Introduction

The *Atlas of Hawaiian Watersheds & Their Aquatic Resources* was created to provide an accounting of the information on watersheds, streams, and the animals that inhabit the streams available to the resource managers at the Division of Aquatic Resources (DAR). Management issues surrounding Hawaiian streams are numerous, and it is difficult to find appropriate balance between the varied uses of stream water, stream ecosystems, and stream animals. Water issues range widely: How much water should be left in the stream to protect the stream animals as compared to how much can be diverted for human use (instream flow quantity issues)? How much pollution can be naturally handled by the stream, and how much is too much (water quality issues)? What is critical habitat for the protection of Hawaiʻi's unique native stream animals (habitat quantity, quality, and animal population issues)? These are just a few of the issues facing resource managers that are trying to assure the continuation of the incomparably beautiful Hawaiian stream ecosystems and their unique animals.

As the world has moved from information stored on papers in file cabinets to digital information stored on computers, DAR and Bishop Museum have done the same. This *Atlas* represents a large milestone in conversion of Hawaiian stream information to a digital format. Information on a number of different types of stream surveys collected by state biologists back to 1960 has been included. We also asked for and received information and publications from the professional stream research community. We digitized and recorded the information from over 275 papers on Hawaiian streams. This information represents a vast field effort by researchers because a typical paper may take weeks, months, or even years to collect the data. Currently, over 90,000 animal observations are included this *Atlas,* with millions of pieces of information associated with those observations. While this is a huge amount of information, there is more information "out there", and we hope that seeing this *Atlas* will encourage people to send additional information to DAR to be included in the DAR Aquatic Surveys Database and made available to aid in the management of Hawaiian streams statewide.

The *Atlas of Hawaiian Watersheds & Their Aquatic Resources* and the database that stores the information presented in the *Atlas* are designed to be continually updated with new information. Thus, this *Atlas* is to be viewed as a "living document." As new information becomes available, a new version of the watershed information can be generated. We provided a date on the bottom of each page to show when the database was accessed to create the watershed description. In this version of the *Atlas*, all information contained in the database on April 8, 2008 is represented. New surveys, publications, and finds of old information continually happen, and we will strive to provide regular updates of the information presented in the *Atlas*.

Overall, there were several purposes for creating the *Atlas of Hawaiian Watersheds & Their Aquatic Resources.* These include:

- Provide a means to make stream data available to researchers, resource managers, educators, and the general public,
- Provide comparative information on what is known about each stream,
- Use as baseline information for the management of streams statewide,

- Provide a platform to link other data sources (e.g., terrestrial information) to aquatic resource data for "ahupua'a" management, and
- Create a continuously growing document that can be easily updated with new information.

Stream surveys and the DAR Freshwater Database

For more than five decades, the Division of Aquatic Resources (DAR) has surveyed streams, estuaries, lakes, ponds, reservoirs, ditches, and diversions throughout the Hawaiian Islands to provide critical information for monitoring, assessing, managing, and protecting freshwater resources. During the 1990's, the Hawaii Stream Assessment (HSA) was the first attempt to compile data on streams statewide, and, in subsequent years, HSA data and information from additional surveys and relevant biological studies have been combined into the large, growing database maintained by the Division of Aquatic Resources. The data are now retrievable in an almost invariable number of formats from the DAR Aquatic Surveys Database. The five volumes comprising the *Atlas of Hawaiian Watersheds & Their Aquatic Resources* are based on information in the database (http://hawaii.gov/dlnr/dar/streams_survey_data.html).

