habitat at diverted base flow conditions relative to natural conditions for the USGS study area streams in East Maui, calculated with GIS technology by SWCA from stream lengths illustrated in Plate 1 of Gingerich and Wolff (2005).*

Our observations and review of scientific literature published over the past decade helped us realize that the native Hawaiian amphidromous species appear to be far more resilient than once imagined. Natural patterns of frequent drought, flood, and landslides can have devastating impacts on stream biota in individual streams; however, those impacts tend to be temporary. Following natural disturbance, recolonization by algal, invertebrate, and amphidromous species has proven to be relatively rapid (Ford and Yuen 1986; Fitzsimons and Nishimoto 1995; Kido 1996a, 1996b; Sherwood 2002, 2004a).

A potential risk associated with flow restoration in streams that are known to harbor alien species, particularly predatory poeciliid fishes, is the inadvertent dispersal of aliens throughout the stream by enhanced flow. For example, mosquitofish (*Gambusia affinis*) were observed immediately above the diversion structure in Kopiliula Stream during this study. Their origin in the stream is unknown, but they may have been introduced by State or County health department officials or unknowing persons as a hopeful check against disease-bearing mosquitoes. Mosquitofish are members of the live-bearing family Poeciliidae, native to South and Central America, which includes guppies and swordtails. Englund (1999, 2002) suggested that poeciliid fishes may be accountable for the demise of endemic insect taxa including damselflies of the genus *Megalagrion*. The potential for both upstream and downstream dispersal of poeciliids during flood events and the failure of flood flows to eliminate these species from streams is well documented (Chapman and Kramer 1991, Englund and Filbert 1999).

7.0 SUMMARY POINTS

- Contrary to what was once believed, there are no data available to suggest that any of the nine native Hawaiian amphidromous species is at risk of either endangerment and/or extinction in East Maui streams or elsewhere within the State. Native amphidromous species persist in East Maui streams and other streams throughout the State despite 1,600 years of human modifications to the landscape and a century of modern water development.

- Amphidromous species have life histories that are adapted to the extremely variable and unpredictable habitat conditions characteristic of Hawaiian streams.

- Amphidromous species are part of statewide metapopulations and are buffered from isolation by having a continuous source of genetic renewal through interisland oceanic larval transport. As such, they are resilient to changing conditions within individual streams and continue to persist within the Hawaiian Islands as apparently stable metapopulations.

- In Hawaiian streams, dry reaches in both diverted and naturally intermittent and interrupted perennial streams are ephemeral and are periodically wetted by freshets. The presence of amphidromous species above dry reaches throughout the State demonstrates that ecological connectivity is restored during these events allowing migration to occur (Nishimoto, undated video; Parham et al 2008).

- Of the 21 East Maui streams under study, data exist for 18 streams. Of those, 17 streams have amphidromous species reported from their upper reaches, once again confirming that ecological connectivity occurs under existing conditions.

- The system of water diversions in East Maui, while clearly extending the dry end of the wet-dry daily cycle of stream ecology, has not been demonstrated to preclude suitable habitat conditions for sustaining populations of the amphidromous species.

- Under diverted conditions, of the total 106 linear kilometers of stream channels within the study area, 57 percent of the total stream length retained 75 - 100 percent of aquatic habitat at base flow relative to the estimated undiverted conditions. An additional twenty-seven percent of the total stream length retained between 25 - 75 percent of aquatic habitat at base flow relative to the estimated undiverted conditions.

- The extent of larval exchange among breeding populations of amphidromous species in Hawaii is sufficient to result in genetic homogeneity among the main islands.

- No one has yet documented a direct quantitative relationship between the abundance or density of native Hawaiian amphidromous species and weighted usable habitat area (WUA) as estimated through the Physical Habitat Simulation Model (Bovee et al 1998).

