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Significance of Unimpeded Flows in Limiting the Transmission of Parasites from Exotics to Hawaiian Stream Fishes[1]

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Abstract—Streams with a full complement of native amphidromous fishes and macroinvertebrates are common features on windward slopes of four of the five major high islands comprising the southeastern section of the Hawaiian Archipelago. Strong perennial flows and flash floods produced by mountain storms flush away accumulations of debris and sediments, terminate algal blooms, and open up streams where they flow into the sea. Each of these effects is beneficial for the five indigenous fish species, limited to gobioids, which lay their eggs in fresh water and have a lengthy marine larval phase before migrating back into streams where they mature. A fortuitous advantage of the dynamic nature of Hawaiian streams is the elimination or control of introduced fishes (especially poeciliids) carrying helminth parasites capable of becoming pathogenic in native fishes. Results of experiments with artificial streams support the hypothesis that Hawaiian freshwater gobioid fishes are able to move from the ocean into streams as larvae and can occupy discrete sections of streams as adults at water velocities that displace exotics. A basal flow of 20 cm/second or greater at the stream mouth is recommended for stream maintenance and restoration.

The unequaled isolation of the volcanic high islands in the southeastern reach of the Hawaiian Chain has resulted in a depauparate freshwater fish fauna with a high degree of endemism (Devick et al. 1992). A mere five species, all but one limited to Hawai‘i, represent two closely related families (Gobiidae and Eleotridae) that occur in freshwater streams on oceanic islands throughout the tropics. A major if not exclusive source of fresh water for these islands is the orographic rain provided year round by tradewinds lifting moisture from the sea and depositing it as rain on mountain slopes. In Hawai‘i, freshwater fishes and the five species of

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[1]ASIH symposium on freshwater gobies

stream-dwelling macroinvertebrates (three crustaceans, and two molluscs) are amphidromous (Ford & Kinzie 1982). Adult stages and their reproductive activities are confined to fresh water, but, during their life cycles, there are two migrations between streams and the sea. One occurs shortly after hatching when the animals are swept downstream into the ocean, and the other when postlarvae leave the ocean by migrating back into the mouths of coastal streams. This type of life cycle is similar to other forms of diadromy (anadromy and catadromy) in the occurrence of two migrations between fresh and salt water, but amphidromy is distinct from either in that there is no reproductive event immediately following either leg of migration (McDowall 1988). The ultimate success of amphidromous life cycles in assuring the production of offspring and restocking streams with young animals is heavily dependent on maintaining the "mauka-makai connection," i.e., the mountain-ocean corridor that allows movement between the two distinct environments (Devick et al. in press).

There is difficulty in applying the concept of stability to stream ecosystems in Hawai'i (Fitzsimons & Nishimoto in press). Periodic flash floods, generated by severe weather systems passing through the islands or by localized orographic rainfall of only an inch or two in a few hours, often overrun a stream's banks, rearrange its bottom, and carry loose materials out to sea. When the rains stop, water level drops, and, within as few as two or three days, the stream again runs clear. Flash floods are most common during the Hawaiian rainy season usually from February through April, but these events are sufficiently frequent throughout the year that streams on the windward coasts of the major Hawaiian islands are in a constant state of recovery from the most recent flood. However, ongoing studies are demonstrating that indigenous stream animals are not only well adapted to these dynamic conditions but are even dependent upon them. Flash floods prevent accumulations of fine silt and larger debris that would smother or dislodge eggs of aquatic animals. These floods keep streambeds in early stages of ecologic succession in which colonizing species of algae important as food for stream fishes (Kido 1996) remain predominant. Freshets also keep the mouths of streams open and greatly facilitate the transit of animals from or into the ocean. Investigations by R. J. F. Smith (University of Saskatchewan) and colleagues are examining the likelihood that flash floods send physical or chemical signals into nearshore waters that prompt larvae to orient toward land and move into streams. Finally, the study described in this report supports an hypothesis that strong flows and periodic freshets are important in removing or controlling exotic fishes known to convey parasites to Hawaiian stream fishes (Font & Tate 1994).