Watersheds and Ahupua'a

Individual watersheds are the organizational units for the volumes comprising the *Atlas*. As the name indicates, a watershed is a catch-basin or drainage basin for rain and condensate funneled into stream beds that either join other stream beds or terminate at the edge of the sea. Only a few years ago, the terms "ecosystem approach" and "watershed approach" were used interchangeably for broad-based studies of the animals living in island streams. More recently, the term "*ahupua'a*" or "*ahupua'a*-approach" is employed in the literature and in discussions describing broad-scale stream studies in Hawai'i. As used by the ancient Hawaiians, an *ahupua'a* includes the entire watershed and also tide pools and ponds, near-shore waters along the beach, and the sea out to and including the coral reef. An *ahupua'a* provided everything needed by way of food, clothing, and shelter for Hawaiians who, with all the other animals and plants in the *ahupua'a*, conformed to the classic definition of a functioning ecosystem. For stream-dwelling animals in Hawai'i, an *ahupua'a* approach is broader, more encompassing, and certainly more appropriate because all the fishes, mollusks, and crustaceans which make up the freshwater stream fauna have a life cycle that includes a period of time in the ocean.

Islands, Streams, and Stream-Dwelling Animals

Island origin and fate

The Hawaiian Islands are formed one-by-one as the ocean floor (Pacific Plate) moves slowly toward the northwest over a volcanic hot spot that extrudes molten lava above the surface of the sea. Over a period of about 28 million years, the result has been a string of islands stretching more than 1,600 miles from the Island of Hawai'i in the southeast to Midway and Kure atolls in the northwest (Figure 1).