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APPENDIX A
LIFE HISTORIES OF SELECTED NATIVE HAWAIIAN AMPHIDROMOUS SPECIES

Eleotris sandwicensis **(Vaillant and Sauvage 1875) ʻOʻopu akupa**

Oʻopu akupa is endemic to the Hawaiian Islands. Although it is generically referred to as a goby in the Hawaiian language (e.g. ʻoʻopu), it is not a true goby but is a member of the family Eleotridae (Gosline and Brock 1960). Eleotrids do not have fused pelvic fins, or ʻsucking disk' characteristic of the true gobies. As a consequence, ʻoʻopu akupa are confined to the lower reaches of streams and estuaries (Kinzie 1990) due to their inability to cling to rocks. ʻOʻopu akupa are found in the terminal and lower reaches of streams on all the main Hawaiian Islands and are abundant on Oahu in both altered and unaltered streams (Yamamoto and Tagawa 2000).

Culturally, ʻoʻopu akupa were prized as a food item and are also used as bait for papio by near-shore fishermen (Titcomb 1972). This is one of the largest ʻoʻopu in Hawaiian streams and there are more specific names for this species in the Hawaiian language than for any other ʻoʻopu, including akupa, akupakupa, okuhe, okuhe melemele, okuhekuhe, apoha, oau, and owau (Titcomb 1972). ʻOʻopu akupa are carnivorous and predaceous. Food items most often taken consist of thiarid snails and Asiatic clams, though fishes (including smaller ʻoʻopu akupa) and crustaceans are also consumed (Fitzsimons et al. 2002).

Reproductive biology of ʻoʻopu akupa on Oahu was studied by Sim (2006). She found females and males with mature gonads year-round, suggesting year-round reproduction with a peak spawning season possibly between July to March. This peak spawning period encompasses the rainy season (November to March), which is the spawning season of most Hawaiian gobiids, but is prolonged and extends into the dry season (April through October). It is possible that each female may spawn more than once a year. Batch fecundity in females ranged form 4950 eggs to 54670 eggs and was positively correlated with standard length and wet weight of the individual. The minimum size at maturity has not been documented but the smallest female collected with mature gonads was 54mm SL; the smallest male was also 54 mm SL (Sim 2006).

Both water quality and island location have significant effects on the size and weight of ʻoʻopu akupa (Sim 2006). Specimens were collected from pristine and degraded streams on Oʻahu, Hawaiʻi and Kauaʻi. Mature males and females from pristine streams were significantly larger and heavier than individuals collected from degraded streams. ʻOʻopu akupa that Sim (2006) collected increased in size and wet weight from Oahu to Hawaiʻi to Kauaʻi. She speculated that higher predation pressure on ʻoʻopu akupa and lower food quality in degraded streams may be factors that result in smaller sizes and earlier onset of maturity in these streams.

A young ʻoʻopu akupa (right) photographed in an aquarium, illustrating its distinct dark brown mottled coloration. Photo by John Ford.

Awaous guamensis **(Valenciennes 1837) ʻOʻopu nakea**

As the largest true goby (280 - 340mm SL) inhabiting Hawaiian streams and historically the most popular freshwater food fish, ʻoʻopu nakea was among the first Hawaiian freshwater goby species whose life history patterns were investigated in detail (Ego 1956). Originally described as the endemic *A. stamineus* until Watson (1992) reclassified it, the species is now believed to be indigenous throughout the tropical Pacific. In Hawaiʻi it is found in streams on all major islands having perennial streams (Ha and Kinzie 1996); however, populations of the species are reduced on Oʻahu. ʻOʻopu nakea characteristically inhabits the lower and middle reaches of streams in areas with deeper, slower waters (Kinzie 1988), and is most abundant in larger rivers on Kauaʻi. Kido and Heacock (1991) and Ha and Kinzie (1996) studied the reproductive biology of the species, and found that larger adults migrate downstream with freshets to spawn in large aggregations in riffles just above the terminal, estuarine reaches of streams. Male and female fish had the potential to spawn between August and December (Ha and Kinzie 1996). Size at first reproduction is 73 mm SL for both male and female fish.