Materials and Methods

Native fishes for experimental work were collected with dip nets while snorkeling in Hakalau Stream about 15 km north of Hilo, with small seines and hook-and-line in the Wailoa River in Hilo, and with wire minnow traps in Lokoaka Pond in Keaukaha, Hilo. Introduced fishes were taken by seines and dipnets along the margins of Hakalau Stream and Wailoa River and from brackish ponds in

Lili'uokalani Park near Hilo Bay. After being tested in experimental streams at the Wailoa Fishery Station of the Hawai'i Division of Aquatic Resources in Hilo, Hawaiian fishes were returned in good condition to the exact site where they were obtained; non-native fishes were preserved in 10 percent formaldehyde and later transported to the Louisiana State University Museum of Natural Science for cataloguing into the permanent collection of fishes. Test fishes occurring naturally in streams included gobies *Lentipes concolor* (*'o'opu hi'ukole* for males and *'o'opu alamo'o* for females), 30 fish ranging from 36 to 82 mm total length; *Sicyopterus stimpsoni ('o'opu nōpili)* 30:26–91, *Awaous guamensis ('o'opu nākea)* 46:19–132, *Stenogobius hawaiiensis ('o'opu naniha)* 36:31–114, the eleotrid *Eleotris sandwicensis ('o'opu 'akupa)* 42:60–237, *Mugil cephalus* (mullet, *'awa'awa,* and *pua*) 30:21–356, and *Kuhlia sandvicensis* (*aholehole* or Hawaiian flagtail) 30:22–141. Non-native test fishes were limited to livebearers implicated as the source of parasites affecting native fishes; these exotics included *Poecilia reticulata* (guppy or rainbow fish) 30:28–48, *P. mexicana* (shortfin molly) 30:19–45, *P. latipinna* (sailfin molly) 30:11–48, *Gambusia affinis* (mosquitofish) 30:29–41, *Xiphophorus helleri* (swordtail) 30:31–91, and *X. maculatus* (platy) 30:19–41.

The ability of fishes to "hold station" in flowing water by swimming or attaching to the bottom was measured in two artificial streams. Animals larger than about 100 mm TL were tested in a 1.3-cm high-density polyethylene raceway (1.2 m length, 30.5 cm width and height) suspended in a circular tank (2.4 m diameter, 1.1 m depth) designed and constructed specifically for the study by Pacific Lining Systems, Kailua-Kona, Hawai'i. Water movement was provided by a Minn Kota Model 112 Turbo Pro trolling motor and 12-volt deep-cycle marine battery. Smaller fishes were tested in a rectangular stream formed from ordinary PVC guttering used in home building (13.8 cm width and depth, in four sections 1 and 2 m in length). Flow was created by siphoning water from a tank (3.7 m diam., 1.2 m depth) containing dechlorinated tap water or water from the Wailoa River adjacent to the fishery station. In the larger test stream, a single fish was placed in the test chamber, and water velocity was increased gradually until the fish was no longer able to maintain position and then reduced slightly until the animal was able to move away from the grid blocking the downstream end of the chamber. In the smaller stream, a fish was introduced into the lower end of the flow gradient and allowed to move forward to a position where it remained stationary for a minimum of three minutes. Water velocity was measured by placing the sensor of a Marsh McBirney Model 201D Portable Water Current Meter (accuracy: ± 2% of reading) at the precise forward location of the test fish. Analysis of variance in station-holding ability was used to detect statistically significant differences among test fishes (SAS 1996: General Linear Models Procedure; Duncan's Multiple Range Test; Fisher's LSD). For each species, linear regression was conducted to determine whether station holding was correlated with body length. Smooth river stones, about 110–150 mm each in length, width, and height, were placed in the smaller test stream to investigate the tendency of fishes to use rocks as current refugia or attachment sites. In keeping with local tradition, the stones were returned promptly to the collection site in streams after use.