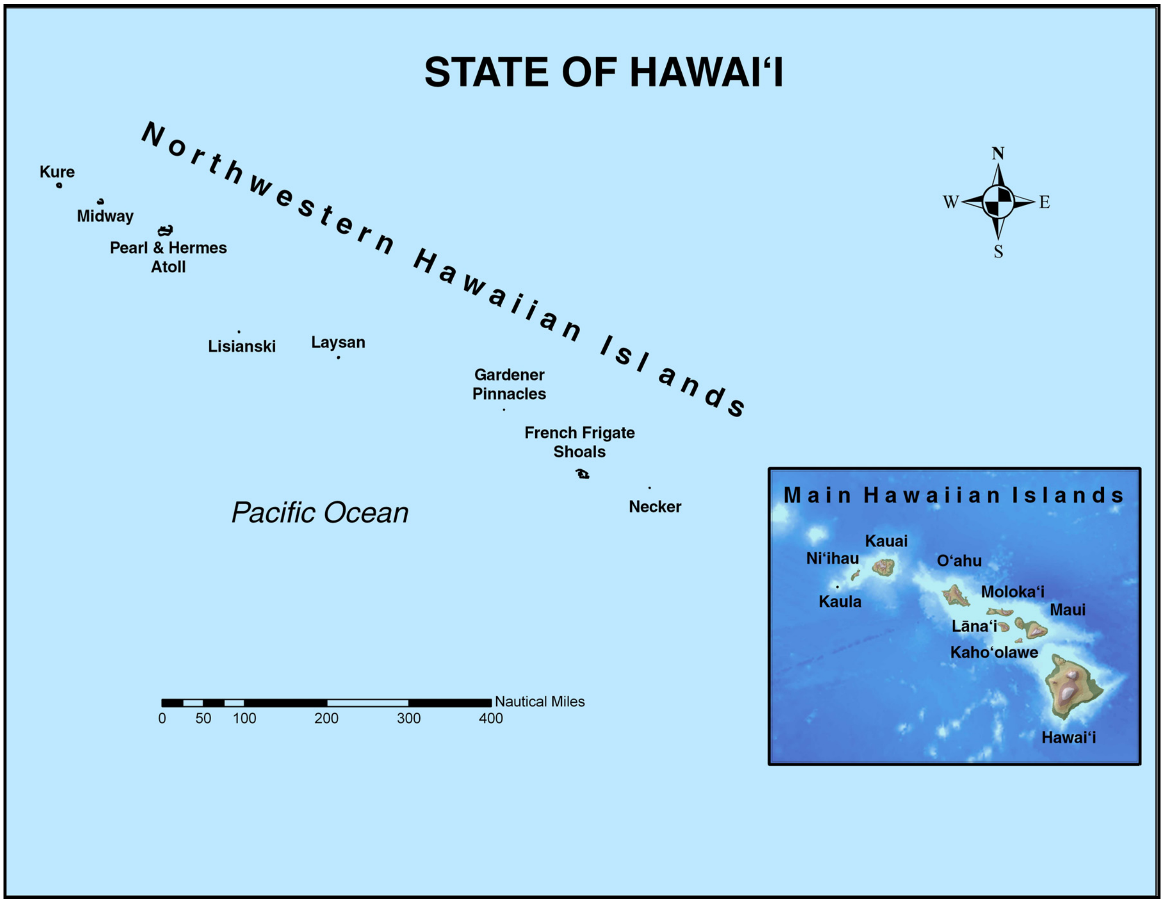


Figure 1. Map of the Hawaiian Islands. This *Atlas* is focused on the watersheds and streams of the Main Hawaiian Islands.

Similar linear patterns in the dispersal of islands and seamounts are evident among the Line Islands, the Tuamotus, the Marshall-Ellice Island Chain, and others to the west and south of the Hawaiian Archipelago. All these islands share a common destiny. Even before island-building volcanism ceases, erosion from wind, rain, and sea set each island on an inevitable course toward eventual submersion back below the ocean's surface. In the last stages of the degradation of an island, it may develop a fringe of coral which persists as a doughnut-shaped atoll after the land mass has finally worn down beneath the sea. This conveyor-belt model for the formation and extinction of volcanic islands is overly simplistic because of the variation that occurs in the history of individual islands. However, the trend is generally acknowledged, and it is well illustrated by the islands that form the Hawaiian chain. Coral atolls are predominant in the geologically older Northwestern Hawaiian Islands while volcanic high islands are the major features in the younger southeastern section. It is only these high islands at the bottom of the chain that have well-defined watersheds and perennial streams, the two subjects of paramount concern for the *Watershed Atlas*.

Island age and stream morphology

Differences in erosion among the high islands also correspond to the differences in their ages. Kaua‘i, the northernmost of the high islands, is about five million years older than the Big Island (Hawai‘i), and the disparity in their age is indicated by differences in the predominant profiles of their streams. As flowing water cuts down through the lava substrate, streambeds generally become less steep, and the streams have fewer large waterfalls and a greater development of estuaries – sites where fresh waters and the ocean mix. Eight stream types have been designated for Hawai‘i on the basis of size, shape, bay development, and slope (Figure 2).

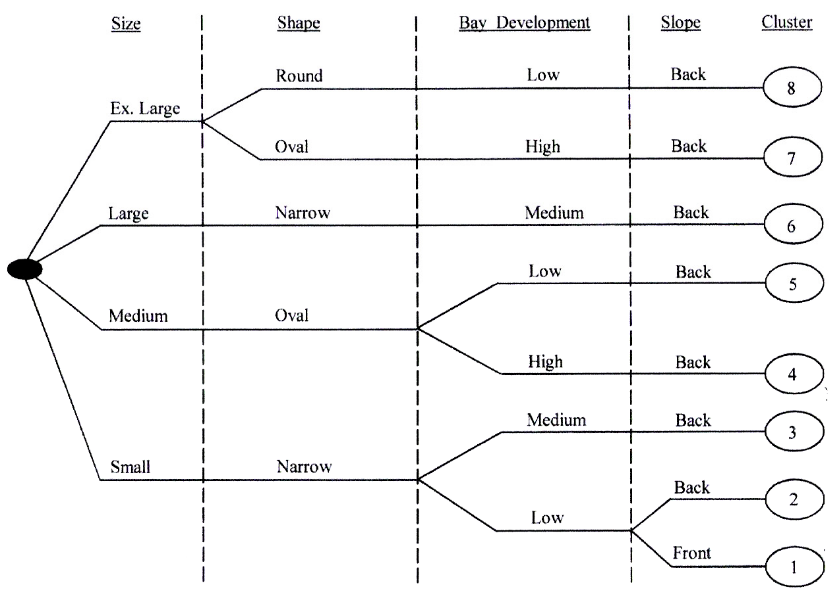


Figure 2. Diagrammatic key to the classification of Hawaiian streams from significant morphological features (from Parham, 2002)

Indigenous aquatic animals are remarkably species specific in the habitats they select as adults, and these habitats are distributed differently among stream types. Biological comparisons between different stream types must include an understanding of the relationship of stream morphology to the animals' behavior and ecology. If not, there is no way of knowing whether the absence of certain native species in a study stream is natural, *i.e.*, to be expected, or caused by human activity.