Ha and Kinzie (1996) estimated fecundity, based to 21 nests measured in the field, to be between 117,600 eggs (for a 144 mm SL female) to 689,500 eggs (for a 217 mm SL female). Ego (1956) estimated well over one million eggs for a 280 mm SL female. Although *A. guamensis* is among the largest gobies, it has very small demersal, spheroid eggs. Eggs are laid on the underside of rocks and tended by male fish for two to four days until hatching (Ego 1956, Miller 1984, Nishimoto and Fitzsimons 1986, Timbol et al. 1990, Lindstrom and Brown 1996). Newly hatched yolk sac larvae are swept downstream and into the sea.

Downstream larval drift occurs throughout the year, and is most prevalent during the first hours after sunset (Lindstrom 1998). The highest concentration of larvae measured from any single hour-long sample was 413 larvae/m^3. Based on these data, Lindstrom (1998) calculated mean daily watershed larval output for all sample dates (n=36) at 0.45 – 1.4x10^6, yielding an annual larval output of 1.6-5.1x10^8 larvae per year from the entire watershed for only the first three hours after sunset. He believed that this was an underestimation of the complete watershed output value. Lindstrom (1998) noted that samples with higher concentrations of drifting larvae were dominated by *A. guamensis* suggesting that this species concentrates its reproductive effort in specific seasons. He calculated that only 2500 breeding *A. guamensis* would be needed to produce the number of larvae calculated, given 2x10^5 as the single spawn fecundity of an average-sized breeding adult (Tamaru 1991).

Adult ʻoʻopu nakea, Awaous guamensis, in Hanawi Stream (left). Buff colored spots on rocks are hīhīwai (Neritina granosa) egg capsules. Photo by John Ford.

Once they reach the sea, larvae develop as part of the marine planktonic community for up to 169 days (Radtke et al. 1988, Radtke and Kinzie 1991). Tate (1997) and Nishimoto and Kuamoʼo (1997) reported that *A. guamensis* post-larvae were transported to river mouths by waves and that they entered streams at any time of the day, though in greatest numbers in the evening, at about 16 mm SL in size. They may spend several weeks in the estuarine or lower reaches before migrating upstream, and are generally limited to the lower 1,000 ft in elevation. They are not strong climbers and are restricted from reaches above waterfalls. Kido et al. (1997a, 1997b) characterized oʼopu nakea as an omnivorous benthic feeder, utilizing primarily algae, and opportunistically feeding upon introduced aquatic insects and terrestrial invertebrates in drift. Their work supported the conclusions of Ego (1956) with regard to algae; however, endemic atyid shrimp or damselflies were absent from oʼopu nakea gut samples collected by Kido et al. (1997a, 1997b) from ʻoʻopu nakea collected in the Wainiha River, Kauaʻi.

Sicyopterus stimpsoni (Gill 1860) ‘O‘opu nopili

Tomihama (1972) provided the first description of *S. stimpsoni* (‘o‘opu nopili) life history from a sample of 400 fishes taken from 17 locations on O‘ahu and Maui. He recorded 162,000 eggs from an 89-mm SL female, and hypothesized that maturation might occur in the second year of life. Although he did not witness spawning, he surmised from ovary examination that o’opu nopili between August and March. Fitzsimons et al. (1993) reported that eggs of less than 0.5mm in diameter are laid in single rows forming a narrow mass under boulders. Eggs presumably hatch within 24 hours. Courtship and territorial behavior are well documented in this species by Yuen (1987) and Fitzsimons et al. (1993); however, details of the species’ reproductive biology in Hawaiian streams are lacking.

Post-larvae returning to streams from the oceanic larval pool are the largest of the post-larval freshwater gobies in Hawai‘i (Tate 1997) and were measured at an average length of 23 mm SL (Tomihama 1972, Nishimoto and Kuamo’o 1997). Recruitment into streams occurs mainly during February to May (Tate 1997), and usually occurs in schools. Returning post-larvae undergo dramatic morphological changes due primarily to their changing diet (Tomihama 1972, Schoenfuss et al. 1997). Tate (1997) described two morphological varieties of *S. stimpsoni* post-larvae and juveniles that apparently represented two distinct behavioral types he found in streams on Hawai‘i and Kaua‘i Islands.

