Hawaii Risk Analyses and Management for Dreissenid Mussels

Prepared For:
US Fish and Wildlife Service

Prepared By
Division of Aquatic Resources
Department of Land and Natural Resources
1151 Punchbowl Street., Room 330
Honolulu, HI 96813

Contents

Introduction

The goal of this document is to summarize what is known about *Dreissena* mussel ecology and spread, analyze the relative risk to Hawaii, and provide recommendations for prevention, response, and control.

Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*) are small (<2 inches) freshwater bivalve mollusks native to Eastern Europe. They exhibit classic invasive traits of broad environmental tolerances and morphological plasticity. In North America, *Dreissena spp*. have had devastating economic and environmental impacts as they have moved steadily outward from their initial introduction. State and Federal agencies have been overwhelmed by the efforts to contain the spread, so that eradication seems unlikely. The transportation of dreissenid mussels at any life cycle stage is prohibited into and within of the 50 United States, as well as commonwealths and territories.

The present project was proposed in 2010 to provide an initial assessment of the risk that *Dreissena* mussels pose to Hawaii. The report will summarize currently available literature on the distribution, biology, impacts, and limitations of zebra and quagga mussels. The report will then evaluate the risk to Hawaii based on likely pathways of introduction and the available data related to habitat suitability. The report concludes with recommendations on how best to further minimize the risk of *Dreissena* mussels.

The chief conclusion of this initial assessment is that, while the relative risk of zebra mussel introduction and establishment is low, the state could take steps to be better equipped to respond rapidly to such an event.

Background

Current Distribution and Spread

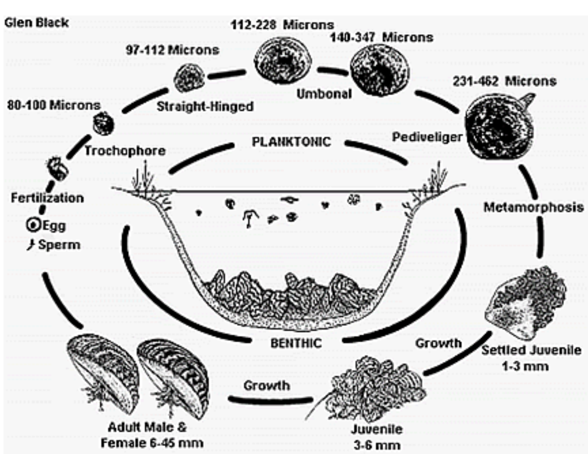
The introduction of both dreissenid species into the Great Lakes region appears to have been the result of discharge of freshwater ballast by transoceanic ships from Eastern Europe that were carrying larvae, juveniles, or adult mussels. Zebra mussels were first noted in Lake St. Clair in 1988. Quagga mussels were identified in the Great Lakes in 1989. Once in the US, they continued to spread. Major habitat alterations such as man-made canals and waterways allow for additional pathways of spread. *Dreissena* mussels can disperse in all life stages: the larvae can spread naturally in downstream currents or in bilge water, bait buckets, and live tanks, while attached adults can move between water bodies in conjunction with infested boats and equipment. By 1991, when the Lacey Act was amended by the Non-Indigenous Aquatic Nuisance Prevention and Control Act to include zebra mussels listed as injurious wildlife, the mussels were already established in 10 U.S. states. Over the next few years the species expanded their US range so rapidly that it was predicted the entire country would be infested by the year 2000 (Strayer 1991; Ludyanski et al. 1993), although the spread eventually slowed by the mid-1990s.

In January 2007, Bossenbroek et al. predicted a low probability of zebra mussels spreading to the western US, although with a moderate to high impact if introduced. Later that month, quagga mussels were discovered established in Lake Mead. Zebra mussels had arrived in California's San Justo Reservoir by January 2008.