Difference in the overall stream type, locations of barriers within a stream, and habitats within a stream are important to the type and number of stream animals observed in a stream. Some of these differences are apparent when viewing the stream from different distances. For example, when flying in an airplane at the front of the watershed and looking upstream, the overall shape and location of large waterfalls is observed (Figure 3). When one hikes along a stream, different habitats become obvious (Figure 4).

Figure 3. Notice the difference in the location of the waterfalls. On the left, the waterfall in Waipio Valley, Hawai‘i is toward the back of the watershed, while on the right in Waikaumalo Stream, Hawai‘i the waterfall is located at the front of the stream. The presence or absence of a barrier changes the type of animals observed in the stream.

Figure 4. Notice the difference in stream habitats. On the left a small waterfall and plunge pool are two different habitats, while on the right the swift water of a stream riffle provides another different habitat. Different species may live in different habitats, and the availability of the habitats affects the number of species observed in a stream.

Orographic rain

Among the eight major islands that comprise the Southeastern Hawaiian Islands, five (Hawai‘i, Maui, Moloka‘i, O‘ahu, and Kaua‘i) project sufficiently far above the surface of the ocean (minimally two to four thousand feet) that their windward slopes are the sites where moisture carried by the trade winds, typically from the northeast, condenses to form orographic rain in response to the cooler temperatures at these elevations (Figure 5). Thus, the windward sides of islands are usually the wet sides of islands, and they are the locations with the greatest proliferation of perennial rainforest streams that support a unique assemblage of aquatic organisms remarkably well adapted for thriving in what may be one of the world's most rigorous and dynamic ecosystems.

Figure 5. Development of orographic rain on the windward side of the Big Island.

Droughts and floods

The mere rotation of the earth ensures the generation of trade winds that drive the islands' water cycle. However, although recurrent, the trades are by no means continuous. Climatic conditions, such as the approach of weather fronts from leeward, can alter the direction of the trade winds and even arrest their flow for an extended period of time lasting a day to several days or even weeks. Although infrequent, periods of drought on the usually wet sides of islands are not extraordinary. In contrast, lingering heavy rain in the upper part of a watershed as a result of local climatic conditions or the passage of a moderate to strong weather system often produces powerful flash floods (freshets) of a magnitude and frequency not seen in continental fresh waters (Figures 6 & 7). Indigenous stream animals, including fishes, mollusks, and crustaceans, have morphological and behavioral adaptations for maintaining position during slight to moderate flash floods, and they benefit from the periodic flushing of silt, leaf litter, and other debris from the stream. An especially severe flash flood carrying a large debris load is capable of pushing adult animals completely out of a stream (as happened with Hurricane Iniki in 1992) (Fitzsimons & Nishimoto, 1993), but members of these native aquatic species will automatically repopulate the stream as larvae or young postlarvae because of their amphidromous life cycles.

Figure 6. Photographs taken at 10:00 am each day from fixed position camera on the bridge over Hakalau Stream, Hawaiʻi over a period of 4 days. Notice the quick rise and fall of the stream discharge in response to rainfall.

