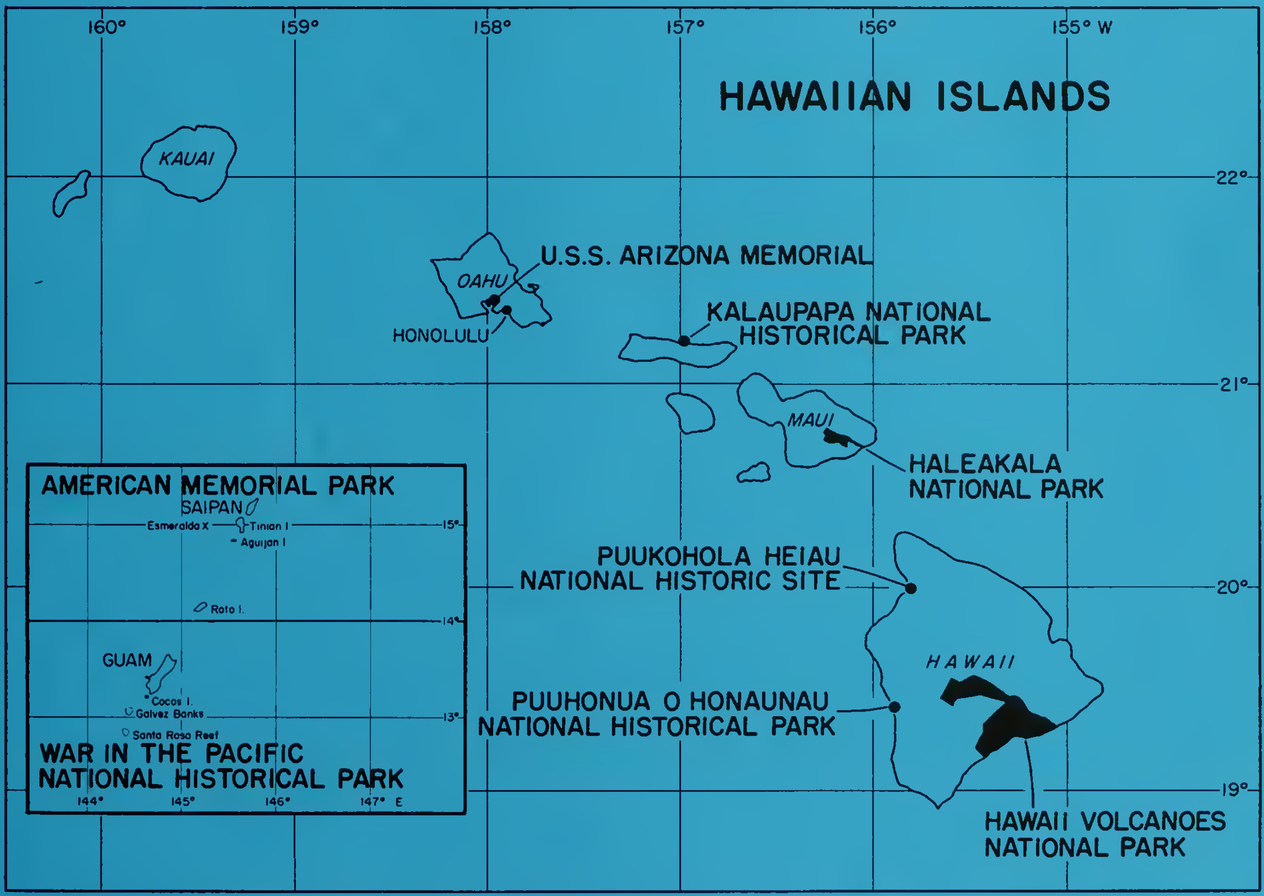
COOPERATIVE NATIONAL PARK RESOURCES STUDIES UNIT
Hawaii

Technical Report 114
Life History Characteristics of the Native Hawaiian Stream Snail
<u>Neritina granosa</u> (hihiwai)

Anne M. Brasher



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ABSTRACT

Amphidromous neritid snails are an important component of island stream ecosystems in the tropics. In Hawai`i, where *Neritina granosa* requires relatively pristine conditions, stream alteration and water diversion are a major threat. During a two-year monitoring study conducted in Waikolu Stream on the Island of Moloka`i, the number of *N. granosa* found at each station showed wide variation. However, the mean number of snails was consistent between seasons and during the two years. Substantially fewer *N. granosa* were found in and above areas of stream diversion. Peaks in reproduction (egg capsule production) occurred in the fall and summer. Recruitment (return of post-larvae from the ocean to the stream) was highest in the spring with a second, smaller peak in the late fall. Consistent with their amphidromous lifecycle, tagging studies showed smaller, younger snails migrate upstream while the majority of adults (snails > 14 mm) stay within 20 m of their original release site. Dewatered sections not only reduce habitat for *N. granosa* but inhibit downstream dispersal of larvae and upstream migration of post-larvae.

INTRODUCTION

Neritid snails form an important component of the stream macrofauna in Hawai'i, yet relatively little is known about them. Vermeij (1969) and Maciolek (1978) discuss shell characteristics and general habitat requirements. Ford (1979) provides a comprehensive description of basic biology and Hodges (1992) analyzes population biology and genetics. All conclude that the snails are relatively rare and have habitat requirements typical of high quality streams, making them vulnerable to habitat destruction including diversions, channelization, and dewaterment.

Hihiwai (Neritina granosa) is a limpet-like snail that typically hides under boulders and in crevices during the day, coming out at night to forage and mate. They tend to be found in lower to mid-stream reaches and are frequently collected by humans for consumption, although a ban on commercial sale went into effect in 1993.

A two year monitoring study was initiated to determine distribution and abundance of hihiwai in Waikolu Stream on the Island of Moloka'i. Life history characteristics including reproduction, recruitment, growth, and movement were examined using population surveys and tagging studies. The information acquired provides a basis for management and baseline data for evaluating results of future monitoring of Waikolu Stream, especially considering planned modifications to the flow regime, and the establishment of methodology to allow for between-stream comparisons throughout Hawai'i.

Life cycle of hihiwai

Hihiwai have an amphidromous life cycle (McDowall 1988). Egg capsules are laid in the stream, on boulders or the shells of other snails. Each egg contains approximately 250 larvae (Ford 1979). After the egg capsules hatch, the larvae wash out to the sea. The planktonic larvae spend an undetermined amount of time in the ocean and then return to a stream where they spend the remainder of their life cycle (Figure 1). Spates (high flood events) have been hypothesized as a cue for both reproduction and recruitment back to the stream (Kinzie 1988).

Habitat requirements

Hihiwai require cool, clear, fast flowing and well-oxygenated water and tend to be found only in undisturbed streams (Ford 1979). Hihiwai are uncommon in, or absent from, modified, degraded, and streams easily accessible by humans (Maciolek 1978). Relatively few streams in Hawai'i contain substantial populations of hihiwai, with the East Moloka'i streams including Waikolu Stream being notable for their abundance of hihiwai (Hawai'i Stream Assessment1990). Because they are relatively uncommon and require habitats typical of high quality streams (Ford 1979; Hathaway 1978; Hodges 1992; Maciolek 1978), hihiwai may serve well as an indicator species of habitat and water quality.

Waikolu Stream

Waikolu Valley lies on Moloka'i's rugged north shore (Figure 2) within the Kalaupapa National Historical Park. Waikolu Valley (156°W, 21°N) is approximately 6.4 km (4 mi) long and the headwaters arise from mountain bogs just above an elevation of 1,219 m (4,000 ft). The upper valley is narrow with steep walls and widens to 1.6 km (1 mi) at the mouth of the valley. Total perennial tributary length is 14.32 km (8.9 mi) and drains an area of 11.9 km^2.

Average annual rainfall in Waikolu Valley is 120 inches per year, with 65% of the annual total occurring during the wet season (November to April) and 35% during the dry season (May to October). Average mean daily discharge in Waikolu Stream from 1960 to 1994 was 18 cfs, and ranged from 6.1 cfs (24 October 1993) to 628 cfs (21 November 1992) during this study (U. S. Geological Survey 1994). Mean daily discharge during this study was 13.7 cfs in 1992, 17 cfs in 1993 and 17.8 cfs in 1994 (water years).

An extensive water collection system exists in upper Waikolu Stream. Water diversion through the 8.2 km (5.1 mi) Waikolu Tunnel began in November 1962. Three surface water diversion structures at approximately 304 m (1,000 ft) elevation include two that collect water from tributaries to Waikolu stream and one on the main stream (referred to here as the "upper dam"). There is also a surface water diversion structure (referred to here as the "lower dam") at 223 m (730 ft) where water is collected and pumped back up to the tunnel. There are three established wells (two in the valley and one in the tunnel) and three new wells, drilled in 1988, in the floor of Waikolu Valley. An annual average of 4.5 cfs is transported through the Waikolu tunnel for agricultural use on the other side of the island (U. S. Geological Survey, 1992-1994).

Since the diversions started, the intermediate reaches of Waikolu Stream carry only 50% of natural undiverted flow conditions, while in the lower reaches the percentage increases to 70%, due to the intermediate surface runoff and groundwater accretion (Diaz, in prep.). These estimated percentages have dramatic seasonal variations; while the difference in flow volume as an average for the rainy period is 10%, during the dry season that difference reaches 22% (Figure 3). The month of August is the most critical period in terms of water withdrawals from the stream, because flows are naturally low during this time (Walsh et al. 1992).

METHODS

Reproduction, recruitment (return of hihiwai from the sea to the stream), and longitudinal distribution and density were recorded during bi-monthly surveys at permanent monitoring stations established from the mouth to the headwaters. Growth and movement were determined during two tagging studies. During the first study 762 snails (mean size 21 mm shell length) were tagged and then searches for recapture conducted four times over a period of slightly more than one year. During the second study 789 more snails (11 to 13 mm shell length) were tagged and released. Searches were conducted in a recapture attempt four times over a period of nine months.

Monitoring Stations

Permanent monitoring stations were established at twenty-seven randomly chosen locations from the mouth to the headwaters of Waikolu Stream (Figure 4). Using a sampling area at each station of one hundred square meters, ten quarter meter square quadrats were randomly selected using a Cartesian coordinate system (Appendix A). Monitoring stations were simultaneously established for Waikolu Stream and Oheo Gulch, Kipahulu District of Haleakala National Park, as part of a plan to establish permanent monitoring protocol for the National Park Streams (see Hodges 1994 for details of the Oheo Gulch studies). These stations were monitored in Waikolu Stream every other month over a two-year period (1992-1994).

Survey Techniques

To count the snails each observer paced off the meters to the appropriate quadrat location based on the coordinate system, and placed a thin wire quadrat plot frame on the streambed. Wearing a facemask, the observer collected all snails visible within the quadrat and measured them using calipers. All loose gravel, cobble, and rocks were then removed until bedrock was reached and additional snails within the quadrat were collected and measured. Shell lengths were measured as the greatest distance between the apex (origin of whorl) and the anterior margin (Ford 1979; Hodges 1992; Schneider and Lyons 1993). Snails were returned to the stream after being measured. The number of newly recruited snails ($\leq$ 5 mm) within each quadrat was also recorded. After each quadrat was counted, unhatched egg cases were counted in an adjacent undisturbed 156 cm^2 quadrat (one quarter of the plot frame).

Tagging methodology (Study 1)

The first tagging study was done in January 1993 using individually numbered tags from Floy Tag & Manufacturing, Seattle, Washington. These tags allowed us to follow the growth and movement of individual snails. Hihiwai (16 to 33 mm shell length, mean size 21 $\pm$ 2.43 mm) were collected, their shells blotted dry and the tags attached using super glue. Each tagged snail also received a blue mark using colored road chalk and super glue, to allow us to determine tag retention. Tags were allowed to dry for 20 minutes and snails were then returned to the stream. A total of 762 snails were tagged; 254 at Station 220, 258 at Station 420, and 250 at Station 940 (Figure 5).

Tagged snails were recaptured after 2,4, 9 and 14 months. Retrieval was conducted at night when most snails had left the crevices between boulders and were crawling about feeding and mating. Retrieval was typically conducted on three consecutive nights (one for each station) and lasted approximately 4 hours (3 to 6 hours range). The final retrieval was conducted on five nights over a two-month period because of frequent flooding making stream access impossible.

To collect tagged snails, two observers moved side by side along the stream channel using handheld flashlights and headlamps to illuminate the stream. When a tagged snail was found, it was measured and its location (relative to release) recorded by two assistants on the stream bank. Snails were carefully wedged under boulders when they were returned to the stream to prevent them from being swept away by the current and/or captured by the introduced prawn Macrobrachium lar. The search for tagged snails was conducted from 100 m downstream to 100 m upstream of the original release site, with observers moving systematically upstream.

Tagging methodology (Study 2)

The second tagging study began in September 1994 using color-coded tags from Hallprint Tags, Australia. These tags were smaller and flatter than the Floy Tags, allowing us to tag much smaller snails than in the first study. Snails were collected, measured with calipers, and sorted into size classes of 11, 12 and 13 mm. All 11 mm snails received red tags, 12 mm snails received blue tags, and 13 mm snails received yellow tags. While we were not able to follow individual snails using Hallprint tags, Hallprint tags were more efficient because they were easier to attach to the shell and recording error was reduced. Three digit numbers (Floy tags) leave more room for recording error than a color (Hallprint tags). Tags were attached using super glue, and allowed to dry for a few minutes before the snails were returned to the stream. A total of 251 (red) 11 mm, 253 (blue) 12 mm, and 265 (yellow) 13 mm hihiwai were tagged and released at Station 330 (Figure 6). All snails were released at one station during the second tagging study to increase retrieval efficiency.

Tagged snails were recaptured after 1,3,5 and 8 months. Retrieval was conducted in the same way as the first study except that three or four observers were in the water collecting tagged snails, and the search area ranged from 50 m downstream of release to 120 m upstream. The downstream search distance was decreased from 100 m to 50 m in the second study because very few snails were found more than 30 m downstream in the first study, and those that were, were seen as incidental drift (snails dropped by the collector and washed downstream) rather than active movement by the snails. The upstream distance was increased slightly because we expected these smaller snails to migrate greater distances.

Tagging control

To evaluate the impact of the tagging procedure, snails were tagged with Floy tags and placed in aquaria in April 1993. Thirty-three snails with tags and thirty-three snails without tags (16 to 31 mm shell length, mean size 20 $\pm$ 3.09 mm) were randomly placed in four aquaria, with equal numbers of tagged and untagged snails in each aquarium. Snails were measured after two, five and ten months.

Tag retention

All snails tagged in the first study received a blue road chalk mark applied with super glue. This allowed us to test tag retention in the field. The control aquariums also provided information on tag retention for the first tagging study. During the second study, 30 snails were tagged and placed in a 55 gallon aquarium (along with fish). Tag retention and mortality were noted, but snails were not measured.

Length-Mass Regression

Ninety snails were collected from Waikolu Stream in August 1995 and transported live to the laboratory at Haleakala National Park Field Station of the National Biological Service. Snails ranged from 10 mm to 32 mm. Shell length was measured, and total and body weight calculated. Each snail was measured and weighed (total weight). Snails were then immersed in boiling water for 20 seconds to loosen the muscle from the shell. Body weight (with operculum attached) was then determined. A length-mass regression was calculated for total weight (with shell) and for body weight.

RESULTS AND DISCUSSION

Survey

Distribution

Sampling stations were surveyed every other month for a period of two years. Data are missing from some sampling stations during three sampling periods. Flooding in November 1993 prevented Stations 1780-2400 from being counted. Stations 1780 and above (except Station 2030) in February 1994 and Stations 30-330 in September 1994 were also not counted.

Initially, stations to 2780 (meters from the mouth) were included. Since no hihiwai were observed during reconnaissance surveys to 500 meters above Station 2640, this was assumed to be their upper limit and was the highest station surveyed during the first five sampling periods. To improve future monitoring and assessment capabilities, stations 2780-3358 were added in September 1993, in anticipation of potential flow restoration or additional depletion. However, during the September 1993 survey, there was no water at Stations 2780, 3077, or 3217. Stations 3918 and 4028 were counted once in September 1993 but eliminated as permanent monitoring stations because of the difficult access to their headwater location.

Longitudinal distribution

At each sampling station, ten quarter-meter square quadrats were surveyed. For all sampling periods combined, the mean number of snails per station was highly variable, and density decreased in the upper stations (Figure 7). New recruits (≤ 5 mm), which were passing through stations as they migrated upstream are not included here, and are presented separately for clarity. Few snails were found at Stations 70 and 2030 where the habitat was a shallow pool with a sand and gravel substrate and few boulders.

A dramatic decrease in snail densities was observed in and above the areas affected by water diversion. Areas between Station 2640 (just above the lower dam) and Station 3558 (below the upper dam) were often completely dry during sampling periods. Even when there was water, snails were rarely present in these areas. In addition to not providing suitable habitat, a completely dry stream prevents both downstream dispersal by larvae and upstream migration by post-larvae (spat) and juveniles. Station 2640 had higher mean number of snails than upper stations, probably because it had more water. A tributary flowing into Waikolu Stream below Station 2780 allows the stream to flow in this area.