At left is a male ‘o‘opu nopili, Sicyopterus stimpsoni (photo by Mike Yamamoto, DAR); and at right is a ventral view of S. stimpsoni illustrating the sucking disk created by fused pelvic fin that helps enable all freshwater gobiid fishes to navigate torrential streams (photo by John Ford)

Their oceanic larval development is estimated to be between three to six months (Kinzie 1990). Postlarvae returning to streams from the sea undergo a rapid growth phase characterized by a cranial metamorphosis that is correlated with their changing diet and intraspecific behavior (Schoenfuss et al. 1997, Keith 2003). Postlarvae are rheotactic and quickly move upstream (Smith and Smith 1998). This allows them to clear obstacles in intermittent streams. The returning postlarval ‘hinana’ of this species constituted the bulk of the goby fry fishery in Hawai‘i (Titcomb 1972, Bell 1999). Titcomb (1972) also indicates that adult ‘o‘opu nopili were also greatly relished as food by prehistoric Hawaiian communities.

‘O‘opu nopili characteristically inhabit the lower and middle reaches of streams. Adults are generally herbivorous, and their diets change as they mature (Julius et al. 2005). Kido (1996, 1997a, 1997b) reported that their principal food source consisted of a variety of diatoms. Fitzsimons et al. (2003) reported that adult fish tend to ‘farm’ large feeding rocks through continual feeding over a period of days. Julius et al (2005) reinforced this concept and hypothesized that both farming activity and repeated freshets act to constantly renew patterns of algal succession. Hence, these natural disturbance events are believed to be crucial to maintenance of ecological integrity in Hawaiian streams.

Lentipes concolor (Gill 1860) ‘O‘opu alamo‘o, ‘O‘opu hi‘ukole

So striking is the sexual dimorphism in ‘o‘opu alamo‘o (Lau 1973), that it was originally described as two distinct species (*L. concolor* Gill 1860; *L. seminudus* Günther 1880). It characteristically inhabits the middle and upper reaches of streams commonly to an elevation of 1,500 feet, but sometimes as high as 3,000 feet, except in streams with terminal waterfalls where it may be the dominant fish throughout the stream course (Maciolek 1977, Kinzie and Ford 1982). It is believed to be omnivorous, ingesting equal quantities of algae, diatoms, insects, oligochaetes, and atyid shrimp (Lau 1973). Reproductive biology of ‘o‘opu alamo‘o has been studied in Hawai‘i, Maui, and Moloka‘i Island streams (Maciolek 1977, Kinzie 1993, Way et al. 1998). Maciolek (1977) suggested that female *L. concolor* matured at about 50 mm SL. He found ripe females between August to May and suggested that spawning might occur year round. He observed between 7,000 and 14,000 eggs in two females examined. Kinzie (1993) found 23 nests between October and May, having between 1,300 to 24,700 eggs each. He also observed nine clutches laid by a single o’opu alamo’o in an aquarium during the same months that nests were found in the field. Based on his observations, he suggested that a single female *L. concolor* 73 mm SL in length was capable of producing 55,200 - 69,000 eggs a year. Adult male ‘o‘opu alamo‘o are territorial.

Female ‘o‘opu alamo‘o, Lentipes concolor, (left) in Palikea Stream, East Maui; and male ‘o‘opu alamo‘o (right) in aquarium. Photos by John Ford.

Territories may vary in size depending in part upon stream discharge (Fitzsimons and Nishimoto 1990). Way et al. (1998) compared the reproductive biology of ‘o‘opu alamo‘o in an undiverted small stream on West Maui (Makamaka‘ole) with that of a diverted stream on Moloka‘i (Waikolu), and found a wide variability in the timing and degree of reproduction in their two-year study. In the undiverted Makamaka‘ole Stream on Maui, ‘o‘opu alamo‘o were reproductively active all year, with reproduction significantly correlated with elevated stream discharge. In the diverted Waikolu Stream on Moloka‘i, ‘o‘opu nopili reproduction appeared to occur on a ‘boom or bust’ cycle and varied widely in relation to streamflow. Way et al. (1998) concluded that *L. concolor* is capable of adjusting its fecundity in response to environmental changes.