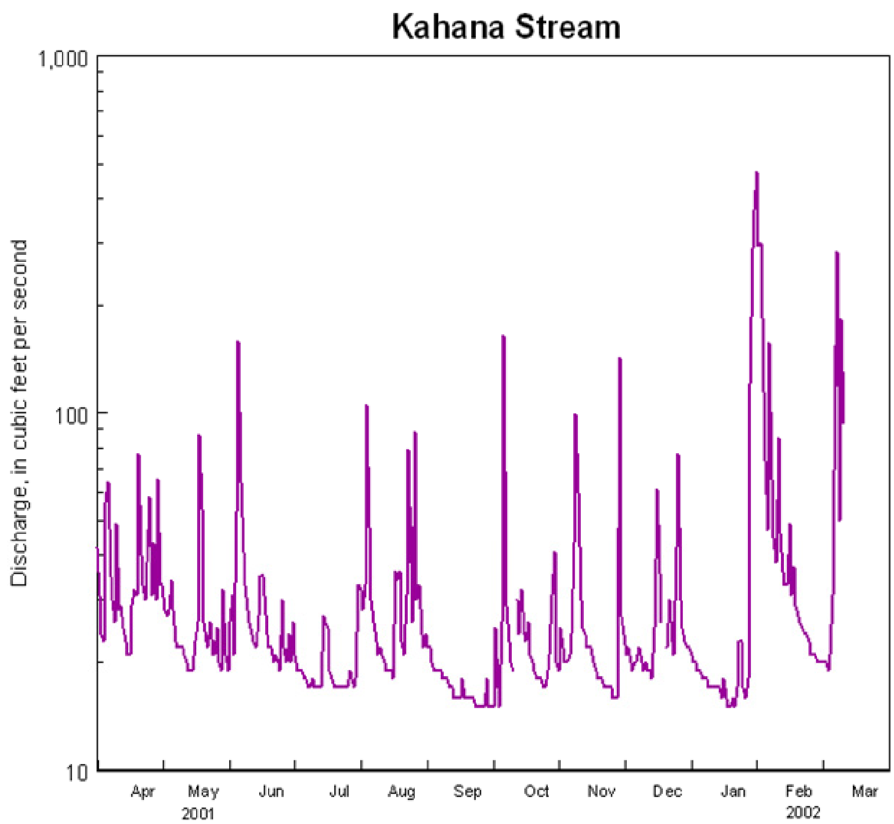


Figure 7. An example of the variation in stream discharge for Kahana Stream, O'ahu (data from USGS gage station). Notice the frequent spikes (freshets) in the flow and how quickly the flow returns to a lower discharge.

Amphidromous life cycles

Amphidromy is one kind of diadromy (meaning two migrations) in which newly hatched larvae (sometimes referred to as free-living embryos) are swept downstream into the ocean where they live for a period of time (as much as six months in one Hawaiian fish species) before migrating back into fresh water where they eventually mature, reproduce, and complete the life cycle (Figure 8). Amphidromy is a boon to stream restoration because, once a problem is corrected, the recruitment of native animals into the stream will occur naturally. No biologist is needed to restock formerly altered streams.

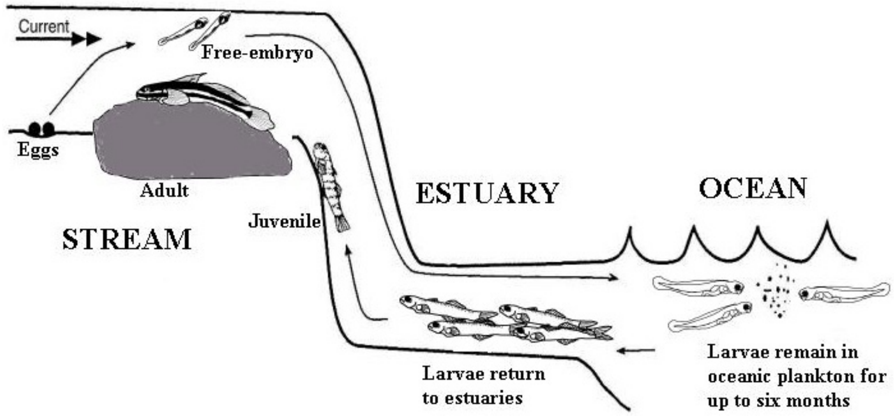


Figure 8. Amphidromous life cycle of indigenous stream animals.