Seasonal variability

An analysis of the mean number of snails per station over the two-year sampling period showed densities over time to be very consistent (Figure 8). Again, data for newly recruited snails (≤ 5 mm) is not included here, and is analyzed separately for clarity. Because data from the five stations closest to the mouth (where hihiwai densities are highest) is missing for September 1994, none of the data from that sampling period is included here. The mean number of snails per station appears to be decreasing slightly over time. Because the upper stations (with relatively few snails) were not added until September 1993, mean number of snails per station over time was also calculated without these upper stations (Figure 9). After the upper stations are removed from the calculations, mean number of snails seems consistent between seasons and over the two-year monitoring period, with slightly more snails present during the first sampling period, November 1992. Data from September 1993 and later (which includes stations above 2640) should be used for comparison with future monitoring surveys in Waikolu Stream.

Size distribution

Snails measured during the semi-monthly surveys ranged from ≤ 5 mm ("spat", or new recruits) to 43 mm shell length (Figure 10). Newly recruited snails, when present, occurred in very high density. The total number of spat (≤ 5 mm) for all stations and sampling periods combined was over 6500, while the highest total number of adult snails observed at all stations and sampling periods combined was around 400. Otherwise, snails from 14 mm to 24 mm shell length were the most common.

When snail distribution by size is analyzed over the longitudinal gradient (from mouth to headwaters), a number of trends are observed (Figures 11 and 12). Snails over 40 mm are only found in the stations closest to the mouth (Stations 30-70) and most snails ≥ 30 mm are found close to the mouth. This may be due to the fact that "winged" morphs tend to be the largest hihiwai and these morphs are only found below the first significant waterfall, or small dam structure in this case.

Hihiwai face predation pressure from a number of species including the introduced Tahitian prawn Macrobrachium lar, the Black Crown Night Heron Nycticorax nycticorax and humans. A few people have access to the mouth of Waikolu Stream (by hiking along the coast) or can drive through the water diversion tunnel to get to the upper reaches. People who do get to the stream are most likely harvesting snails. However, because of the relative isolation, human predation pressure is likely less than in other Hawaiian streams.

In the very highest stations (3558-4028) only snails over 25 mm were observed. This is most likely a remnant/isolated group of snails. A substantial area downstream is dry during parts of the year, preventing upstream migration by juveniles. The few snails that made it past the diverted area during a time when there was flow, have settled here.

Reproduction and Recruitment

Both reproduction (presence of egg capsules) and recruitment (presence of snails ≤ 5 mm length) were highest at stations close to the mouth. This was especially true for post-larval recruitment. No spat (≤ 5 mm) were ever observed above Station 1060.

Reproduction

Egg production showed both seasonal and yearly variation (Figure 13). Data analyzed are through Station 2640 only, as little egg production was observed above this station. During the first year of monitoring, peaks in reproduction were observed in the late fall (November 1992) and summer (July 1993). Again in year two, the highest levels of reproduction were in November (1993) and late May (1994). However, mean levels of egg production were generally lower during the second year of monitoring. An alternative pattern that may be present is a peak in egg production during the late spring to summer, with levels decreasing through the following winter. This pattern would require additional sampling years to verify. Both years show very little egg production in January.

Post-larval recruitment

Post-larval recruitment was recorded during the bi-monthly monitoring surveys. All snails ≤ 5 mm (spat) in each quadrat were counted. Spat were observed only at stations close to the mouth (Figure 14). The predominance of spat (≤ 5 mm) at Station 70 occurs because the recruiting snails seemed to "stack up" here in a deep pool with a gravel substrate, waiting until night to continue the upstream migration. In one single quadrat at Station 70, I counted over 2000 spat (May 1993). Spat were not observed above Station 1060, presumably because by the time they have migrated that distance they have grown to 6 mm, or larger, shell length.

Recruitment was highly variable (Figure 15). The enormous recruitment event in May 1993 and high variation in number of recruits between sampling times essentially swamps the rest of the sampling periods, so for clarity the data is also plotted without error bars and accounting for the large number of snails in May 1993 (Figure 16).

During the first year, a pattern emerges with peaks in recruitment in November and May. It appears that there was substantially less recruitment during the second year. Two possible explanations are that 1) there was little post-larval recruitment during the second year of our monitoring study or 2) that recruitment occurred but our sampling regime (every other month) was unable to detect it. In fact, two weeks before the snail sampling in May 1994, we saw thousands of post-larval hihiwai returning to the stream. And in May 1995 (after the baseline monitoring study had already been completed) we again saw a major recruitment event.

Juveniles (6-9 mm)

Because our monitoring encompasses snails of all sizes, our data are able to indicate recruitment events even if we miss new recruits migrating upstream during our bi-monthly sampling. Snails measuring 6 to 9 mm can be assumed to have recently returned to the stream (perhaps 1 to 3 months earlier). When the data are analyzed, the recruitment events in November and May of 1993 show up as 6-9 mm snails during the following sampling periods (January and July) and the recruitment in the second year of sampling is confirmed by the abundance of 6-9 mm snails.

There is high variation in number of juvenile (6 -9 mm) hihiwai, both between quadrats within a station, and between stations (Figure 17). As with the 5 mm snails the patterns are easier to see if the data are graphed without error bars (Figure 18).

Tagging

First tagging study

Snails were tagged in January 1993 and recaptured after two months (March 1993), four months (May 1993), nine months (October 1993) and fourteen months (March 1994). A total of 208 hihiwai were recaptured in March 1993, 165 in May 1993, 85 in October 1993 and 27 in March 1994. 243 snails were recaptured once, 93 twice, 15 three times, and none were re recaptured all four times.

Many snails recaptured were not found the first time, but were in subsequent recaptures, and 46% of the tagged snails were found at least once. 104 hihiwai were not found the first time but were found in the second, or second and one or more of the subsequent recaptures. 37 were not found in the first or second retrieval but were found in the third, or third and fourth retrieval. Four tagged hihiwai were found for the first time in the final retrieval. Snails not found in earlier recaptures but found in subsequent ones, can be assumed to have been present but not detected.

One tagged snail was found in a bird midden, and another was collected by a person hiking through the stream (and then reported to me). This could potentially have happened to other tagged snails as well. We saw snails being eaten by prawns at night, so secured the tagged hihiwai under rocks or boulders as they were returned to the water after being measured.

Total movement.--The majority of tagged snails were found within 30 m upstream or downstream of release during all four recaptures (Figure 19). Snails far downstream (for example 60 m) are likely to have been "passively transported" rather than purposefully moving in migration. Snails were occasionally dropped during recapture, and caught in the current, and washed downstream.

Snail locations were recorded to the nearest tenth of a meter, but the data are presented here in 5 m increments for clarity. Three tagging stations allowed us to detect movement outside of the 100 m upstream, 100 m downstream search area. Interestingly, no tagged snail was ever found outside of the search area for its release station.

By station.--Slightly more snails were recaptured at the upstream stations (420 and 940) than the downstream station (220) (Table 1). And over time, the number of snails recaptured dropped significantly at all three stations. It can be hypothesized that snails closer to the mouth would more likely be migrating than those further upstream. Thus tagged snails at Station 220 would be expected to show more upstream movement than those at Station 940.

In March 1993, two months after tagging, more snails at Station 220 showed upstream movement than snails at the other two stations (Figure 20). Mean distance moved was 10 ($\pm$ 20) m for Station 220, 1 ($\pm$16) m for Station 420 and -3 ($\pm$ 18) m for Station 940. 73%, 93% and 95% of the recaptured snails were within 20 m of the release site at Stations 220, 420, and 940 respectively.

Similar trends were observed four and nine months after tagging (Figure 21 and Figure 22). 56%, 68%, and 70% of recaptured snails were within 20 m of the release site at Stations 220, 420, and 940, respectively. And, overall, snails at the station closest to the mouth (Station 220) showed the most upstream movement, while those at the farthest upstream station (Station 940) showed a net downstream movement (Table 2).

By March 1994 (fourteen months after the original tagging) too few snails were recaptured to reach any meaningful conclusions about movement during this time period although the previous trends still appear (Figure 23).

The first tagging study showed the majority of the snails to stay within 20 m of the release site. Hihiwai showed the most upstream movement at the station closest to the mouth (Station 220) and the least at the station farthest from the mouth (Station 940). Snails at Station 940 showed slightly more downstream movement than those at Station 420 and, especially, Station 220. It is difficult to interpret this, as downstream movement is likely to have been the result of snails being dropped, or not securely lodged, after being re-measured during the recapture, and thus being swept downstream by the current. However, very few snails were found between 0 and 20 m downstream at any recapture period for Station 220, while at stations 420 and 940 snails could often be found in this area slightly downstream of release. Perhaps snails closest to the mouth tend to always move upstream in search of food and mates, while those further upstream have "settled" and search is a small radius (<20 m) both up and downstream.

Growth.--Tagged hihiwai grew an average of 0.22 (± 1.15) mm after two months, 0.95 (± 1.13) mm after four months, 1.18 (+ 1.70) mm after nine months, and 1.91(+ 1.76) mm after fourteen months. There was high variability in growth rates within and between each of the three release sites and between each of the four recapture periods (Table 3).

Tag retention.--The aquarium study showed all tagged snails to retain their tags throughout the one year they were maintained in aquaria. In the field, tag retention was very high but decreased over time. Of all the snails recaptured, 3% had lost either a tag or the blue chalk mark after two months, 12% after four months, 16% after nine months, and 38% after fourteen months (Table 4).

Second tagging study

The second tagging study was conducted because we hypothesized that the short distances moved and slow growth rate we observed were due to the fact that the snails tagged in the first tagging study were already adults. Younger, smaller snails (11-13 mm) were therefore used for the second tagging study.

Snails were tagged in September 1994 and recaptured after one month (October 1994), three months (December 1994), five months (February 1995) and eight months (May 1995). A total of 209 hihiwai were recaptured in October 1994, 169 in December 1994, 90 in February 1995 and 79 in May 1995. These retrieval rates are nearly identical to those in the first tagging study (Figure 24).

Total movement.--Tagged hihiwai showed much more rapid upstream movement in the second tagging study, and no tagged snails were ever found more than 30 m downstream of the release site (Figure 25). During the first study, large numbers of tagged snails remained at the original release site, or within 5 m up or downstream. In the second study, the mode had shifted to 10 m upstream after just one month (October 1994), and to 25 m upstream after five months (February 1995).

By size.--Initially, almost twice as many 12 and 13 mm tagged snails were found than 11 mm snails (Table 5). Over time, the proportion recaptured became more similar between sizes, although more 12 and 13 mm snails were always found. Perhaps smaller snails suffered higher mortality rates, or they migrated out of the study area more quickly.

Results of the second tagging study did not indicate significant differences in migration rate between the three sizes. After one month, no snails had moved more than 10 m downstream, and showed a mean upstream movement of 21(± 16) m, 18(±15) m and 18(±16) m for sizes 11, 12, and 13 mm, respectively (Figure 26). A similar pattern was observed after three months (Figure 27).

After five months (February 1995) the modal distance of tagged snails was further upstream for 11 and 12 mm snails (25 m from release) than 13 mm snails (15 mm from release) (Figure 28). By May 1995 (eight months after release), the pattern is less clear (Figure 29), and the mean distance migrated is similar for all size classes (Table 6).

Growth

Hihiwai in the second tagging study grew more rapidly than hihiwai in the first tagging study. 11 mm and 12 mm snails showed faster growth rates than 13 mm snails during all four recapture periods (except for the 11 mm hihiwai at the five month recapture) (Table 7).

The population monitoring data suggests that hihiwai grow rapidly from $\leq$ 5 mm when returning to the stream to around 9 mm in just a few months. If snails are then growing 1 to 3 mm a year after they reach 9 mm, with growth slowing as they age, as suggested by both of the tagging studies, then (assuming most snails attain a 29 mm standard maximum length) life span could be estimated to be 6 to 10 years.

Aquarium Study

Tag retention

Both aquarium studies (with Floy tags and with Hallprint tags) showed all tagged snails to retain their tags throughout the one year they were maintained in aquaria.

Survivorship

During the first aquarium study, three snails with tags and two without tags died by the end of the year-long aquarium study. One tagged snail died in the second aquarium study.

Growth

A t-test showed no significant difference in size (shell length) between tagged and untagged snails at the beginning ($p=.608$) or end ($p=.323$) of the aquarium study. However, none of the snails showed any real growth in the aquaria, most likely due to an inadequate supply of the appropriate algal food. Tagged snails started the study with a mean size of 20.45 ($\pm$ 3.19) mm and ended with a mean size of 20.67 ($\pm$ 3.03) mm. Untagged snails started with a mean size of 20.06 ($\pm$3.01) mm and ended with a mean size of 20.00 ($\pm$ 2.13) mm.

Length-Mass regression

Length-mass regressions were calculated using both linear and exponential equations (Figure 30). Equations were calculated for body weight (without shell) and total weight (with shell). Both linear and exponential equations showed a good fit to the data, with the exponential regressions providing a slightly better model.

Linear models were:

$$\text{BODYWEIGHT} = -1.894 + 0.169 * \text{LENGTH}$$
$$\text{TOTAL WEIGHT} = -3.677 + 0.325 * \text{LENGTH}$$

Exponential models were:

$$\text{BODYWEIGHT} = .0004 * \text{LENGTH}^{2.696}$$
$$\text{TOTAL WEIGHT} = .0010 * \text{LENGTH}^{2.616}$$

The linear model resulted in an R^2 of .92 and .92, and a total sum if squares of 308 and 84, for body weight and total weight respectively. The exponential model resulted in an R^2 of .95 and .96, and a total sum of squares of 57 and 53, for body weight and total weight respectively.

CONCLUSIONS

Summary

Waikolu Stream is notable for supporting a large population of the relatively uncommon native Hawaiian stream snail, hihiwai (Neritina granosa). Because hihiwai are easier to identify, collect and measure than gobies (typically used in stream evaluation surveys in Hawai`i), they are especially amenable to monitoring programs, and the habitat requirements of hihiwai make them a good indicator of water quality.

The methods presented in this report provide techniques for monitoring population density and distribution of hihiwai, and the important life stages of reproduction and recruitment (post-larvae returning from the ocean to the stream). During this study, sampling stations were surveyed every other month for a period of two years. This baseline data can be used for comparison with future surveys to monitor the condition of Waikolu Stream and to evaluate the impact of any future changes to the stream system. The number of hihiwai found at each station during the baseline surveys showed wide variation, but the mean number of snails was consistent between seasons and over the two-year monitoring period.

Snail densities recorded in and above the areas affected by water diversion were dramatically lower than in the lower stream reaches. Areas of the stream between the lower and upper dam were often completely dry during sampling periods. Even when water was allowed to flow through this area, snails were rarely present. In addition to not providing suitable habitat, a completely dry stream prevents both downstream dispersal by larvae and upstream migration by post-larvae (spat) and juveniles.

In the very highest elevation stations, no snails less than 25 mm were observed. This is most likely a remnant/isolated group of snails; the few snails that made it past the diverted area during a time when water was allowed to flow have settled here. Restoration of continuous water flows would presumably allow for recolonization of this area.

Egg production showed both seasonal and yearly variation. Peaks in reproduction occurred during the late fall, late spring and summer. Reproduction was higher the first year than the second and both years showed little egg production in January. Recruitment occurs throughout the year, with the largest event in May and a second major recruitment in November.

The majority of all adult snails tagged during the first study were found within 30 meters upstream or downstream of release, suggesting that once snails settle out, they stay in that area. This illustrates the importance of continually flowing water, since once the hihiwai settle they are unlikely to begin an additional upstream migration, even if there is flow in a previously dry area.

The younger, smaller hihiwai tagged in the second study showed much more rapid upstream movement than snails in the first. Hihiwai in the second tagging study also grew more rapidly than the older, larger snails in the first tagging study, and during the second study the 11 mm and 12 mm snails grew more rapidly than the 13 mm snails.

The population monitoring data suggest that hihiwai grow rapidly when returning to the stream (reaching 9 mm in a few months). If snails are then growing 1 to 3 mm a year after they reach 9 mm, with growth slowing as they age, as suggested by both of the tagging studies, hihiwai life span could be estimated to be 6 to 10 years.

The tagging studies show that snails do not move very fast or very far once they have settled out, making it difficult for them to pass barriers of dry stream during either floods or brief periods of increased water flows. During periods when water was present in the stream area between Stations 2640 and 3217, fish moved immediately into these areas (personal observation), while snails rarely did. It appears that prolonged periods of continuous flow are necessary for hihiwai to be able to migrate through periodically dewatered sections of a stream.

Future research

Future research on hihiwai should focus on providing additional information on its life history. Specifically, cues for reproduction and recruitment should be analyzed and the duration of the oceanic larval life stage determined. Additional information is also needed on the habitat requirements of hihiwai, especially flow regimes and water quality. Potential impacts of water diversion and periodic dewatering on these variables should be evaluated.

Because sections of Waikolu Stream support a large population of hihiwai and the stream is relatively isolated it provides an ideal opportunity to investigate the impacts of predation by the introduced prawn Macrobrachium lar on hihiwai. Lower flow velocity and increased water temperature that often accompany stream diversion provide a favorable environment for the introduced prawn, potentially increasing its threat to the native hihiwai. Additional information is also needed on the diet of hihiwai, and how it may be affected by stream alteration.