Results and Discussion

The three most common and most most damaging parasites in native stream fishes have been introduced into the Hawaiian Islands by man (Font & Fitzsimons, in press, Font & Tate 1994). The origin of the leech, *Myzobdella lugubris*, is uncertain, but it is possible that they were transported into Hawai'i in shipments of fishes or crabs. The other two parasites, a nematode *Camallanus cotti* and the Asian tapeworm *Bothriocephalus acheilognathi,* probably were introduced when livebearing fishes of the family Poeciliidae (mosquitofish, swordtails, platys, guppies, and mollies) were brought to the islands for mosquito control and the aquarium trade. The occurrence of these endoparasites in Hawaiian stream fishes coincides with the presence of infected poeciliid fishes in the same streams; in high-gradient streams without exotics, indigenous fishes lack these parasites.

Freshwater copepods are intermediate hosts for both species of introduced endoparasites. In Hawai'i and in their natural distribution in the New World tropics and in subtropical North America, poeciliid fishes live in slack-water habitats favorable for copepods. Thus, reduced flows in Hawaiian streams enhance populations both of the livebearers and copepods and increase the likelihood that the infected invertebrates will be eaten by the fish final hosts, whether exotic or native.

Against this background, the present study proceeded from the assumption that continuous strong stream flow and occasional freshets may provide a natural mechanism for eliminating or at least reducing the number of these exotic fishes and thus prevent or slow the spread of potentially pathogenic parasites to native stream fishes.

BEHAVIOR OF FISHES

Without exception, the species of fishes occurring naturally in Hawaiian streams were capable of retaining a position in test streams at flow rates exceeding those of the non-native poeciliids (Fig. 1). *Lentipes concolor* were significantly more adept at withstanding strong currents than any of the other test species. *Sicyopterus stimpsoni* followed as second in station holding. *Awaous guamensis*, although less capable than the two above species, was clearly separable in performance from other native or introduced fishes in Hawaiian streams. According to the statistical comparison employed, *K. sandvicensis* were either distinctive (Duncan Grouping) or allied in station-holding behavior with the goby *S. hawaiiensis* (Fisher's LSD), which, in turn, were significantly different from other fishes (LSD) or grouped with mullet *M. cephalus* (Duncan Grouping). The eleotrid *E. sandwicensis* and all seven species of poeciliid fishes were assignable to a single group on the basis of their station-holding abilities.

Larger live bearers occasionally exhibited bursts of rapid swimming into currents with a flow well above 20 cm/second, but these continuously swimming animals dropped back into positions well below this flow rate usually in less than one minute. Although the poeciliids ranged from juveniles a few days old (*Poecilia latipinna*, 11 mm total length) to large adults (*Xiphophorus helleri*, 91 mm), the range of response exhibited by these livebearers during station holding was unex-

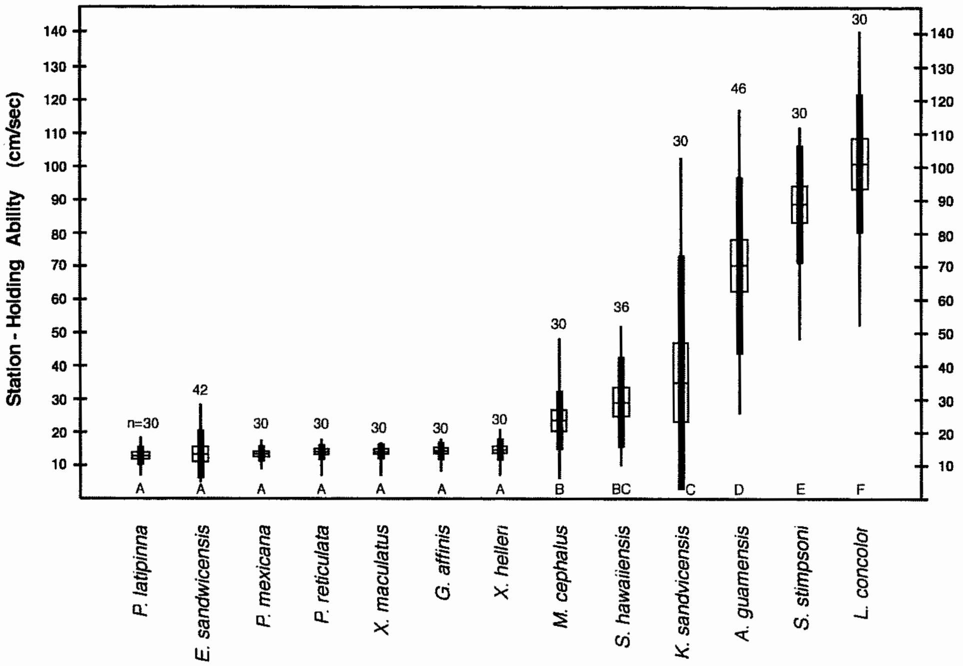

Figure 1. Station holding in Hawaiian stream fishes and introduced poeciliid fishes.