Native species

The unparalleled remoteness and isolation of the Hawaiian high islands are accountable for the reduced number of species and high degree of endemism among the species of indigenous animals and plants that occur there naturally. This fact is well illustrated by the animals that live in island streams. The entire native vertebrate fauna and larger invertebrates (macroinvertebrates) of most Hawaiian streams includes only five species of fishes, two species of mollusks (limpets), and two species of crustaceans (prawn and shrimp). All but one species (fish) occur only in Hawaiʻi. Many marine species enter estuaries and the lower reaches of streams, but a total count of nine includes all native species limited to brackish and fresh water as adults.

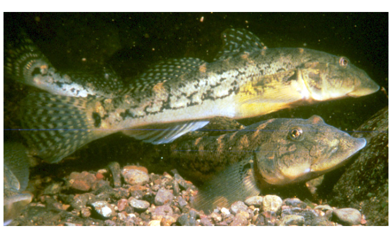
Hawaii's stream fishes belong to two families, the Gobiidae and Eleotridae, which are common throughout the islands of the Indo-Pacific in estuaries, streams, in near-shore habitats such as tidal pools and ponds, on sandy flats, and among coral reefs. Many species of eleotrids occur throughout the world in temperate and tropical seas and brackish lagoons and estuaries, and the gobiids, also widely distributed, comprise not only the largest family of fishes, but also the world's largest family of vertebrates. Gobioid fishes (eleotrids and gobies collectively) in Hawaiian streams have their nearest relatives in the Western Pacific Ocean. The ancestors of the Hawaiian stream fishes were very likely those stream species with a protracted period as marine larvae capable of being transported over the long distance from the Western Pacific to Hawaiʻi probably by Japan's Kuroshio Current. The origin and dispersal to Hawaiʻi by stream-dwelling macroinvertebrates may be similar to those of fishes, but interisland affinities and the marine phase of the life histories of the Hawaiian species of stream mollusks and crustaceans apparently have never been studied.

Stream fishes and macroinvertebrates are predictably distributed within and among streams. The eleotrid, *Eleotris sandwicensis* (ʻoʻopu ʻakupa) and goby *Stenogobius hawaiiensis* (ʻoʻopu naniha) are most common in estuaries and in the lower reaches of streams below the first waterfall of a meter or more. *Awaous guamensis* (ʻoʻopu nākea) and *Sicyopterus stimpsoni* (ʻoʻopu nōpili) occur in the middle reaches of streams, and *Lentipes concolor* (‘o‘opu hi‘ukole for males, ‘o‘opu ‘alamo‘o for females) usually occurs farther upstream beyond the instream range of the other fishes. The limpet *Neritina vespertina* (hapawai) is limited to the brackish water of estuaries, and the other limpet *N. granosa* (hīhīwai or wī) is most common in the lower and middle reaches of streams. The native prawn *Macrobrachium grandimanus* (‘ōpae ‘oeha‘a) occurs in estuaries and in areas of lower stream reaches where current is reduced. *Atyoida bisulcata* (‘ōpae kuahiwi) can occur anywhere along the length of a stream, but these small atyid shrimp are most dense in the upper reaches of streams. Streams that slope gradually from the headwaters to an estuary are likely to have all nine species of aquatic animals. High-gradient streams that have no estuary may have only the upstream species (*A. guamensis*, *S. stimpsoni*, *N. granosa*, *L. concolor*, and *A. bisulcata*). Those streams that end in a waterfall that drops about 10 meters (ca. 30 ft.) directly onto the beach probably will have *S. stimpsoni*, *L. concolor*, and *A. bisulcata*, while those that drop 20 meters or more onto a beach are likely to have only *L. concolor* and *A. bisulcata*. The effect of stream morphology on the presence/absence of stream species is sufficiently predictable that it is usually possible to know what species are present and where they are located in a stream merely by examining a detailed map with contour intervals.