Once hatched, free embryos of ‘o‘opu alamo‘o swim upward in the water column (Kinzie 1993). This behavior facilitates their transport to the ocean. Their oceanic larval life was measured between 63 to 106 days (Radtke et al. 2001), with significant differences between islands and between warm and cool seasons. Size at recruitment into streams ranged between 13.5 mm TL and 17.9 mm TL, with no differences between islands. However, *L. concolor* recruited at smaller sizes during seasons with warmer sea surface temperatures. Post-larvae entered streams in the hours just after sunrise in waves on incoming tides (Nishimoto and Kuamo’o 1997), and immediately begin their migration upstream at a measured rate of 90 meters/hour (Tate 1997). According to Lindstrom and Brown (1994), exposure to seawater within hours of hatching is critical to the survival of larval ‘o‘opu alamo‘o. They reasoned that larvae in streams that lack connection to the marine environment due to dewaterment, geographic, or geological factors could be doomed. They suggested that base flows in such streams are critical to maintain larval transport to the sea. Lower stream flows might also negatively affect habitat space and hatching success.

Atyoida bisulcata (Randall 1939) ʻŌpae kalaʻole

Edmondson (1929) described the endemic ʻōpae kalaʻole or ʻōpae kuahiwi as being ubiquitous in mountain streams among the Hawaiian Islands. He studied aspects of opae physiology; however, he did not realize that the species was amphidromous and therefore could not explain its distribution among Hawaiian island streams. Originally considered one of two morphologically similar species (*Atya bisulcata* and *Ortmannia henshawi*) from Hawaiian streams, the name *Atyoida bisulcata* is now accepted as the correct name. It was a favorite food of aboriginal Hawaiians, and is still favored for luaus and meals for special occasions. In 1976 it could be found infrequently in fish markets selling for $9/lb.

Couret (1976) found the male to female ratio in ʻōpae kalaʻole M/F ratio to be 1.4. He observed molting both day and night at intervals between 31 and 61 days. Following molting it may take up to two days for the exoskeleton to harden sufficiently to permit the shrimp to move naturally. Unpublished records of the Hawaii Cooperative Fishery Research Unit at the University of Hawaii indicate that opae kalaole have been found in a majority of perennial streams throughout the state. It is rheophilic and moves rapidly upstream following recruitment to inhabit the upper reaches of streams between roughly 300 m and 1,100 m elevation as adults.

At left, is a photo of adult ʻōpae kalaʻole, Atyoida bisulcata, taken in an aquarium by Carl Couret.

ʻŌpae kalaʻole is well adapted to torrential flows and is common in shooting waters, such as cascades and waterfalls, as well as in plunge pools. It is capable of both filter feeding from the water column and grazing from the surface of rocks. Its food consists primarily of detritus and filamentous algae (Couret 1976).

ʻŌpae kalaʻole mature between 15.8 mm and 20.5 mm in length (Couret 1976). Mating occurs when females molt, and egg deposition begins 12 hours after mating. Couret (1976) estimated fecundity between 73 and 3,557 eggs from a study of 23 female ʻōpae. Berried female ʻōpae are found throughout the year suggesting a multivoltine reproductive cycle, a trait common in many other tropical species. Given the frequency of molting and an average time of 66 days between molts, annual fecundity of large female ʻōpae kalaʻole may be 16,000 -17,000 larvae per year (Couret 1976). Reproductive effort of ʻōpae kalaʻole from two East Maui streams was found to be slightly elevated in populations from higher elevations (Ford 1979a).

Hatching of larvae occurs within 19 -21 days of oviposition (Couret 1976). Length of larval life is not well documented. Couret (1976) suggested that opae kalaole recruit into stream mouths from the ocean at 6.2mm SL. Based upon his studies of zoeae (i.e. shrimp larvae) growth and survival, this body length would be reached in approximately 40 days. Juveniles were found1.6 km upstream within a period of 230 days in Waiohue Stream by Couret (1976). Life span is estimated to be in excess of three years (Couret 1976). Burky et al. (2003) recorded both drift and migration of ʻōpae kalaʻole throughout the summer with peaks in late April and early July. They believed drift and migration were influenced by lunar phase; a distinct diurnal drift pattern was found for shrimp zoea with a peak near midnight. They noted that lunar and diurnal movement provides increased probability of oceanic development and reduced mortality in both drift and upstream migration.