pectedly narrow. Flow measurements at collection sites were consistent with the experimental results of station holding for native and non-native fishes in artificial streams. Newly recruited larvae of *A. guamensis* and recently transformed post-larvae of *S. stimpsoni* exhibited sustained swimming speeds in test streams (58–111 and 73–109 cm/second respectively) that would have allowed them to negotiate the current in midstream at the mouth of Hakalau Stream (35–66 cm/sec) during migration into fresh water on the date they were collected immediately inland from the stream mouth. Although adult stream fishes sometimes occurred in areas of the stream with reduced flows, as was typical for *E. sandwicensis* and *S. hawaiiensis* (see below), access to the sites where they were collected would have required these fishes, as larvae or adults, to move against currents exceeding those which displace poeciliids. Poeciliids occurred in water with no measurable current except for swordtails in a spring-fed stream adjacent to Hakalau Stream where flow was 2–6 cm/sec.

Differences in station-holding abilities among native fishes in test streams reflected their usual distribution in high-gradient streams (Fitzsimons & Nishimoto 1991). *Eleotris sandwicensis*, *M. cephalus*, *K. sandvicensis*, and *S. hawaiiensis* typically penetrate no farther upstream than the first waterfall of one or two meters height, while the upstream gobies, *A. guamensis*, *S. stimpsoni*, and *L. concolor*, are noted for their occurrence well inland above falls exceeding 20 m. The eleotrid lacks the fused pelvic fins which enable its near-relatives the gobies to attach to rocks. Although a marine species, *M. cephalus* of all sizes occur in the lower reaches of streams and can be locally abundant in estuaries and in large ponds with access to the ocean. *Kuhlia sandvicensis* occur as adults on the offshore reefs, but the young of this species are present in the lower reaches of most Hawaiian streams. Small *Kuhlia* and mullet, to about 25–30 mm TL, frequently school together in the main channel and in streamside pools in lower reaches of streams. Although they are "true gobies" with a sucking disk formed by the fusion of pelvic fins along the ventral midline, *S. hawaiiensis* are much less adept at hanging onto smooth surfaces than the other three stream gobies. The elongate, weakly muscled disk is functional in the elaborate courtship displays of males (Fitzsimons & Nishimoto 1991) and is better suited for anchoring the fish in the loose sand and gravel common in lower stream reaches (J. Parham, pers. comm.). Studies by Tate et al. (1992) indicate that the behavior of newly recruited *A. guamensis*, *S. stimpsoni*, and *L. concolor* accounts for the instream distribution of adults. Small fishes of all three species have been collected on numerous occasions from the vertical surfaces of waterfalls. Adult *S. stimpsoni* and *L. concolor* have been observed on a few occasions to climb vertically on rocks covered with a thin layer of flowing water, and all three upstream species are competent at gripping rocks in strong flows along the bottom of streams. *Awaous guamensis* usually occur on the bottom in the middle reaches of streams. *Sicyopterus stimpsoni* occupy similar sections of streams, but are most abundant in shallower, swifter riffles; unlike the other stream gobies in Hawai'i, *S. stimpsoni* also uses the mouth for climbing and hanging onto large rocks and boulders. *Lentipes concolor* are locally famous for their remarkable climbing ability (Nishimoto & Fitzsimons 1986); they typically move much farther inland than other stream fishes and can climb waterfalls with a sheer drop of over 120 m. *Lentipes concolor* are likely to be the only fish species present at elevations above 500 m.

Three species (*Eleotris sandwicensis*, *Xiphophorus helleri*, and *Kuhlia sandwicensis*) exhibited a negative correlation ($p < 0.05$) between station-holding ability and body size (total length). The larger the fish, the slower the current in which it was able to maintain position. However, the results for *K. sandvicensis* indicate very different responses from the two disparate size groups of test fish (Fig. 2). Smaller *Kuhlia* exhibited swimming speeds at flow rates rivaling those during station holding by *L. concolor*, but the group of larger fish were comparable to poeciliids.