Management recommendations

First, it is recommended that the National Park Service continue the monitoring program established by this study. At the completion of this study, Park Service staff were trained in the monitoring methods. The baseline data collected during this study can be compared with future monitoring surveys to evaluate the impacts of changes in the stream system (such as an alteration of the current flow regime). An adequate long term monitoring program for hihiwai in Waikolu Stream would require a yearly survey, preferably in mid summer to insure the detection of the May recruitment event. A trained team of four observers could conduct a hihiwai survey in Waikolu Stream over a one-week period.

Second, additional monitoring surveys would be required in the event of a major change in the stream system (such as a large increase in the amount of water being diverted from the stream, a return of continuous flow to the area that is now often dry, or the introduction of alien species to the stream that may be potential threats to hihiwai). Further studies may also be necessary to evaluate the impact of such changes on the population structure, and especially reproduction and recruitment.

Lastly, a continuous flow from the headwaters to the mouth of the stream allows native species such as hihiwai to disperse to the ocean as larvae and to migrate back upstream to reproduce and complete their life cycle. Densities of hihiwai are substantially lower in, and upstream of, the diverted portion of Waikolu Stream. The restoration of continuous flow to the currently dewatered portions of Waikolu Stream would improve habitat for hihiwai, and would enhance both downstream dispersal of larvae and upstream migration by post-larvae (spat and juveniles).

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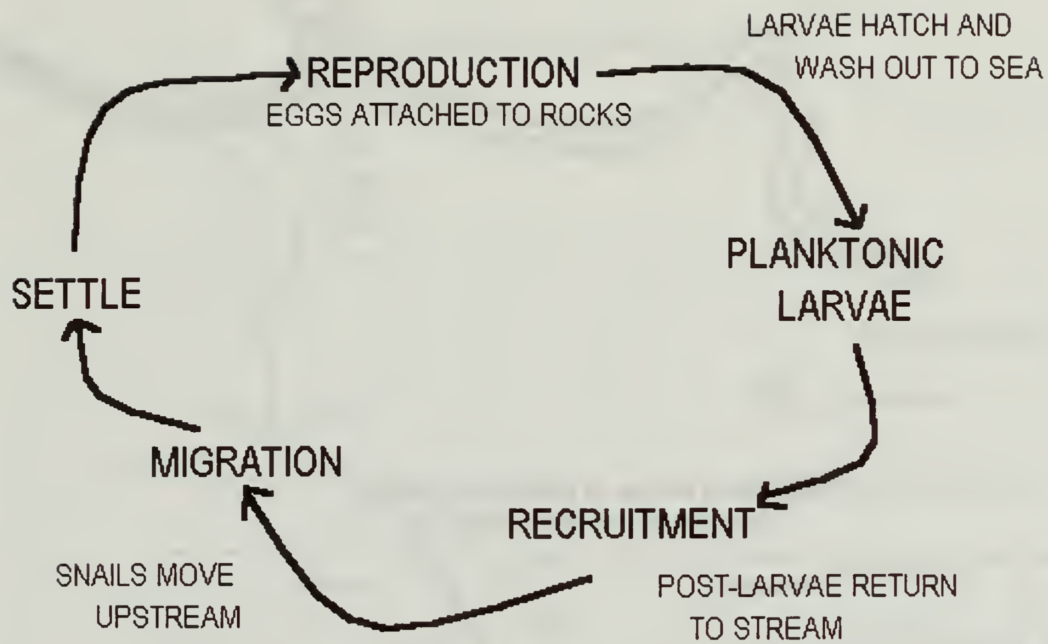


Figure 1. Amphidromous life cycle of hihiwai.

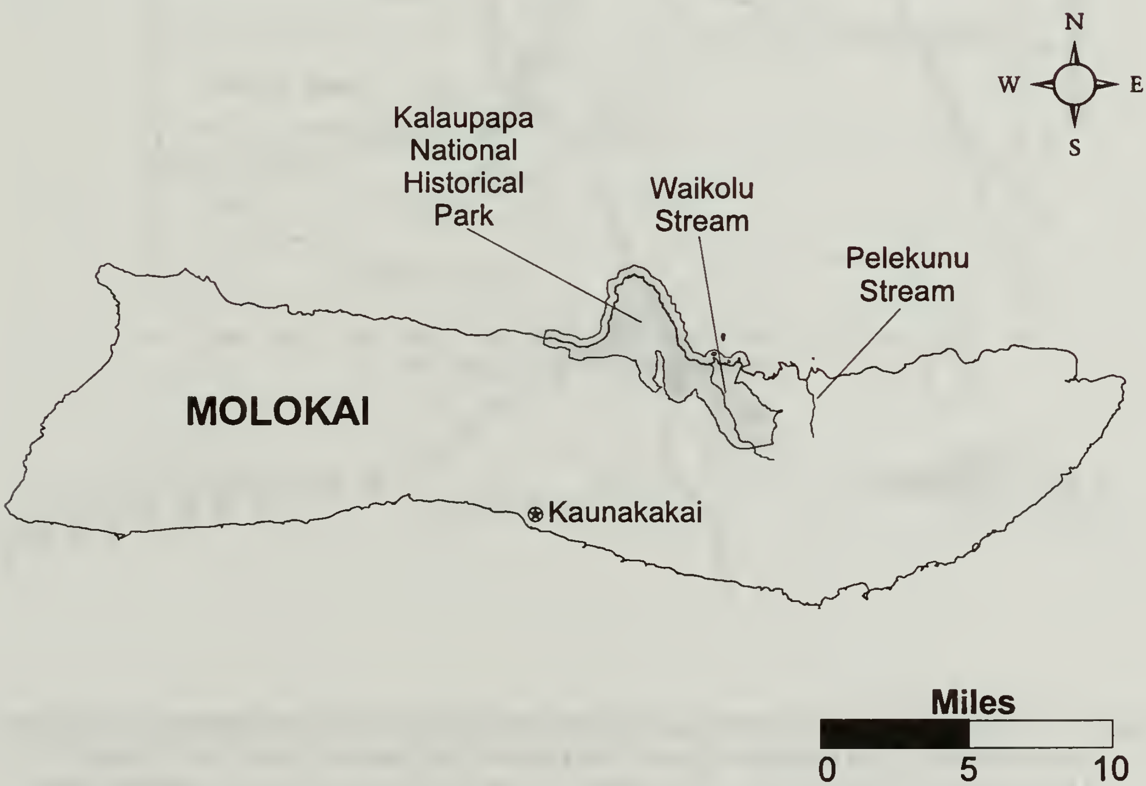


Figure 2. Island of Moloka`i

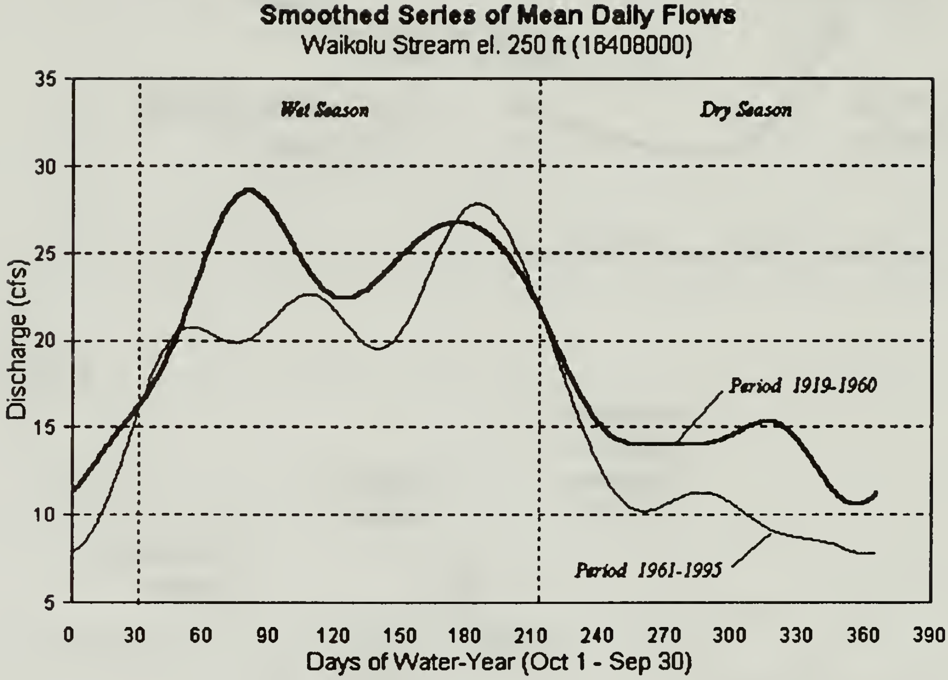


Figure 3. Impact of water diversions on flow volume in Waikolu Stream. Seasonal variation of mean daily flows comparing pre- and post-tunnel periods (from Diaz, in prep.). Mean daily flows from 1921 - 1995 at the "lower" USGS stream gage, located below the diversions.

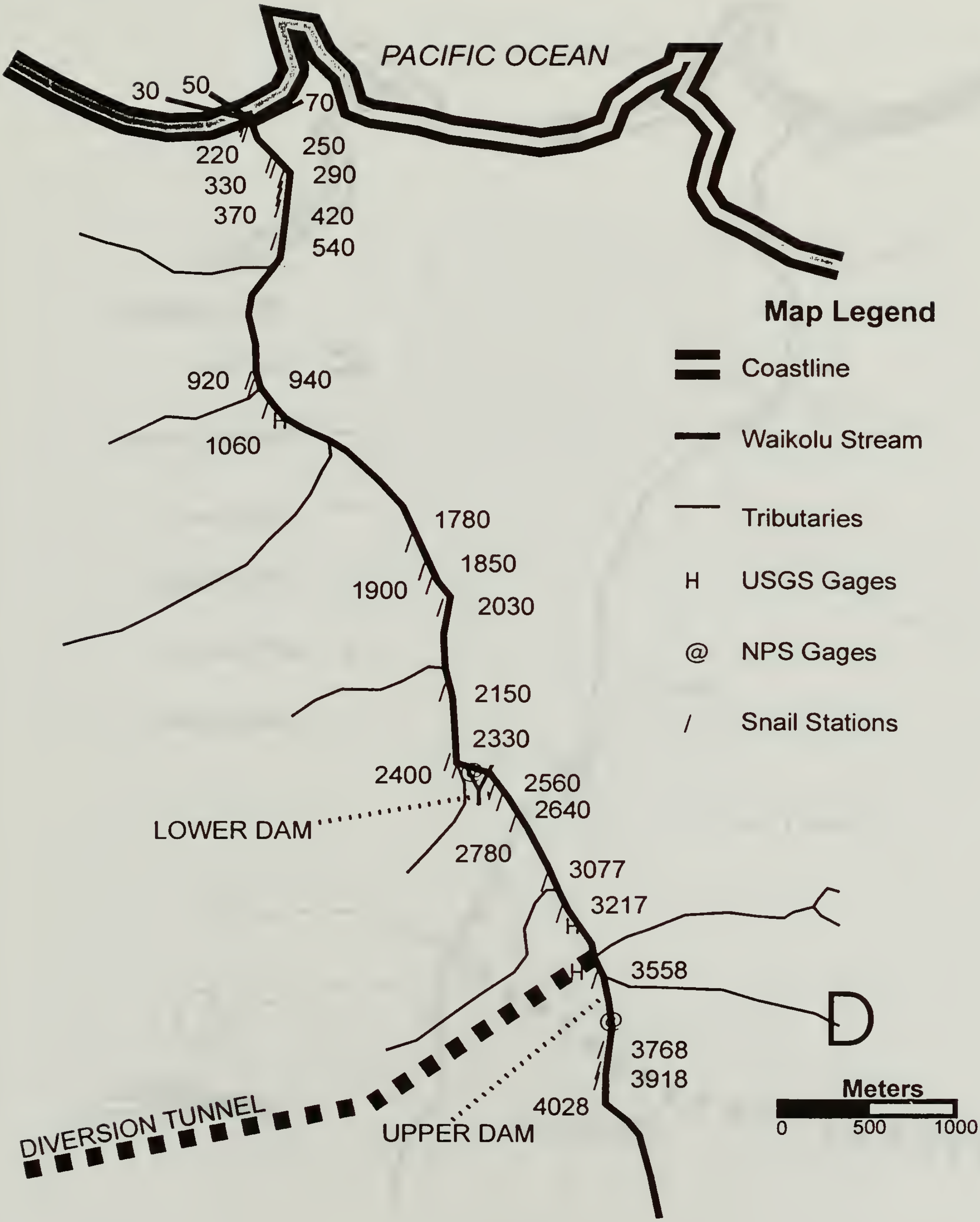


Figure 4. Location of monitoring stations in Waikolu Stream.

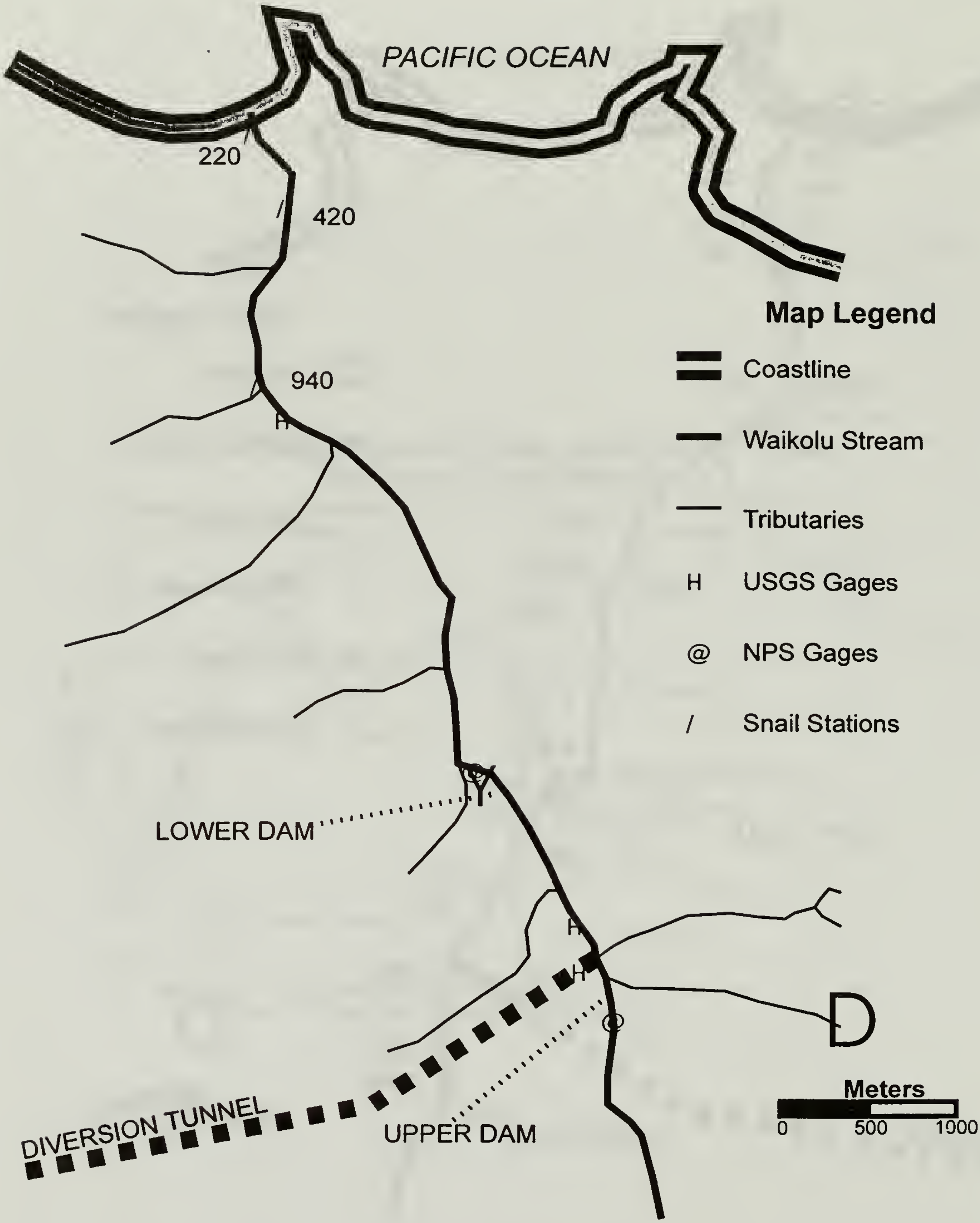


Figure 5. Location of first tagging release stations.