Couret (1976) noted that diversion structures and dry streambeds in East Maui tended to serve as temporary barriers to migration. However, he also noted that adults could also invade the upper reaches of streams through the irrigation ditches. Couret (1976) concluded that this species' success in inhabiting highly ephemeral Hawaiian streams is due in part to its amphidromous multivoltine reproductive cycle, high capacity for interisland dispersal, anatomical adaptation against desiccation, well-developed climbing ability, and its ability to utilize multiple food sources.

Neritina granosa (Sowerby) Hīhīwai or Wī

Hīhīwai (or wī as it is sometimes known on Hawaiʻi Island) is an amphidromous, rheophilic gastropod found clinging to rocks and boulders exposed to swift currents in the lower reaches of clear, steep gradient streams (Ford 1979b). Two other endemic, amphidromous neritid gastropods, *Neritina vespertina* (hapawai) and *Theodoxus cariosus* (pipiwai) may sometimes be found in estuarine reaches of streams. The endemic hīhīwai was traditionally gathered as food by native Hawaiians, and was at one time collected for commercial sale. Today, it is still collected for food on a recreational level.

The species is uncommon in larger, gentle gradient rivers and is usually confined to the terminal riffles above estuaries in such streams (Maciolek 1978). Although 5,000 hīhīwai were transplanted to Oʻahu from Kauaʻi in 1938, hīhīwai is only occasionally found in small numbers in two or three windward Oʻahu streams. Ford (1979b) found that hīhīwai are limited to reaches with continuous flow in velocities greater than 13 cm/s. He found the greatest densities of adult hīhīwai in the terminal and lower reaches of shallow, well-oxygenated streams, and usually within the central portion of the stream channel.

At left, is a ventral view a large adult hīhīwai, Neritina granosa, illustrating its muscular foot and orange septum (photo by Dr. Richard Valdez). At right is a dorsal view of a large hīhīwai taken in situ (photo by John Ford).

They remain hidden against predation by native Black-crowned night herons and Wandering tattlers during the day, and emerge from under boulders at night to graze on diatoms and microalgae on the surface of silt-free boulders, rocks, and cobbles. Post-larval and juvenile hīhīwai have a strong rheotactic response and orient into currents during their recruitment from the oceanic larval pool. Like the amphidromous ʻoʻopu and ʻōpae, juvenile hīhīwai migrate upstream across all substrata at rates measured at 3.5cm/sec (Ford 1979b).

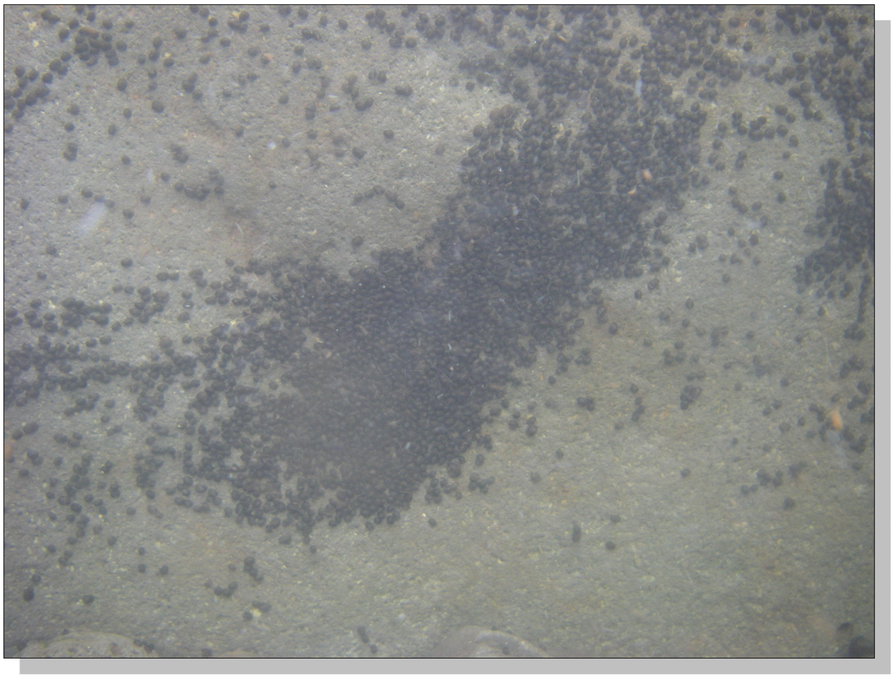
Small individuals may be commonly found on the vertical faces of waterfalls and cascades in the lower reaches of streams they inhabit. Ford (1979b) reported seeing ʻchains' of up to 80 juveniles in physical contact with one another migrating upstream. Their upstream migration may be driven in part by a search for suitable diatom and microalgal food sources that are also utilized by other native species. He also followed cohorts of post-larvae (spat) and juveniles as they moved upstream from the mouth of the stream.