In tests of fishes with station-holding abilities limited to currents near or below 20 cm/second, *Eleotris sandwicensis* was the species most adept at using river stones in maintaining position at current velocities where they were pushed downstream over the smooth bottom of the test streams. In six 10-minute trials with six rocks evenly distributed throughout the length of the artificial steam, only one of five fish did not wedge itself against the upstream edge of a rock or swing around into the lee. When rocks were placed in two clumps of three or a single pile of six stones, all 30 test fish (five fish in six tests) showed a strong response in their orientation to the rocks. In the same tests, less than one-fourth of the livebearers *P. reticulata* and *X. helleri* used current refugia provided by individual stones, but

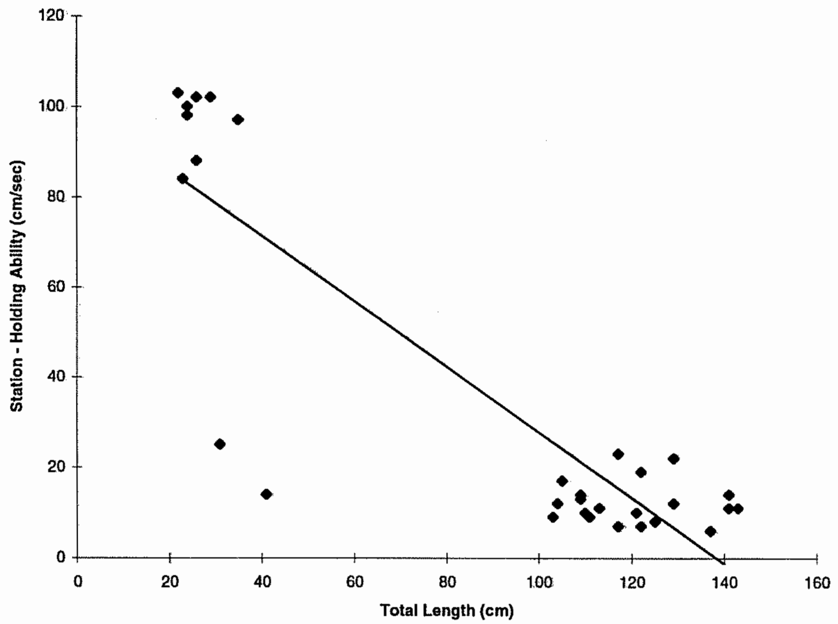

Figure 2. Relationship between size and station-holding ability in *Kuhlia sandvicensis*.

all fish eventually accumulated in the lee of the single large clump. The mollies (*P. latipinna* and P. *mexicana*), platys (*X. maculatus*), and mosquitofish (*Gambusia affinis*) seldom placed themselves in the lee of individual stones, and less than half accumulated in the slack water immediately downstream from piles of rocks.

IMPLICATIONS OF THE STUDY

Native stream gobies and those marine species that enter the lower reaches of Hawaiian streams are able to negotiate currents at velocities that displace poeciliid fishes known to carry endoparasites that infect indigenous species. The eleotrid has a station-holding ability over slick-bottomed test streams that groups them with poeciliids. However, the positive thigmotactic behavior of these heavy-bodied benthic fish allows them, like the gobies, to maintain a position in streams at velocities that wash away the exotics.

The data presented here suggest that a stream with a base flow of 20 cm/second or greater will be ideal for native fishes and will eliminate or at least suppress non-native poeciliids and the copepod intermediate hosts carrying helminth parasites. Even in water courses where poeciliids persist in low-flow areas along stream margins, a brisk flow in the main channel will lessen the likelihood of contact between exotics and indigenous fishes and will reduce the likelihood of native fishes ingesting infected copepods. In such streams also, introduced fishes will be subject to culling by periodic flash floods. Without question, the first step in stream restoration is the return of water (Devick et al. in press). From this study, we recommend that the target velocity be no less than 20 cm/second at the mouth.

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