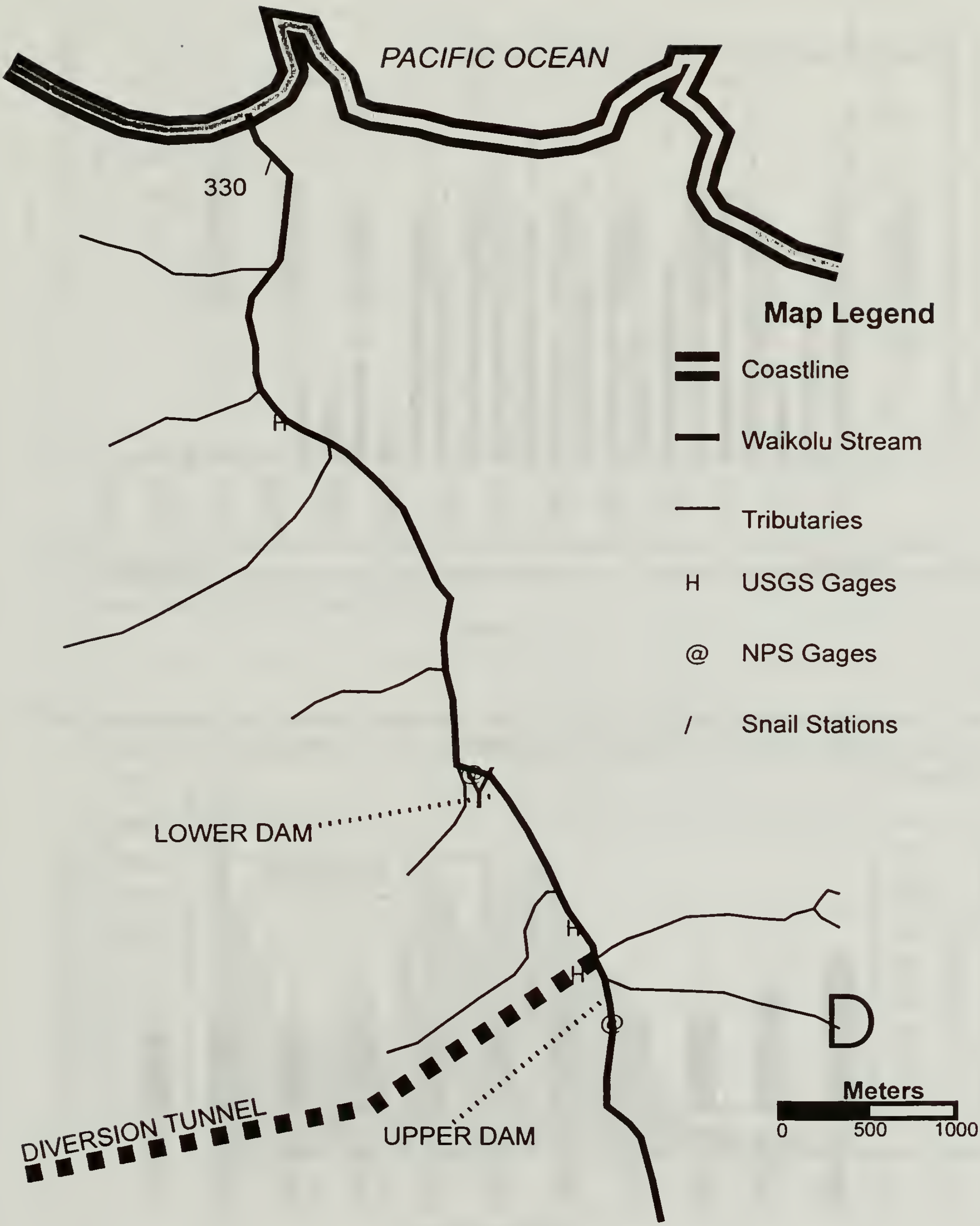


Figure 6. Location of second tagging release stations.

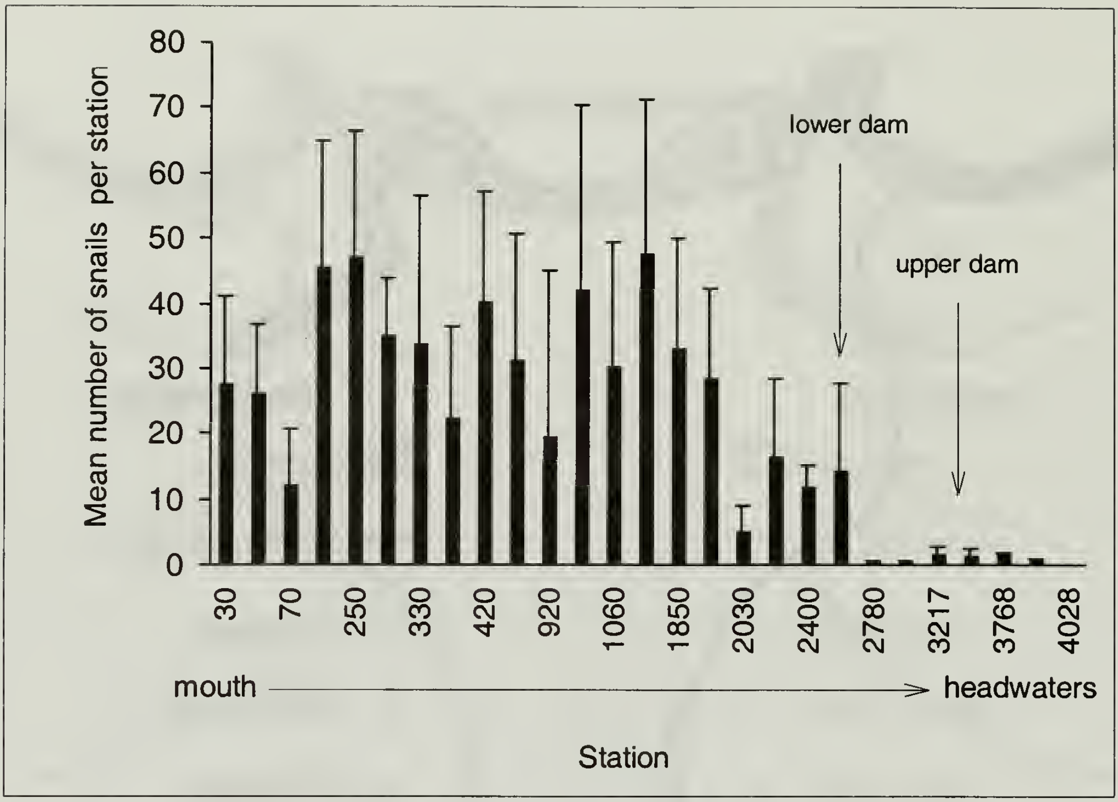


Figure 7. Longitudinal distribution of hihiwai. Mean number of snails (not including recruits) at each station for all sampling stations combined. Error bars equal one standard deviation.

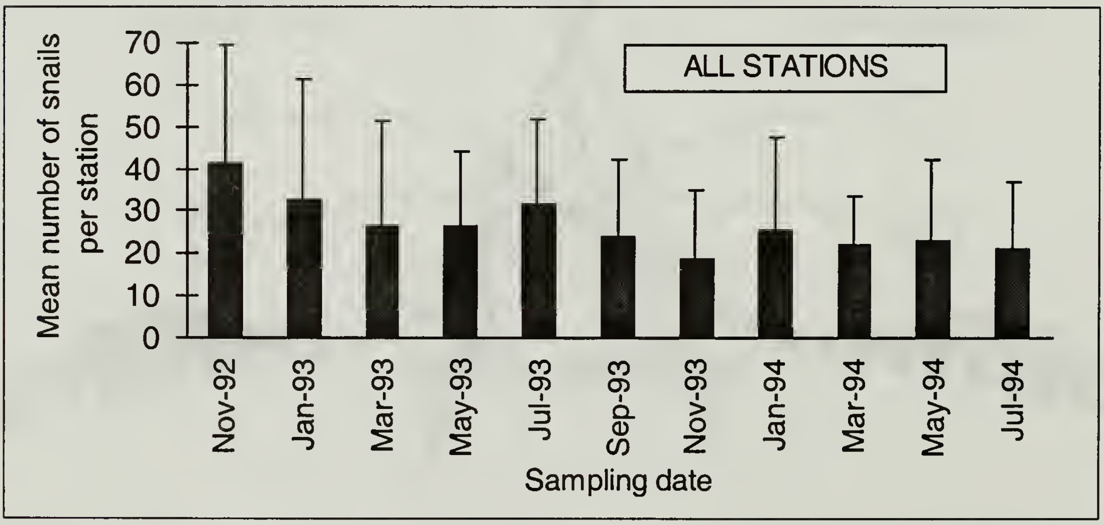


Figure 8. Seasonal variation in hihiwai density. Mean number of snails (not including recruits) per station at all stations combined. Error bars equal one standard deviation.

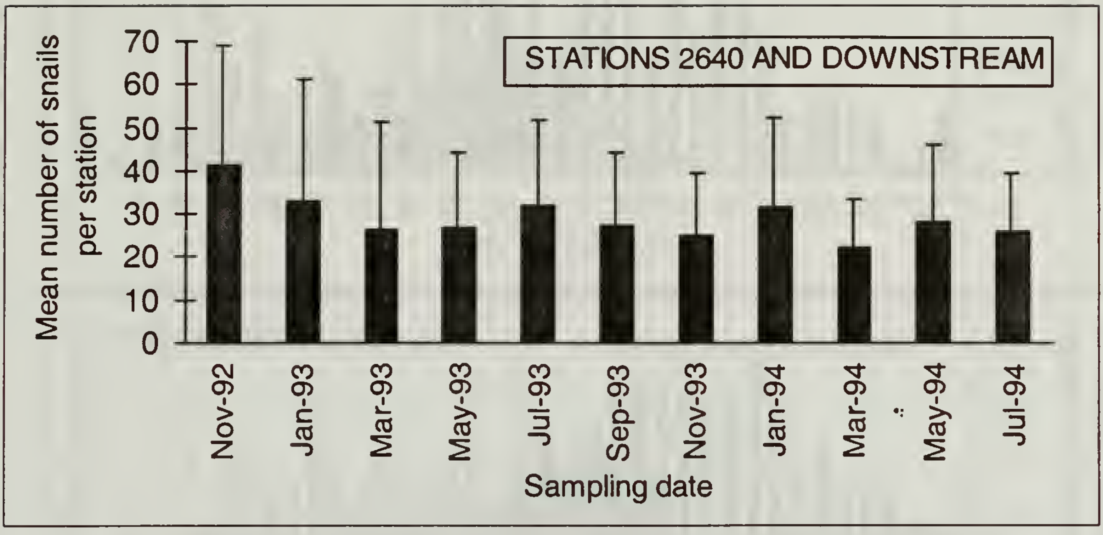


Figure 9. Seasonal variation in hihiwai density. Mean number of snails (not including recruits) per station for stations at and below 2640 (meters from the mouth). Error bars equal one standard deviation.

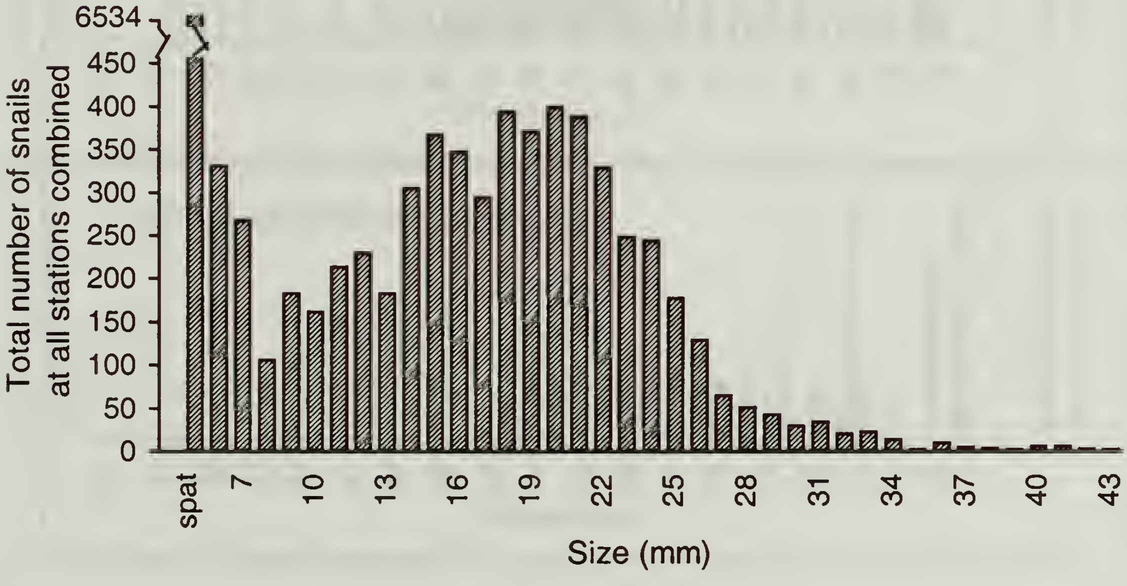


Figure 10. Size distribution of hihiwai. Total number of snails at all stations during all sampling periods combined.

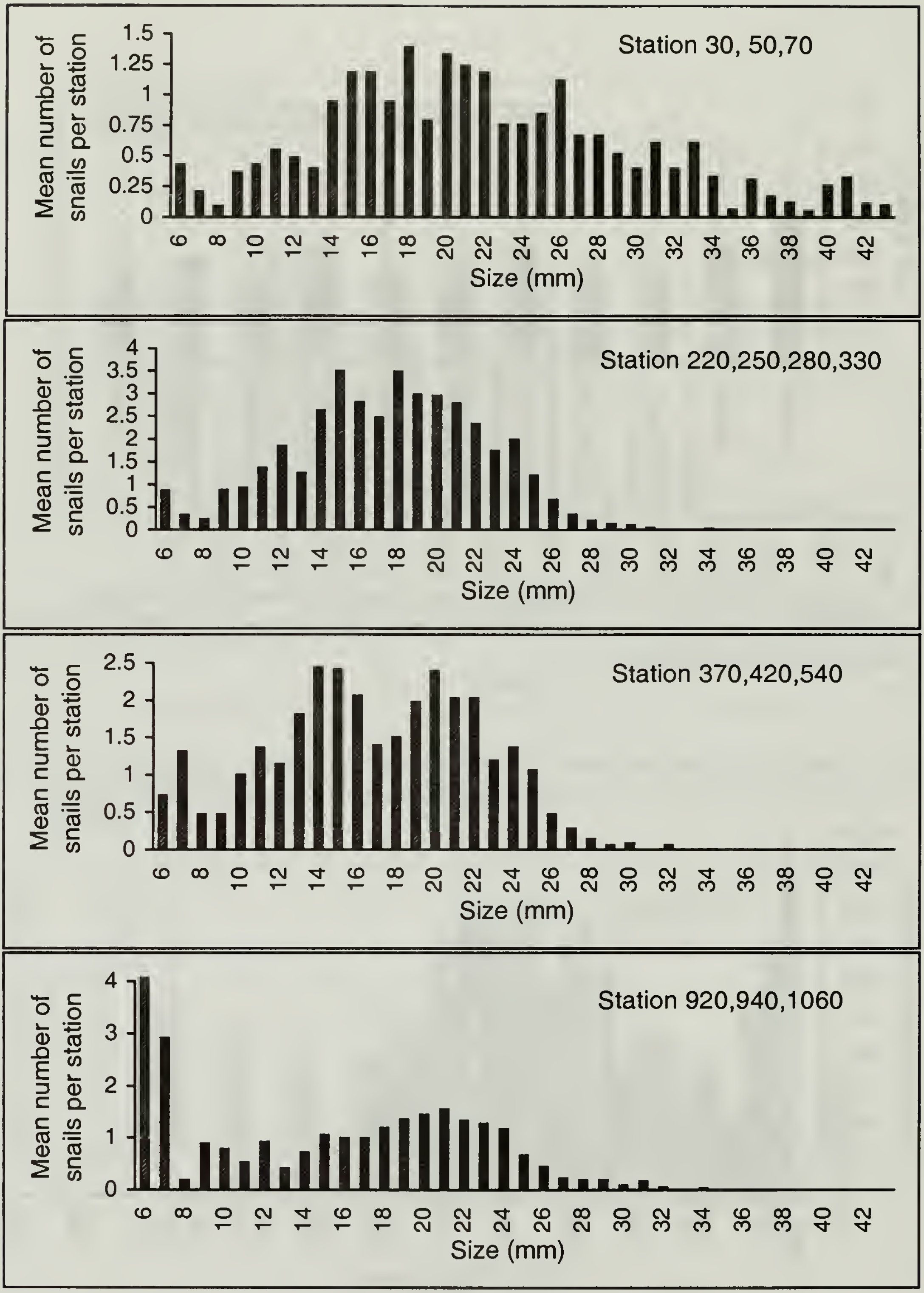


Figure 11. Size distribution of hihiwai along an elevational gradient. Stations 30 to 1060 (meters from the mouth).