Biology and Invasive Traits

Figure 1. Dreissenid life cycle

Dreissena mussels are dioecious, having separate male and female individuals, with eggs released by females to be fertilized in the water column. Females reach maturity in 1-2 years, after which they can annually produce over one million eggs. In warmer climates spawning can occur throughout the year. The resulting veliger larvae remain planktonic for up to a month, enabling considerable spread downstream. Once settled, the mussels will attach via byssal threads to any suitable hard surface, including plants and hard-shelled animals. Younger mussels will often settle on older, larger mussels, resulting in massive clumping colonies known as druses. They are filter feeders, and in some lakes have removed enough phytoplankton and particulate matter to drastically alter water clarity, causing an overgrowth of benthic plants and a change in the trophic structure of the invaded waterway. The mussels are also interesting from the perspective of filter-feeding biology, due to the fact that they are both epifaunal and siphonate (i.e. characteristics of mussels and clams, respectively) (Ackerman1999).



While often referred to interchangeably, there are some differences between zebra and quagga *Dreissena* mussels. Zebras have attained faster rates of spread, but the slower-spreading quaggas have a suite of parameter tolerances that over time seem to give them an edge.

- Substrates: Zebra mussels prefer to colonize hard surfaces, while quagga mussels have increased tolerance for soft-bottom sediments in addition to hard substrates.

- Temperature: Zebras seem to prefer warmer, shallow water. Quaggas can thrive in those conditions but also do well in colder and deeper water.
- Food: Quaggas can filter smaller food particles than zebras, incorporating bacteria as well as phytoplankton and zooplankton into their diet.

Figure 3 Identifying characteristic of zebra and quagga mussels

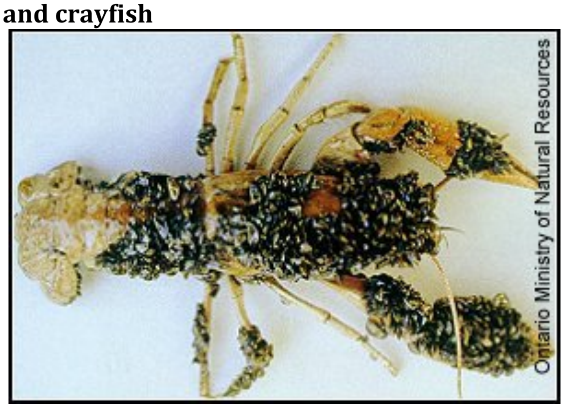
This suite of differences may explain why quaggas, even though they are slower to spread, have been shown to outcompete zebras in areas where both mussels have established (Jones and Ricciardi 2005). The absence of quagga mussels from areas where zebra mussels are present may be related to the timing and location of introduction rather than to physiological tolerances.

This exotic species is remarkably versatile and adept at exploiting new niches. Dreissenids can colonize new areas by arriving as floating larvae, but also can relocate as adults. Settled mussels have the ability to detach from their initial location, move downstream to a new location, then reattach by producing new byssal threads. This capacity allows them to move to more suitable sites with either better conditions or less competition (Grutters et al. 2012). Dreissenid mussels can also invade new waterbodies by hitchhiking over land, attached to boats and gear. When stressed, they can close their shells, and can be out of water for up to a month in cool humid environments.

Environmental Impacts

The environmental impact of *Dreissena* mussel establishment can be quite drastic. In North America, the effect of

Figure 2. Dreissenid mussels on unionid clam and crayfish



Dreissena establishment is evident throughout the food chain. The mussels not only out-compete native filter feeders for space but also for food, as *Dreissena* mussels in high densities are capable of significantly reducing the planktonic food on which the native species also depend. The invaders also colonize the shells of native mussels and clams, causing further competition for food and impairing the native's ability to move, burrow, and reproduce (Parker at al. 1998).

As plankton is filtered out, water clarity increases light penetration, causing a proliferation of aquatic plants that can change species dominance and alter the entire ecosystem. The mussels also encapsulate unwanted food particles as pseudofeces, which can pollute the water and cause an increase in benthic detritivores. As the waste particles decompose, oxygen is used up, the pH becomes very acidic and toxic byproducts are produced.