Some Native Hawaiian Stream Animals

‘O’opu hi‘ukole
Lentipes concolor

‘O’opu nōpili
Sicyopterus stimpsoni



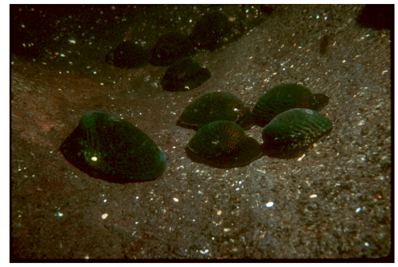
‘O’opu nākea
Awaous guamensis

‘O’opu naniha
Stenogobius hawaiiensis

‘O‘opu ‘akupa
Eleotris sandwicensis

‘Ōpae kala‘ole (kuahiwi)
Atyoida bisulcata

‘Ōpae ‘oeha‘a
Macrobrachium grandimanus



Hīhīwai
Neritina granosa

Hapawai
Neritina vespertina

Shore fly
Scatella oahuensis

Fragile Forktail damselfly
Ischnura posita

Hawaiian upland damselfly
Megalagrion hawaiiense

Alien species

Hawai‘i has the regrettable distinction of being the world’s most conspicuous example of what not to do in the introduction of non-native species. The long list of aliens includes plants and animals, both terrestrial and aquatic, and, among the latter, both marine and freshwater. Some introduced species have not proliferated, and a few appear to be harmless. However, many have become invasive and have exerted hugely negative effects on the islands’ flora and fauna. Freshwater streams and estuaries have been especially severely affected. Entire lakes, streams, and estuaries have become choked with non-native vegetation to the point that native plants are crowded out, egg-laying sites for stream fishes and invertebrates are buried beneath vegetation, mud, and silt, and the water no longer has sufficient dissolved oxygen to support aquatic animals.

Alien freshwater fish species now outnumber native stream species 44 to 5, and the number of introduced species is likely to increase in spite of efforts to protect native species. Several years ago, a single non-native fish family (the Poeciliidae, including introduced mollies, swordtails, and mosquitofish) was identified as the source of internal parasites (roundworms and tapeworms) well documented to be pathogenic in indigenous stream fishes on all islands (Font, 2007). In many streams where the parasites are established, removing every non-native fish would have little effect because the life cycle of the worms now can be sustained by the natural residents alone. The only workable half-remedy appears to be maintaining strong flow in streams and allowing freshets to flush them out periodically. Non-native fishes and invertebrates are much less capable of keeping position in a strongly flowing stream and are less able to withstand the scouring effect of a flash flood. Although all aliens may not be eliminated by stronger flow and more effective flash floods, perhaps a reduction in their numbers will have a beneficial effect.

Some Introduced Freshwater Animals

Smallmouth Bass
Micropterus dolomieui

Banded Jewel Cichlid
Hemichromis elongatus

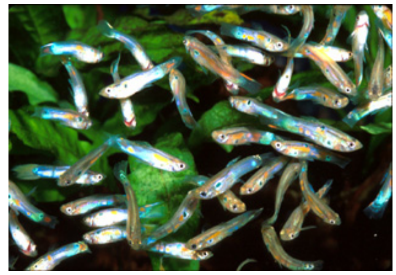
Bristlenose/bearded Catfish
Ancistrus c.f. temmincki

Suckermouth Catfish
Hypostomus c.f.

Green Swordtail
Xiphophorus helleri

Liberty/Mexican Molly
Poecilia sp. Hybrid complex

Mosquito fish
Gambusia affinis



Guppy
Poecilia reticulata

Tahitian Prawn

Macrobrachium lar

Blackchin Tilapia
Sarotherodon melanotheron

Asiatic freshwater clam
Corbicula fluminea

Crayfish

Procambarus clarkii

Wrinkled Frog
Rana rugosa

Apple snail
Pomacea spp.

Wattle-necked Softshell Turtle
Palae steindachneri

Wrinkled Frog Tadpole
Rana rugosa

Diving Beetle
Rhanttus gutticollis

Chinese Dragonfly
Crocothemis servilia

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http://hawaii.gov/dlnr/dar/streams.html

http://hawaii.gov/dlnr/dar/streams_bibliography.html

http://hawaii.gov/dlnr/dar/streams_survey_data.html

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