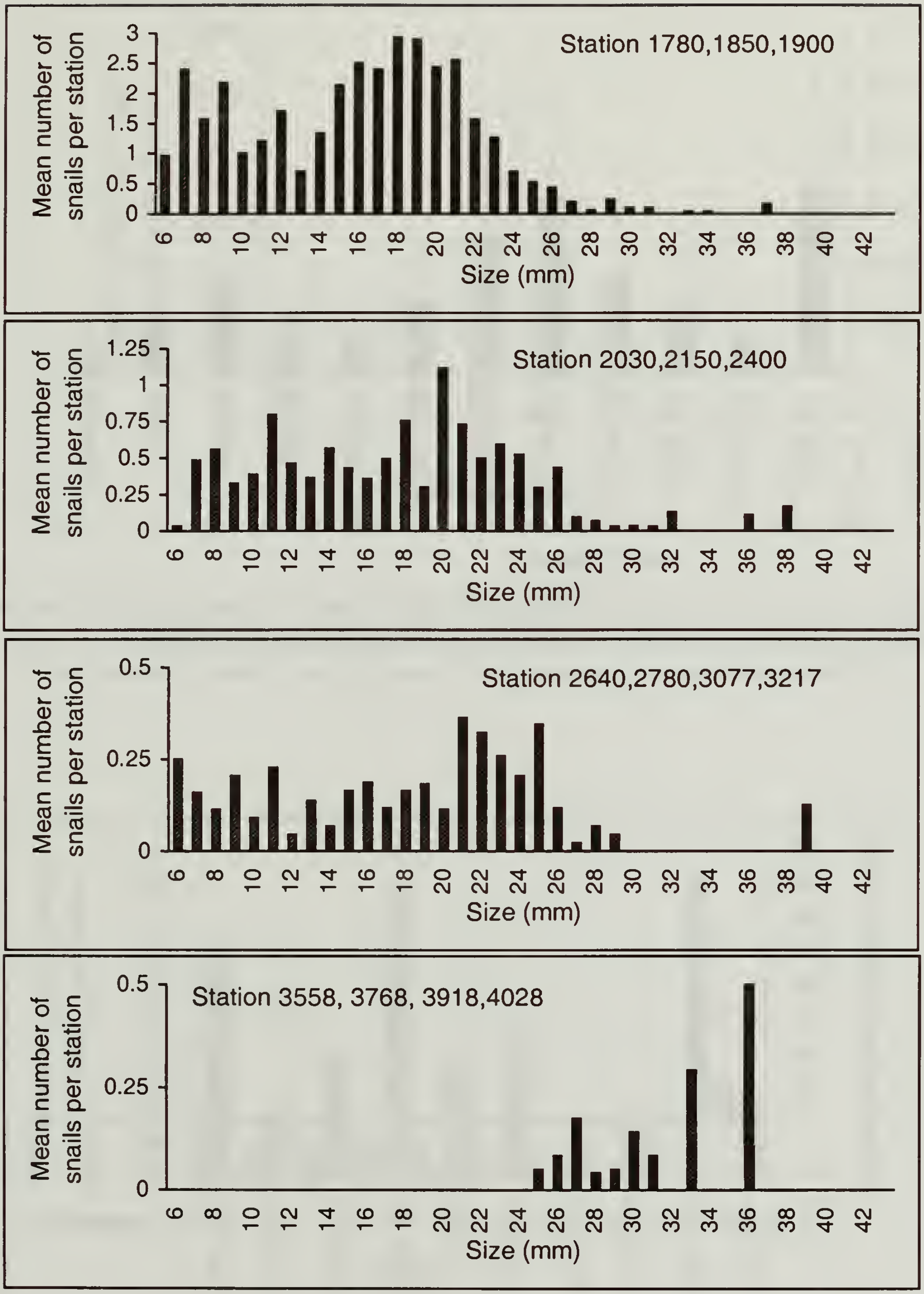


Figure 12. Size distribution of hihiwai along an elevational gradient. Stations 1780 to 4028 (meters from the mouth).

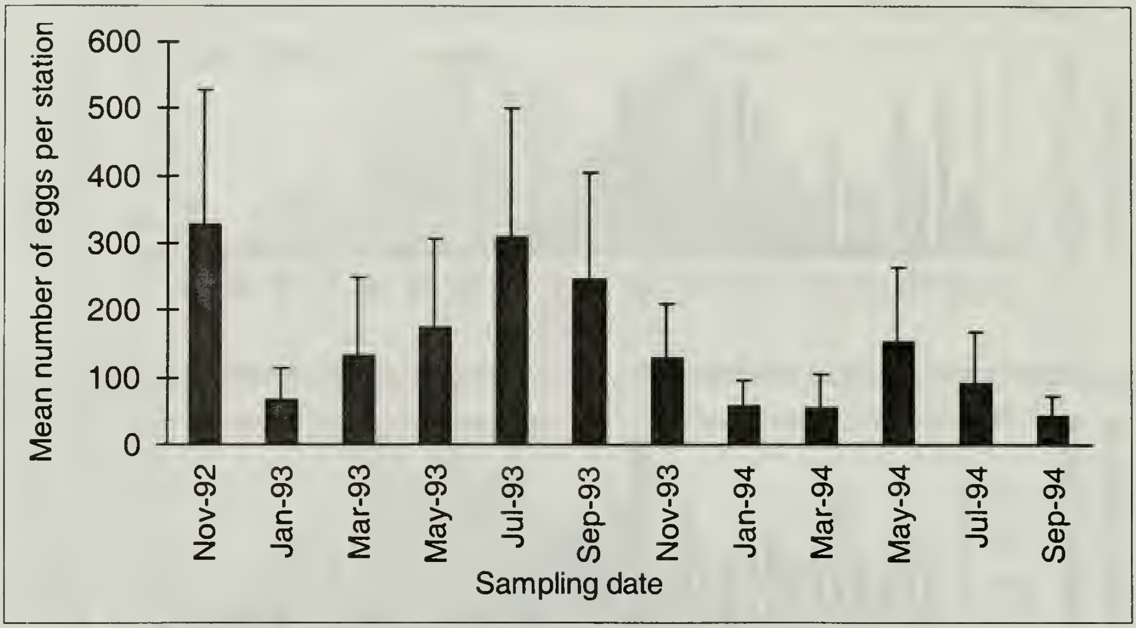


Figure 13. Seasonal variation in hihiwai egg production. Mean number of egg capsules per station at all stations combined. Error bars equal one standard deviation.

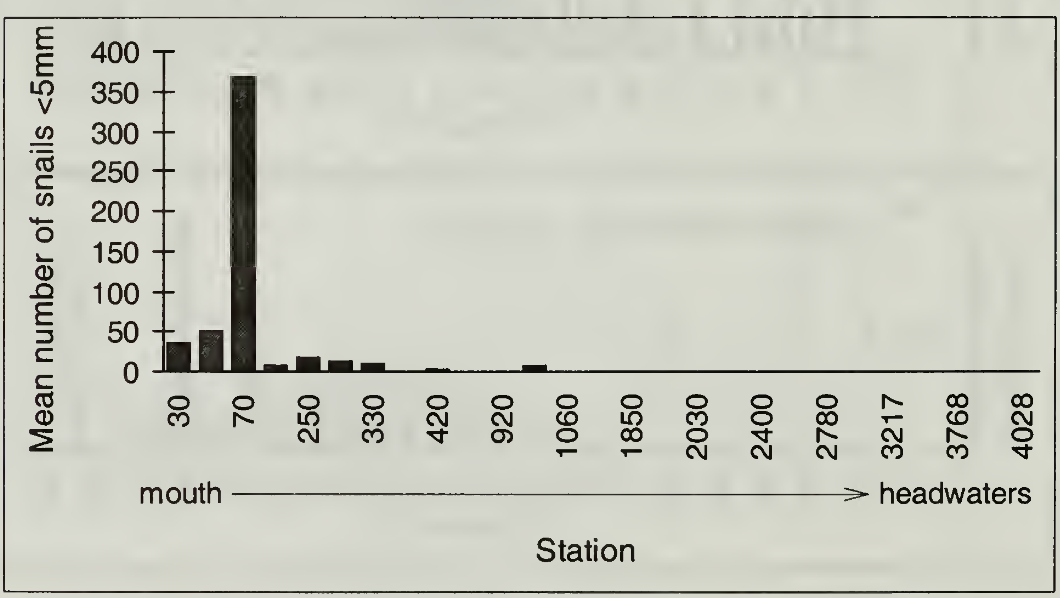


Figure 14. Longitudinal distribution of post-larval hihiwai. Mean number of snails (≤ 5 mm) at each station for all time periods combined.

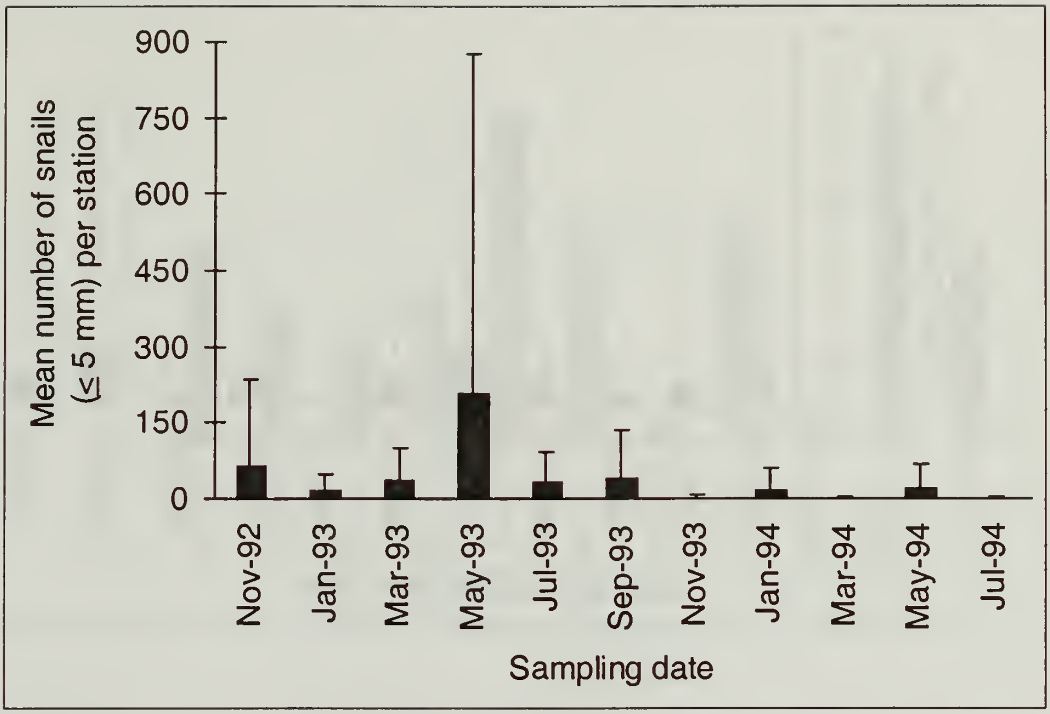


Figure 15. Seasonal variation in post-larval recruitment. Mean number of hihiwai (< 5 mm) per station at all stations combined. Error bars equal one standard deviation.

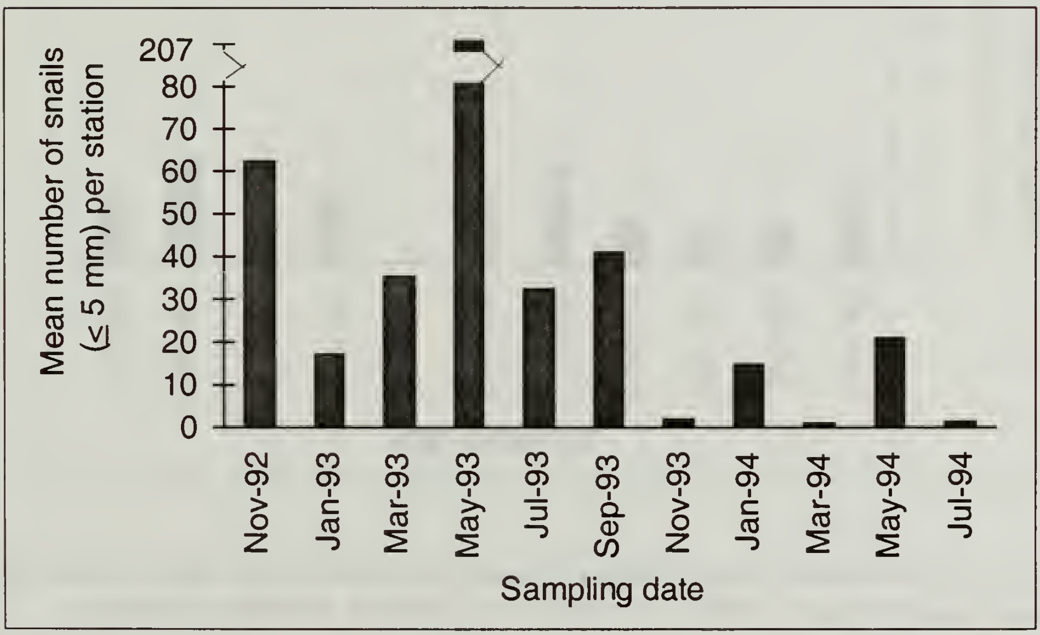
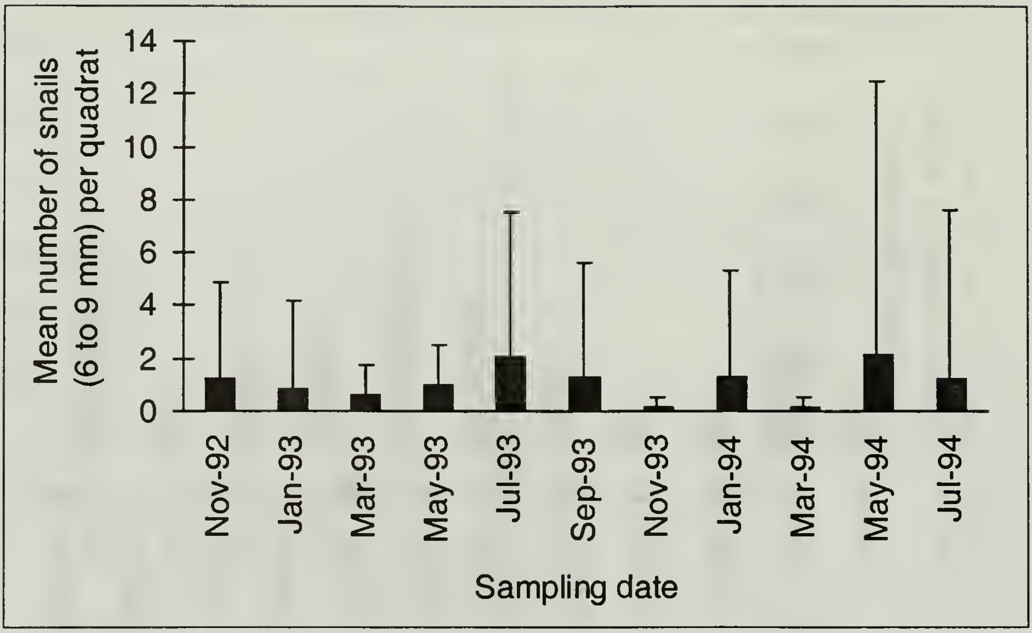


Figure 16. Seasonal variation in post-larval recruitment. Mean number (error bars omitted) of hihiwai (≤ 5 mm) per station at all stations combined.



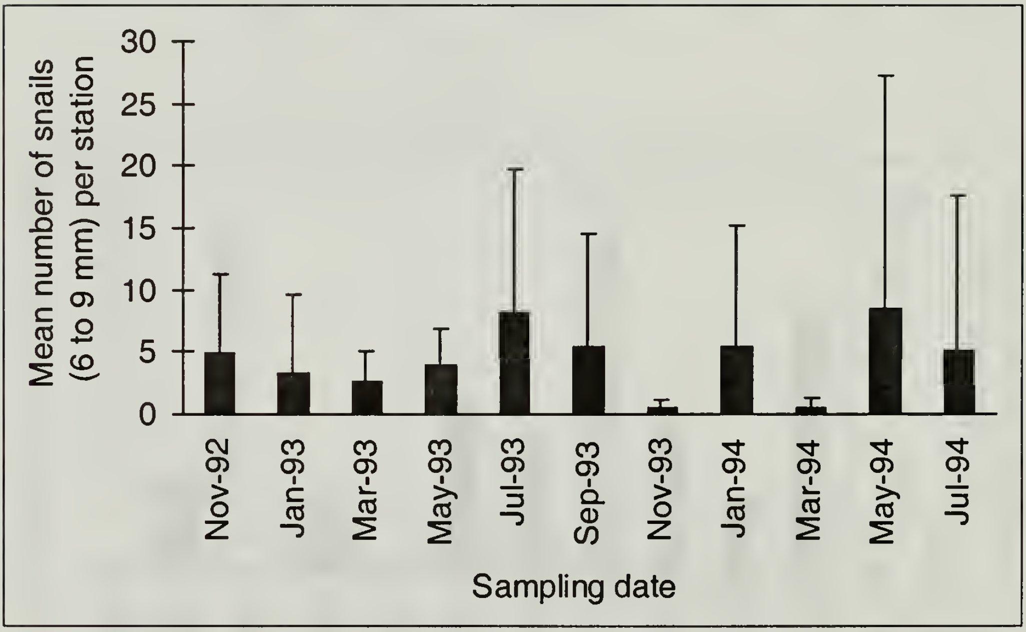


Figure 17. Seasonal variation in mean number of young hihiwai (6-9 mm). Mean number of snails per quadrat and per station, at all stations combined. Error bars equal one standard deviation.