Like other amphidromous species, the distribution of hīhīwai is influenced by the geomorphologic profile of individual streams. Hīhīwai densities tended to increase upstream reaching a maximum density in plunge pools at the base of waterfalls. The largest individuals were found in the lower reaches of study streams. Ford (1979b) did not find hīhīwai in waters deeper than 2 meters or in still water pools. Maciolek (1978) stated that hīhīwai occupy streams up to 400 meters in elevation; however, finding hīhīwai at this elevation is uncommon. In East Maui streams, hīhīwai may be expected to reach only 185 meters in elevation due primarily to the reduction of stream flows by irrigation ditches. Brasher (1997a) found similar results for hīhīwai in Waikolu Stream, Molokaʻi, which is also affected by a surface diversion. Except perhaps in freshets, hīhīwai are poorly represented in downstream drift (Barnes and Shiozawa 1985).

Studies of hīhīwai reproductive biology are limited. Eggs are fertilized internally and encapsulated, and egg capsules are deposited on rock surfaces as well as on the crenulated shells of hīhīwai themselves (Ford 1979b). Ford (1979b) found a mean number of 248 larvae in egg capsules he examined from two East Maui streams. While fresh eggs capsules were discovered year round, peak production in East Maui occurred between June and August and tapered off by late fall. On Molokai, Brasher (1997) observed peak breeding in the late fall, late spring, and summer. Veliger larvae may hatch within 30 days but apparently have the ability to delay hatching. Based upon cage experiments, Ford (1979b) hypothesized that females may possess annual fecundities between 4,740 and 10,140 larvae. Females do not die after spawning and appear to be iteroparous.

Veliger larvae are carried into the sea when they are between 150 – 175 micrometers (µm) in length and begin development as free-swimming zooplankton (Ford 1979b). Individual hīhīwai held experimentally in freshwater after hatching showed little or no movement until seawater was added (Ford 1979b). Mature protoconch lengths in hīhīwai were measured between 540 µm and 640 µm, and spat (recruits) visible to the naked eye were measured at 2 mm in shell length (Ford 1979b). Both Ford (1979b) and Brasher (1997a) observed significant recruitment events in May and November. Circumstantial data found a one to two month lag between the appearance of fresh egg capsules and recruits in study streams (Ford 1979b); however, this is insufficient evidence upon which the length of larval life (LLL) can be determined.

Kinzie and Ford (1982) examined four polymorphic loci in hīhīwai from East Maui streams and found that none deviated significantly from the Hardy-Weinberg equilibrium model, suggesting that populations from different locations may represent a single gene pool. Hodges (1992) studied population genetics of hīhīwai and determined that a significant portion of recruits in study streams originated as larvae from the same streams (e.g. they returned to the stream of their birth). However, sufficient larvae transport occurs within and among the islands to prevent genetic isolation of populations (Kinzie, personal communication).



Hundreds of juvenile hīhīwai were observed on cobbles and boulders in the terminal reach of Waikolu Stream, Molokaʻi, by SWCA biologists Robert Kinzie and John Ford in on September 30, 2008 (photo by John Ford).

Civil No. 19-1-0019-01 (JPC)

Defendant A&B/EMI’s Exhibit AB-126

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