Economic Impacts

Dreissena mussels are a devastating biofouling organism. They have an affinity for steadily flowing water, and have been profligate pests in lakes, streams, and clogged water-piping and delivery systems on the mainland. When water piping systems are colonized by Dreissenid mussels, flow is drastically reduced. The mussels' impact on industrial and municipal facilities has been profound; a congressional study found that between 1993-1999, the costs to the power industry were $3.1 billion, with additional costs to communities and industries of $5 billion. (QZAP, 2010)

Figure 4. Photograph of quagga mussels clogging a pipe. Note the dime in the foreground of the photo for scale (dbw.ca.gov)

Figure 5. Beach covered with sharp mussel shells. Upper Thames River Conservation Authority

In the Great Lakes region, *Dreissena* mussels have been detrimental to tourism. The shells of dead mussels now litter the beaches in significant enough numbers to require beachgoers to wear footwear as protection against being sliced by the sharp shells.

Limiting factors

The presence and abundance of *Dreissena* mussels is influenced by various physical and chemical parameters. In order to successfully invade a new ecosystem, the mussels must find habitats that suit their tolerances for salinity, flow, temperature, minerals, and water quality. Those that are most relevant to constraining either initial establishment or spread in Hawaii are discussed here.

Salinity

Both quagga and zebra mussels are freshwater species with a very low tolerance for salinity. Adults can be found in salinities up to 1‰, and can tolerate higher salinity for longer; they respond by closing their shells to avoid exposure, although prolonged total closure can stress the animal and causes hypoxia. Larvae of both species are limited to salinities below 2‰ and are killed quickly by brief exposure to even low salinities of 5‰.

Temperature

Dreissenid mussels can survive in very cold water, but will only spawn when temperatures warm to suitable minimums, reported as 9°C for quaggas and 12°C for zebras (Claxton and Mackie 1998). For most temperate waters there are no lower thermal limits for dreissenid colonization, but heat is probably a limiting factor for mussel spread. The thermal tolerance of veligers is reportedly lower than adults, with total mortality of veligers exposed to 30°C for 4.5 days (Craft and Myrick 2011). Adults have been shown to perish with high heat water sprays, used to clean off mussels that have attached to boat hulls. For longer heat exposure of several days, the upper limit for both species has been reported to be approximately 30°C (Karatayev 1998). When experimentally subjected to a range of higher temperatures, quaggas displayed less resilience than zebras. Exposed to 30°C for two weeks, all quaggas died while all zebras survived. At 35°C, all subjects of both species were dead within 24 hours (Spidle et al. 1995). The upper tolerance for quaggas' optimal metabolic health is approximately 25°C.

pH

The concentration of hydrogen ions determines the acidity or alkalinity of a solution, which is measured as pH. pH is measured on a logarithmic scale from 0-14, 0 being the most acidic, 14 the most basic, and 7 being neutral. Each unit is equal to a ten-fold difference in acidity.

There are varying reports in the literature regarding dreissenid pH tolerances, although all seem to agree that adult mussels are more tolerant of extremes in either direction than are veligers. In European lakes, zebra mussel occurrence was associated with a pH of at least 7.3 (Cohen and Weinstein 2001), which is supported by at least one controlled experiment which identified the acceptable range for veliger development as 7.3-9.4 (Sprung 1993).

pH 6.3-6.9 is considered too acidic for zebra mussels (Ramcharan et al 1992, Neary and Leach 1992)

Calcium

Dreissena mussels have high calcium requirements for shell building. The calcium limitations on *Dreissena* distribution and potential spread have been examined by many, although the results are variable. Cohen and Weinstein's (2001) review concluded that 20mg/L was the lower limit for successfully reproducing populations to establish, supporting an earlier study which set calcium (Ca) preferences at 20-125 mg/L (Ludyanski et al. 1993). However, others report that 12-15mg/L is the minimum concentration for growth and reproduction. It has been suggested (Whittier et al. 2008) that risk based on calcium is considered *very low* at concentrations below 12mg/L, and with a range of 12-20mg/L determined to be *low*. Zebra mussels survive better than quaggas at low levels of Ca.