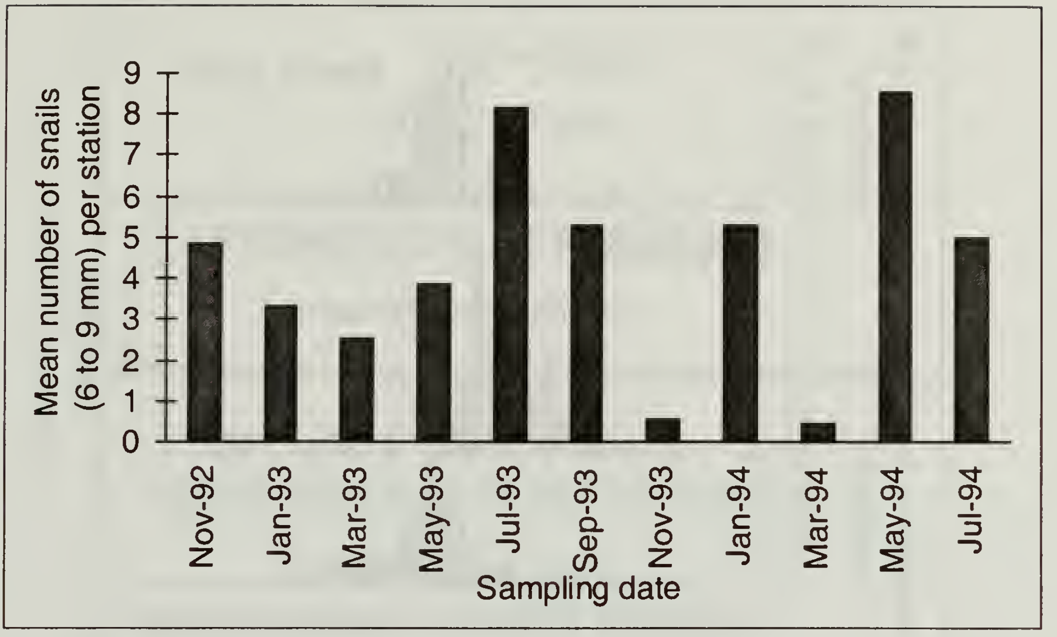


Figure 18. Seasonal variation in mean number of young hihiwai. Mean number (error bars omitted) of snails (6-9 mm) per station at all stations combined.

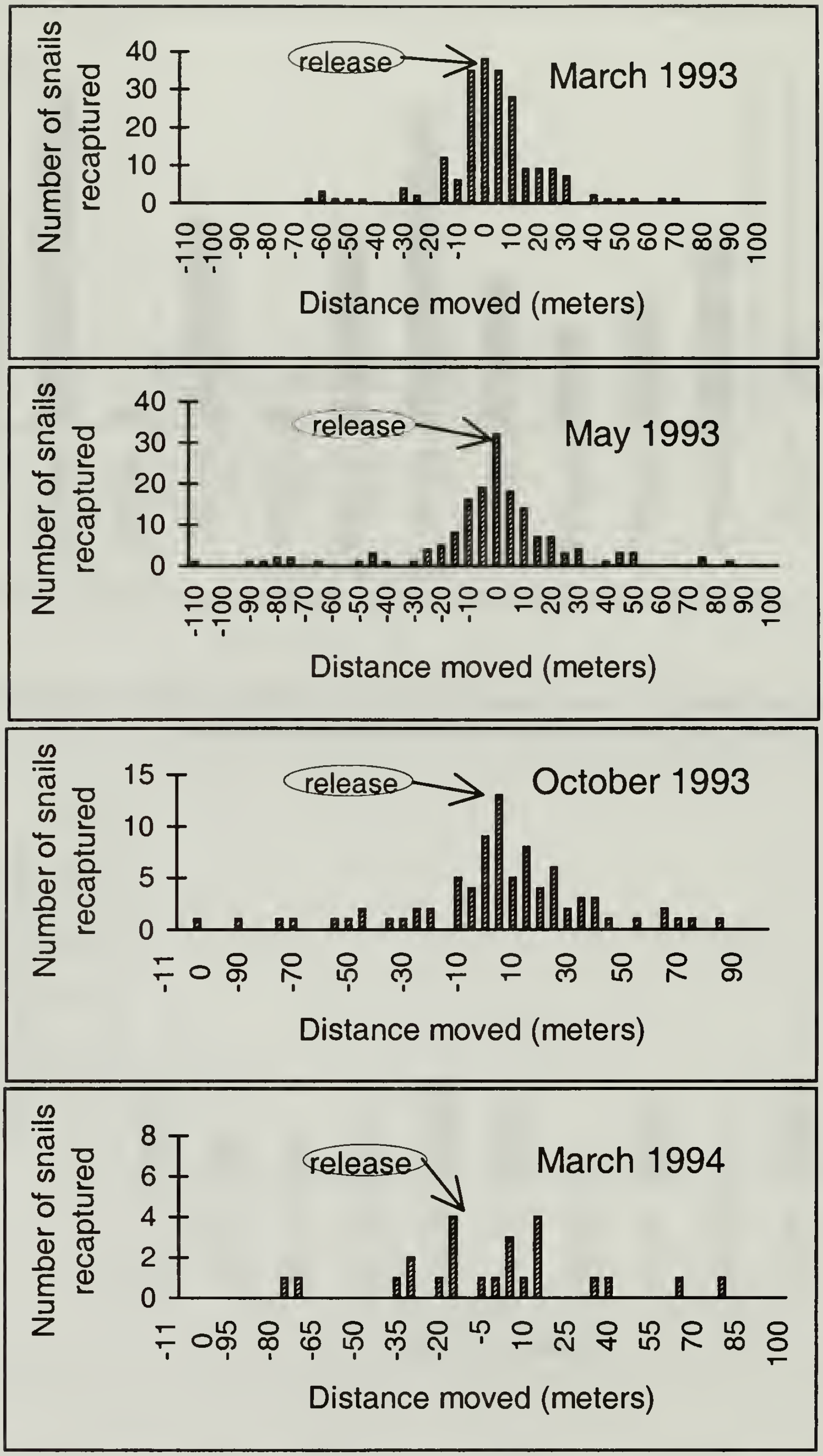


Figure 19. Distance moved from the release site by tagged hihiwai during four recapture periods of the first tagging study. All three release stations combined.

MARCH 1993

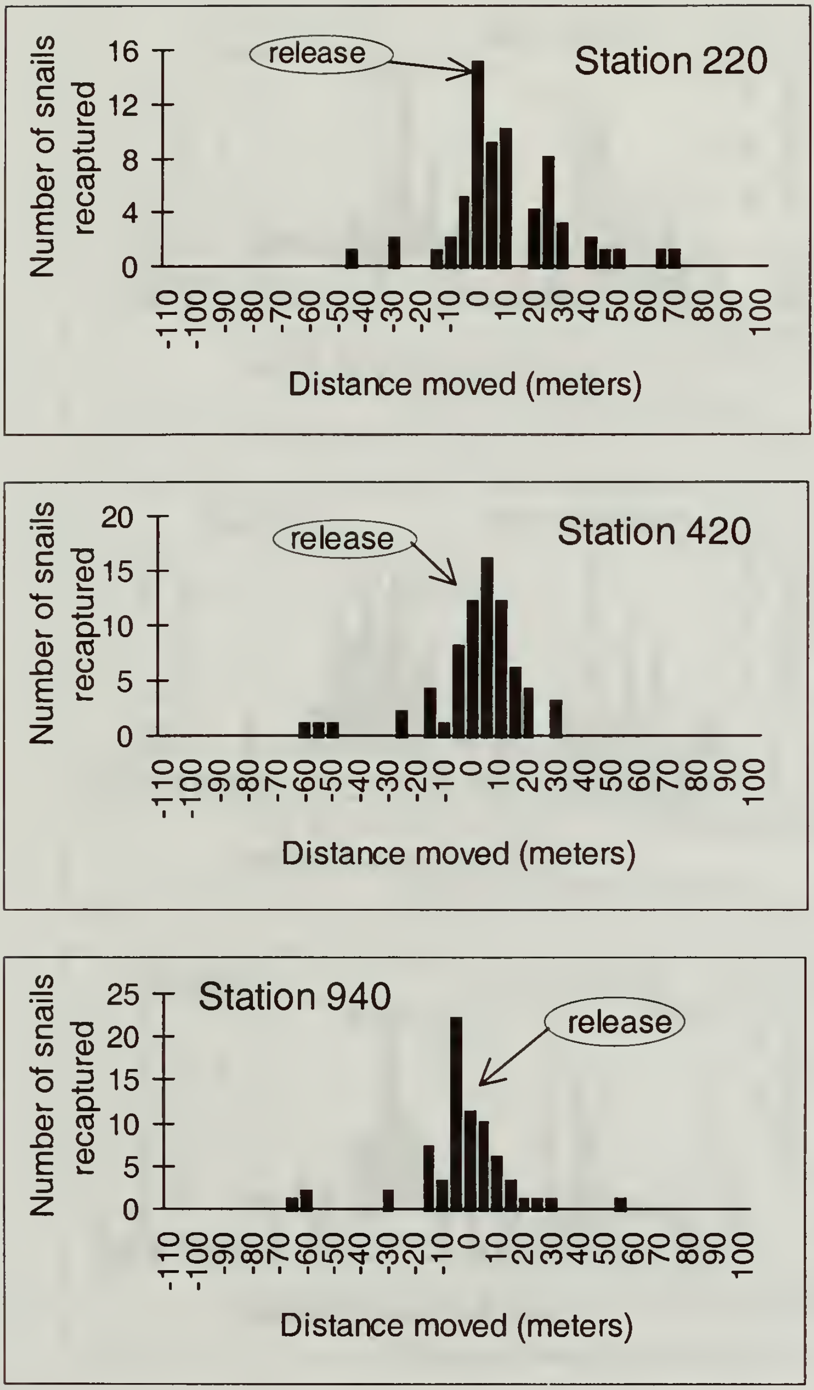


Figure 20. Distance moved after two months by tagged hihiwai at three different stations; 220 420 and 940 (meters from the mouth).

MAY 1993

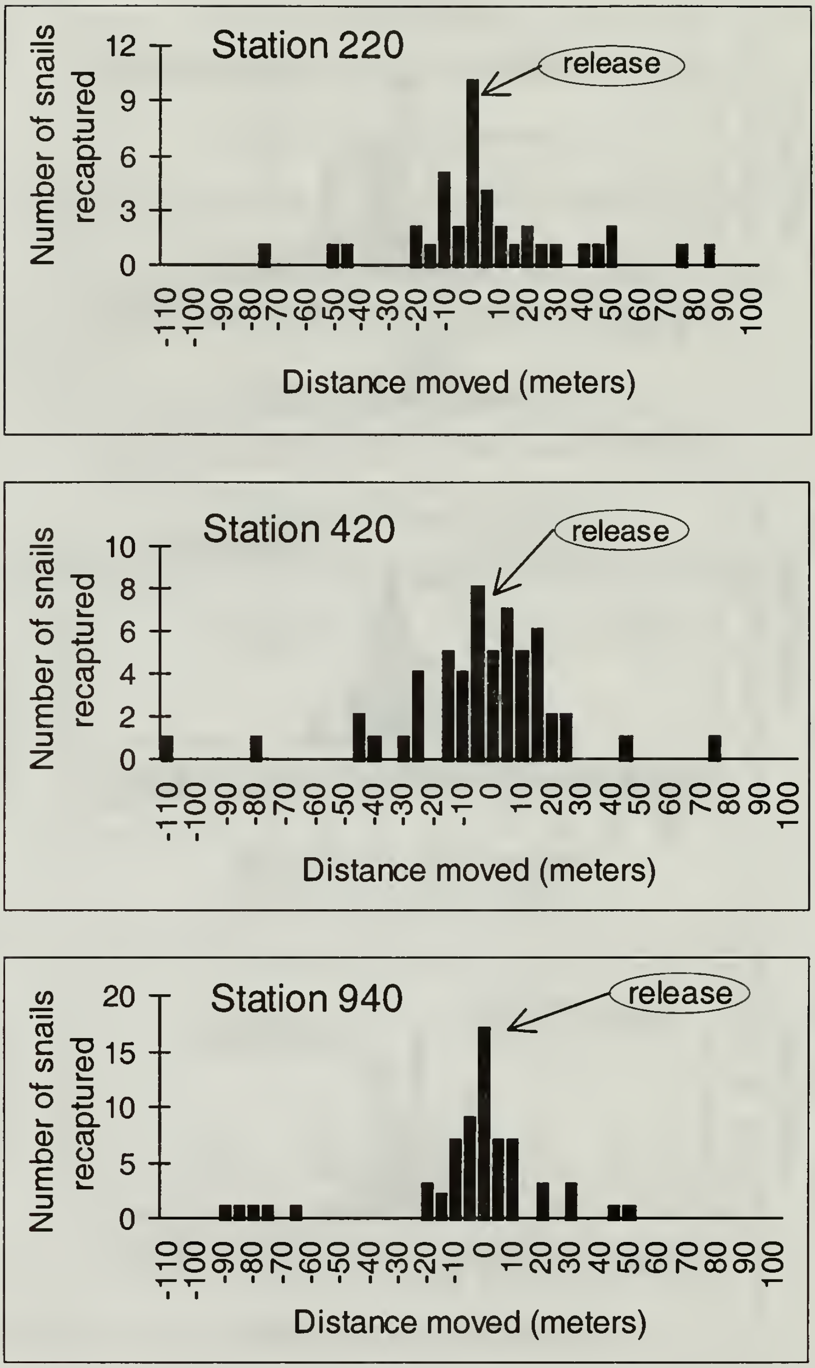


Figure 21. Distance moved after four months by tagged hihiwai at three different stations; 220, 420 and 940 (meters from the mouth).

OCTOBER 1993

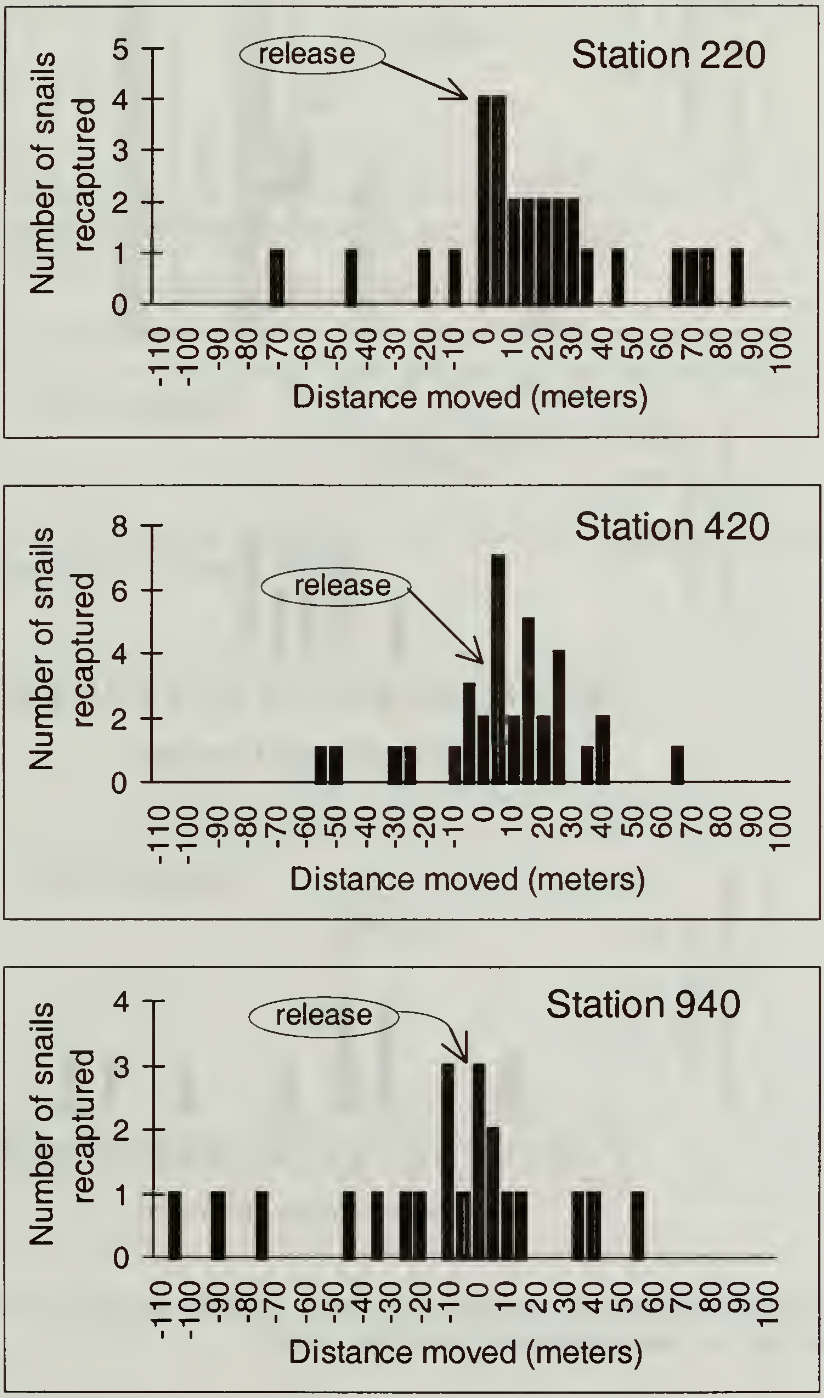


Figure 22. Distance moved after nine months by tagged hihiwai at three different stations; 220, 420 and 940 (meters from the mouth).

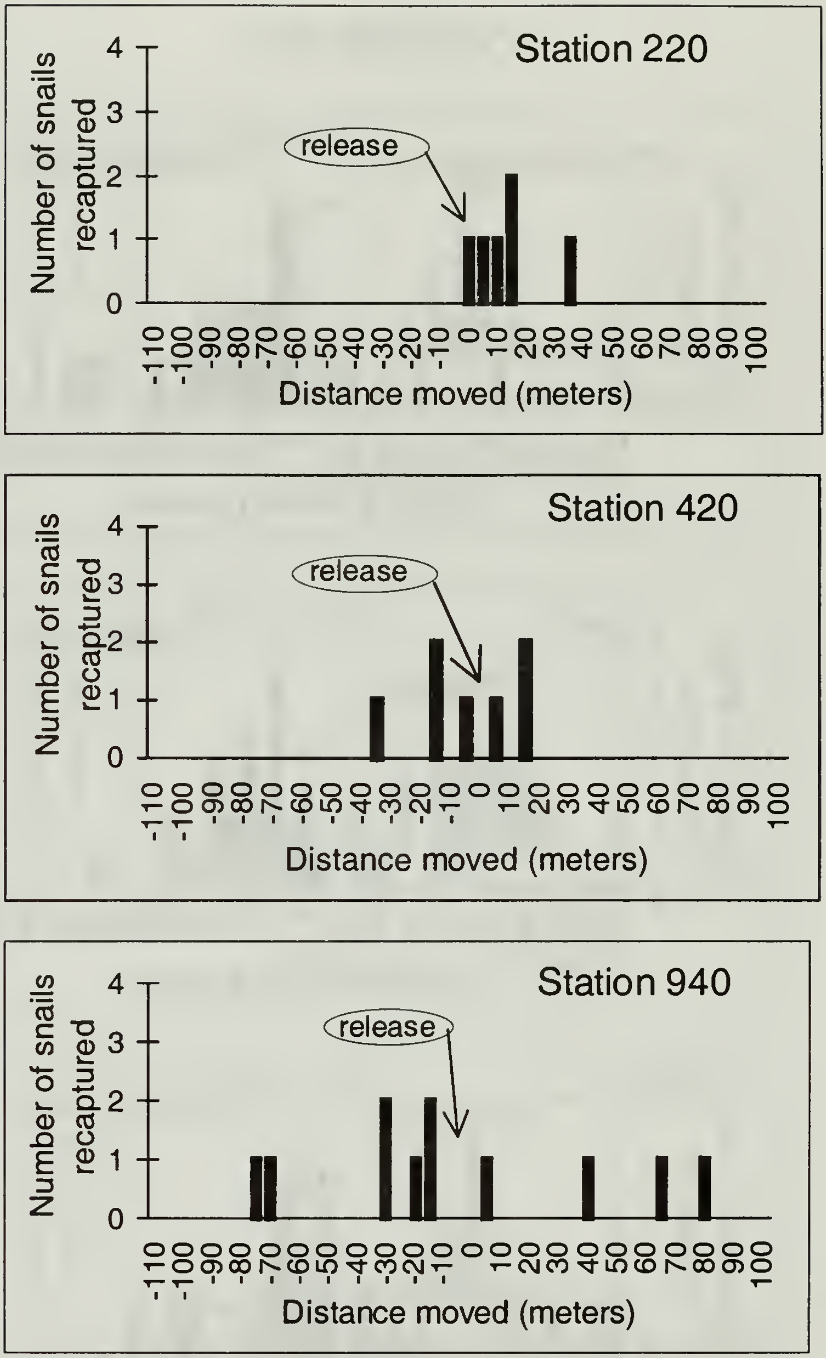


Figure 23. Distance moved after fourteen months by tagged hihiwai at three different stations; 220, 420 and 940 (meters from the mouth).

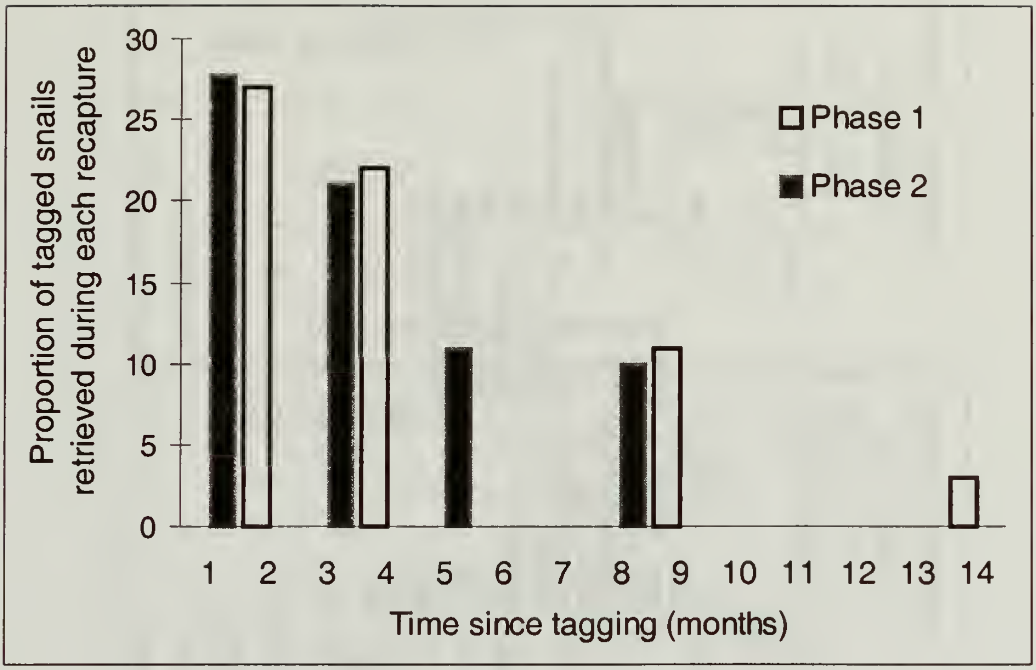


Figure 24. Proportion of originally tagged hihiwai that were recaptured during subsequent months during the two tagging studies.

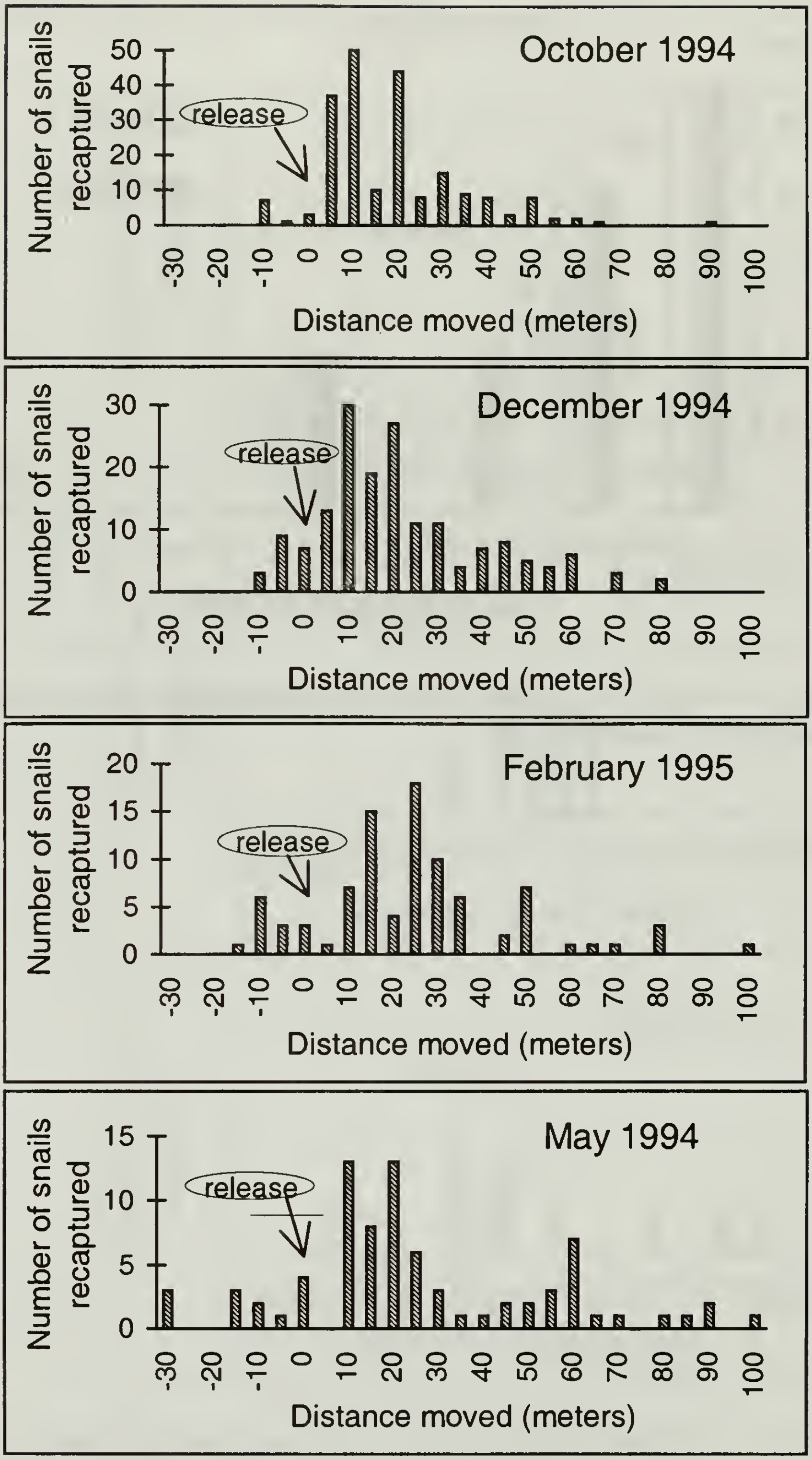


Figure 25. Distance moved from release site by tagged hihiwai during four recapture periods of the second tagging study.

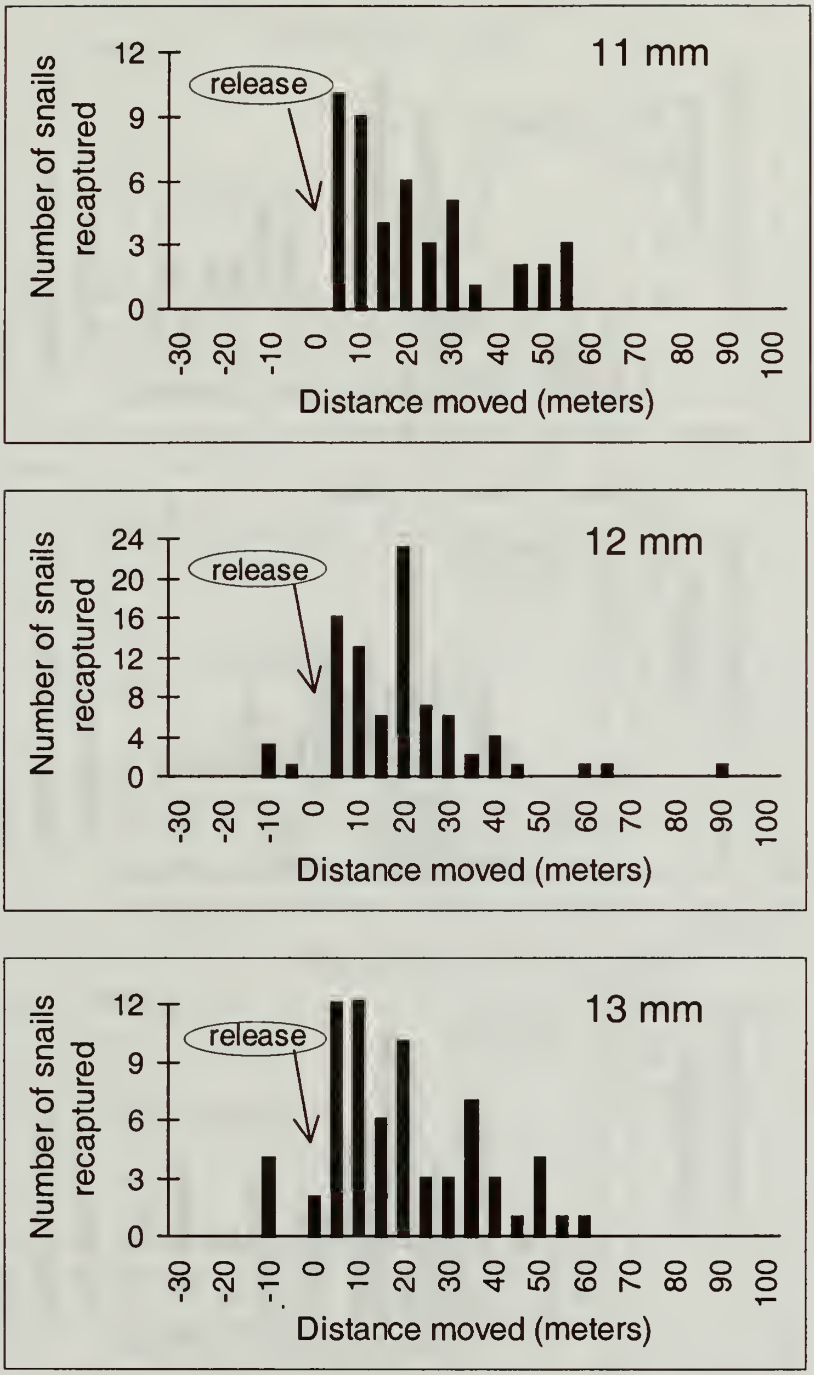


Figure 26. Distance moved after one month by tagged hihiwai of three different sizes; 11 mm, 12 mm and 13 mm, at Station 330.

DECEMBER 1994

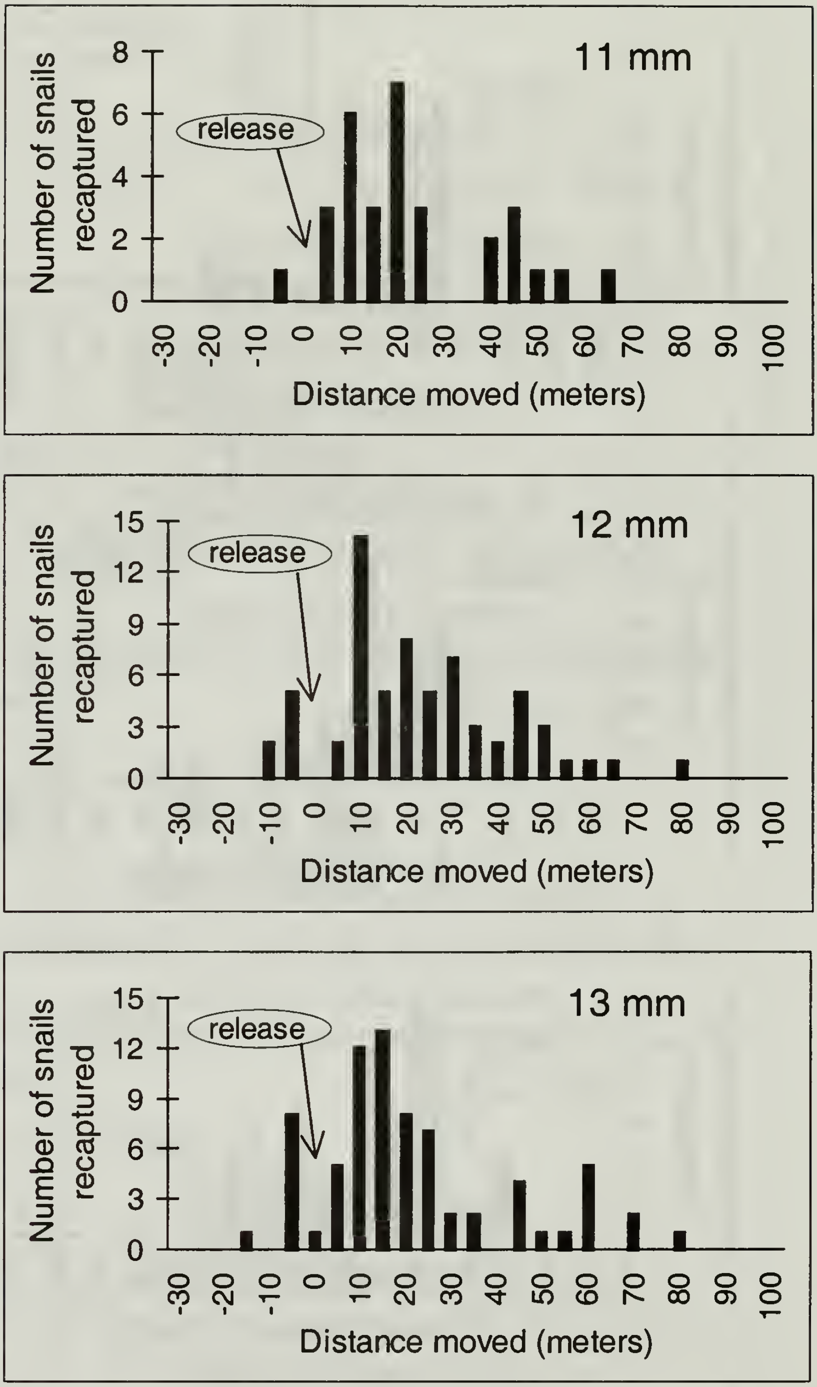


Figure 27. Distance moved after three months by tagged hihiwai of three different sizes; 11 mm, 12 mm and 13 mm, at Station 330.

FEBRUARY 1995

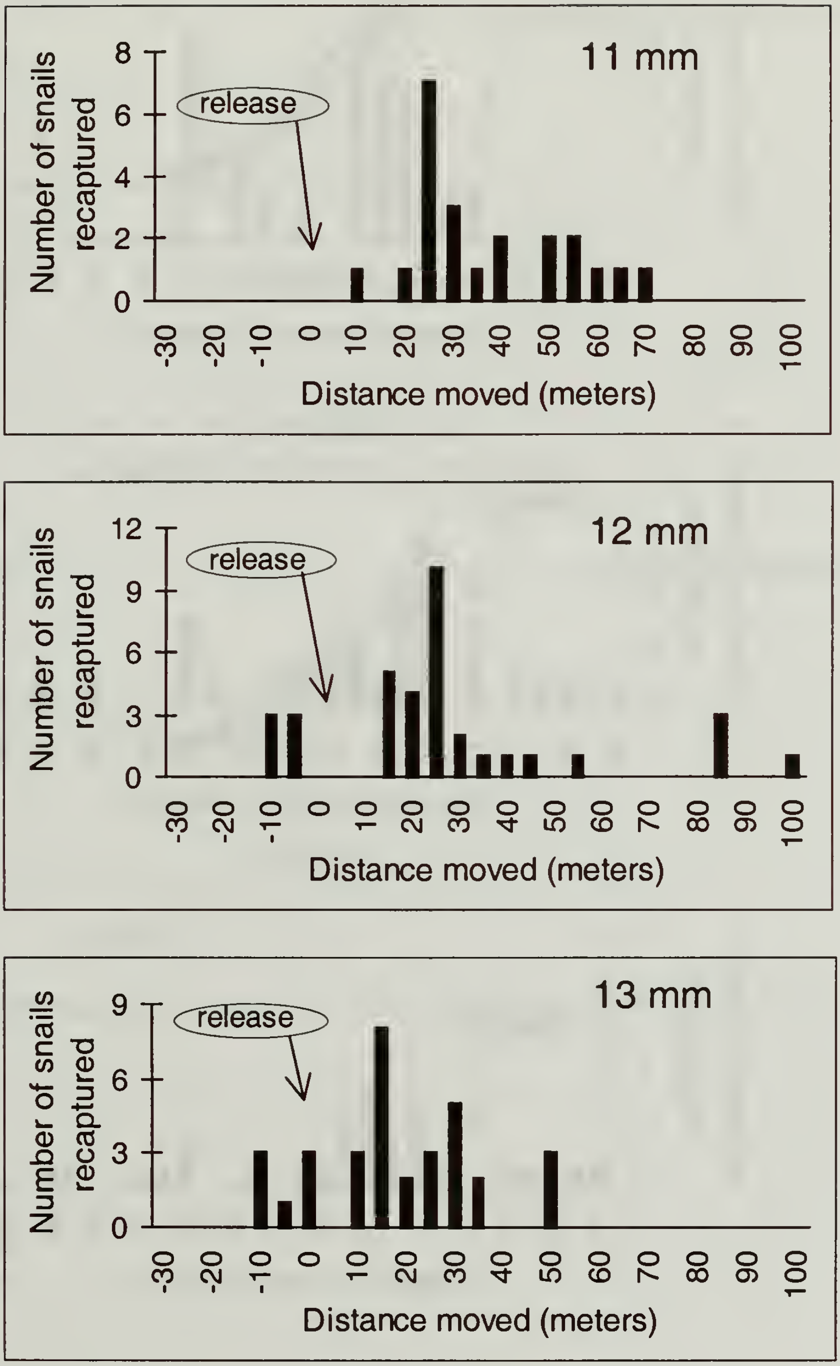


Figure 28. Distance moved after five months by tagged hihiwai of three different sizes; 11 mm, 12 mm and 13 mm, at Station 330.

MAY 1995

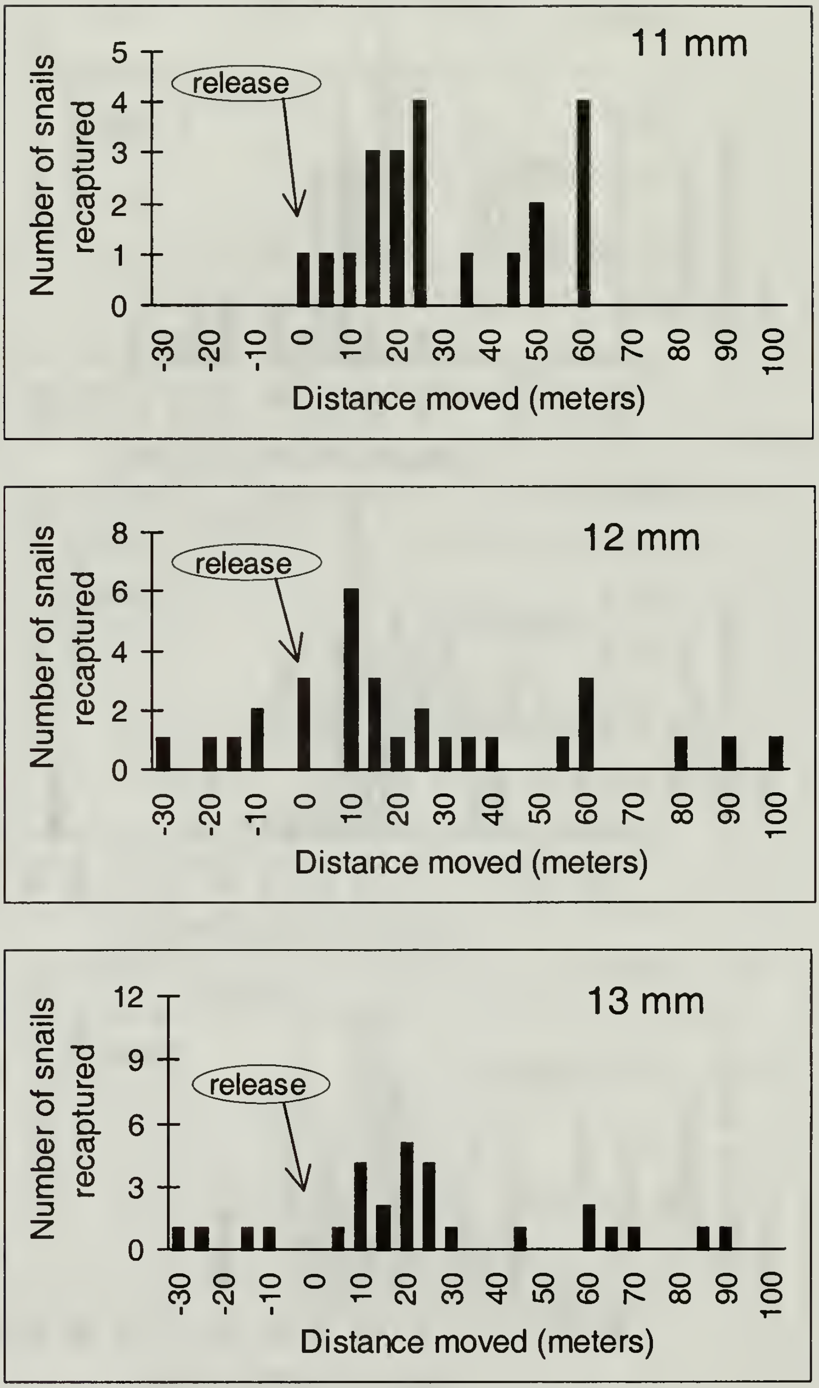
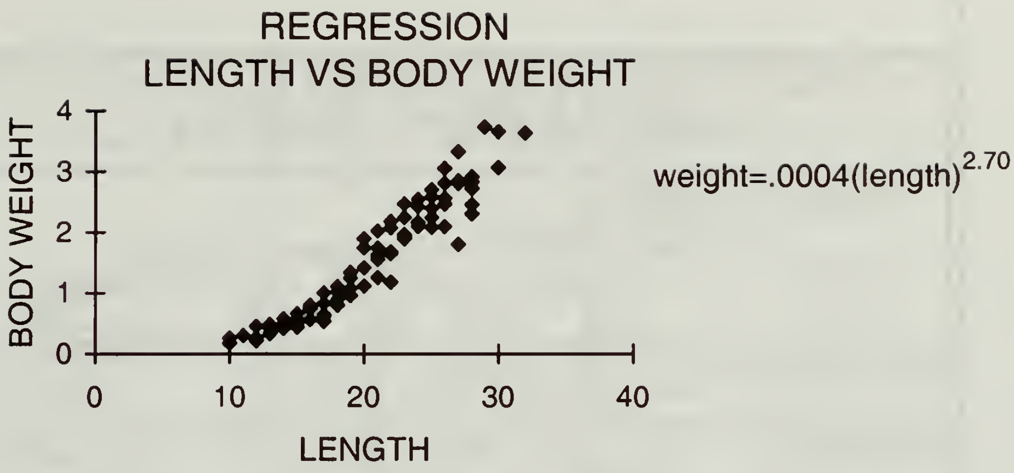


Figure 29. Distance moved after eight months by tagged hihiwai of three different sizes; 11 mm, 12 mm and 13 mm, at Station 330.



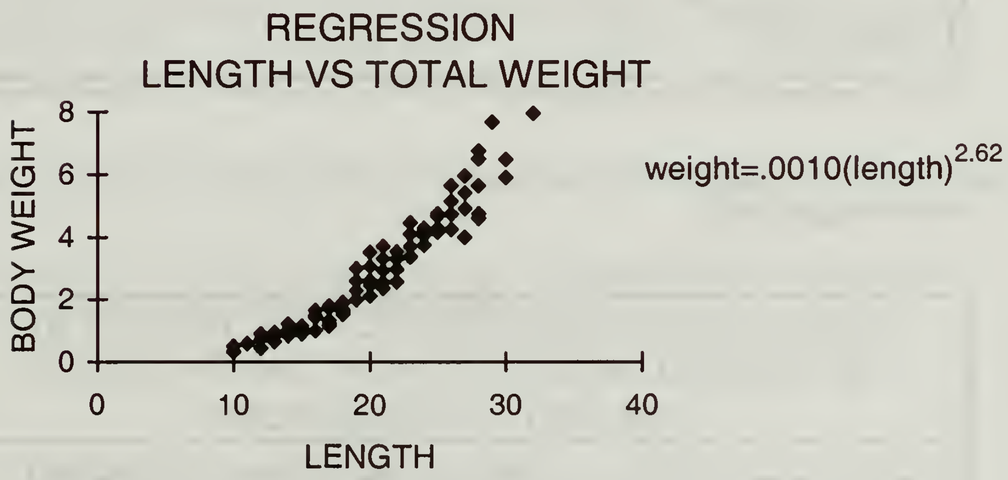


Figure 30. Length-mass regressions for ninety hihiwai collected in Waikolu Stream.

NUMBER OF HIHIWAI RECAPTURED AT EACH STATION DURING THE FIRST TAGGING STUDY			
Retrieval date	Station location		
	220	420	940
March 1993	66	71	71
May 1993	40	56	65
October 1993	28	34	21
March 1994	6	7	11

Table 1. Number of tagged snails found at each station during the four retrieval periods of the first tagging study.

MEAN DISTANCE MOVED FROM THE RELEASE SITE BY TAGGED HIHIWAI AT EACH STATION DURING THE FIRST TAGGING STUDY			
Time since tagging	Distance moved (meters) since release		
	Station 220	Station 420	Station 940
2 Months	10 ± 20	1 ± 16	-3 ± 18
4 Months	5 ± 30	-4 ± 27	-4 ± 26
9 Months	16 ± 34	8 ± 23	-12 ± 40

Table 2. Distance moved (± one standard deviation) by tagged hihiwai at each station during the first tagging study. Mean includes the negative values of downstream movement.

CHANGE IN SIZE OF HIHIWAI DURING THE FIRST TAGGING STUDY			
Time since tagging	Change in shell length (mm) since tagging		
	Station 220	Station 420	Station 940
2 Months	0.16±1.16	0.69±1.00	-0.17±1.13
4 Months	0.58±0.78	0.82±1.31	1.29±1.07
9 Months	2.14±1.21	0.79±1.59	0.52±1.94
14 Months	1.67±1.75	1.71±1.11	2.20±2.20

Table 3. Mean (± one standard deviation) growth of tagged snails as change in shell length (mm) at each station during the first tagging study.

NUMBER OF HIHIWAI RECAPTURED DURING THE FIRST STUDY, LACKING ONE OF THE TAGGING MARKS				
	Retrieval date			
	March 1993	May 1993	October 1993	May 1994
No blue mark	3	3	6	6
No tag	3	17	8	3

Table 4. Number of tagged snails found during each of the four recaptures that had lost either the numbered tag or the blue chalk dust mark.

NUMBER OF HIHIWAI RECAPTURED DURING THE SECOND TAGGING STUDY			
Retrieval date	Snail size (mm)		
	11	12	13
October 1994	45	85	79
December 1994	31	65	73
February 1995	22	35	33
May 1995	21	30	28

Table 5. Number of tagged snails of each size found during the four retrieval periods of the second tagging study.

MEAN DISTANCE MOVED FROM THE RELEASE SITE BY EACH SIZE OF TAGGED HIHIWAI			
Time since tagging	Distance moved (meters) since release		
	Size 11(mm)	Size 12(mm)	Size 13(mm)
1 Month	21±16	18±15	18±16
3 Months	23±17	23±19	21±20
5 Months	35±16	25±27	18±16
8 Months	31±18	24±32	25±30

Table 6. Distance moved (± one standard deviation) by each size class of tagged hihiwai during the second tagging study. Mean includes the negative values of downstream movement.

CHANGE IN SHELL LENGTH (mm) OF HIHIWAI DURING THE SECOND TAGGING STUDY			
Time since tagging	Original size (mm)		
	11	12	13
1 Month	0.96 ± 0.54	0.90 ± 0.70	0.75 ± 0.84
3 Months	1.66 ± 1.00	1.87 ± 0.75	1.45 ± 0.78
5 Months	1.27 ± 1.10	1.69 ± 0.96	1.42 ± 1.13
8 Months	2.31 ± 1.31	2.52 ± 1.24	1.75 ± 1.00

Table 7. Mean growth (± one standard deviation) of tagged snails, as change in shell length (mm) during the second tagging study.

APPENDIX A. Quadrat locations for monitoring hihiwai in Waikolu Stream

Sampling stations were chosen using a random number table, and located in the stream by pacing off the number of steps equivalent to the number of meters from the mouth. Preliminary work showed that with minimal practice, observers could accurately pace a selected distance in meters.

Ten quadrats were chosen at each station, following a Cartesian coordinate system, again using a random number table. Observers reached each quadrat by pacing off the appropriate number of steps (up, and across) equivalent to meters. For example; a quadrat location of (4,2) would be paced four steps up and 2 steps left (from the origin: 0,0 of the station).

Quadrat locations for monitoring hihiwai in Waikolu Stream

30	250	420	1060
0,2	2,7	0,0	0,8
2,6	4,3	1,1	0,9
4,2	4,8	3,7	1,9
4,5	5,4	3,8	2,3
5,3	5,7	5,2	2,4
7,4	7,0	5,4	3,3
8,3	7,6	6,3	3,8
10,5	8,1	7,0	4,6
11,2	9,0	10,7	6,6
11,3	10,5	11,7	9,3
50	**280**	**540**	**1780**
0,5	0,2	1,3	0,0
1,7	1,1	1,4	1,1
2,0	2,6	1,6	3,2
2,7	4,7	6,0	5,2
3,1	5,3	6,2	7,0
3,8	5,7	7,8	14,1
6,6	7,0	9,5	15,0
6,9	7,3	9,6	15,3
7,7	7,8	10,0	16,0
8,1	8,2	12,2	22,1
70	**330**	**920**	**1850**
1,3	1,9	0,3	0,7
1,4	2,0	1,7	3,0
2,0	2,3	3,4	3,2
3,7	3,7	5,8	3,6
5,4	3,8	7,5	5,2
5,6	4,6	7,7	5,4
9,7	4,9	10,1	8,1
10,1	6,4	12,7	8,7
11,3	7,4	13,2	9,0
12,6	9,0	13,4	11,7

220
0,8
1,0
1,7
2,1
4,5
5,6
7,4
8,6
9,2
11,2

370
0,9
0,10
1,10
2,1
3,8
4,9
5,6
6,6
7,8
8,11

940
1,7
3,4
4,2
7,1
7,8
10,5
12,0
12,5
13,3
13,4

1900
3,0
3,1
10,3
11,2
11,5
11,6
14,4
14,6
15,0
16,3

2030
0,0
3,3
11,2
13,0
17,1
17,3
21,3
21,4
23,2
23,4

2780
0,1
1,1
1,6
3,5
5,6
7,1
9,3
10,5
13,0
16,3

3768
8,0
9,1
11,4
12,3
12,4
16,4
21,1
23,0
23,1
23,4

2150
0,10
2,6
3,6
3,12
4,12
4,17
5,8
5,9
6,8
6,10

3077
0,2
1,1
6,1
7,0
13,0
13,1
18,0
18,2
18,3
19,1

2400
1,5
1,6
2,4
10,6
11,4
12,2
13,2
14,5
15,3
17,0

3217
2,4
3,0
3,1
9,0
9,3
12,2
13,2
16,4
17,1
18,1

2640	3558
1,0	1,3
1,2	6,5
2,4	7,4
2,5	10,2
10,1	10,3
11,5	10,5
12,1	15,0
13,3	15,5
14,3	16,3
15,0	19,3