Baldwin (2012) found that while adults in waters with at least 13 mg/L have the potential to survive and grow, fertilization and larval development will be reduced in waters with Ca concentrations less than 18mg/L, suggesting that amount as the lower limit for an invasive population.

Finally, a study from Canada reported the calcium threshold for minimal mussel population establishment to be 8mg/L for zebras and 12mg/L for quaggas, while zebra mussels in less than 20mg/L were found to occur at lower abundances. (Jones and Ricciardi 2005).

Substrate and Flow

Fluid dynamic forces significantly affect the ability of freshwater Dreissenid mussels to disperse and feed. Mussels need water flow to bring constant supplies of food within reach of their siphons. Too much flow, however, makes it difficult for the mussels to attach their byssal threads to the substrate. Testing showed that filtering rates were very good at flows of 10cm/sec, while filtering was was inhibited and resulted in reduced plankton clearance at flows of 20cm/sec. (Ackerman 1999). If flow velocity is very high, >2m/sec, mussel attachment can be prevented, and attached mussels can be dislodged through breakage of byssal threads.

Control

After years of infestation in Europe and North America, there is of course a considerable desire to develop a practical control method. Current methods for control in contained settings such as around power plants and water intakes include detwatering, ozonation, heating, mechanical and manual removal, and pipe coatings (Strayer 2009). Modification of piping systems has also been tried, with some industries extending their intakes into depths below zebra mussel tolerances. Unfortunately, quaggas can colonize deeper water and are now affecting some of these modified structures.

A chemical toxicant for lake-wide control of *Dreissena* has not been developed, mainly because it would be deadly to other aquatic life forms and would be difficult to utilize in open lakes or rivers. The first successful eradication using chemical means took place in Virginia, at the small isolated Millbrook Quarry. The 12 acre quarry was treated with 174,000 gallons of potassium chloride to achieve a target concentration of 100mg/L. The treatment was successful; all adults and veligers were eradicated with no contamination of non-target waters. While the results are promising, the circumstances were unusual and provide little basis for chemical eradication on a larger scale in an open water body.

To prevent contamination of uninfested recreational waters, removal of mussels from boats is accomplished with hot water spray. 60°C spray maintained for 5 seconds has demonstrated to be 100% lethal to both species and is the current recommended practice for cleaning boats and equipment originating from infested or possibly infested waters (Comeau et al. 2011)

Hawaii Risk Assessment

When an alien species has clear negative ecological and economic impacts, there is considerable interest in determining its potential distribution (Whittier et. al., 2008). This report provides an initial determination of Dreissenid invasion risk in Hawaii based on currently available data. Physical and chemical properties provide limitations that constrain the success of dreissenids in Hawaii. The potential distribution, rather than being mapped according to the complete range of factors that could limit establishment, is broken down into an assessment of risk for each limiting factor. Coupled with the predicted pathways of introduction and the likelihood of live transport of dreissenids to the state, this report concludes that the risk to Hawaii is low but should not be dismissed.

The most important physical factors for establishing reproducing populations of Dreissenid mussels in Hawaii are temperatures (both initial transport and in surface water) and calcium concentrations. Overall the risk is deemed low for mussel introduction and establishment.

Potential Impacts

If established in Hawaii, Dreissenids could affect fire prevention waters, irrigation ditches, streams, drainage, rivers, and lakes.

- Taro lo'i, an important food crop worth $2.7 million per year (USDA 2009), could also be impacted if mussels were to settle in the sediment or on the bases of plants. Quaggas can colonize soft bottom sediments, so they would be a risk to taro lo'i, but are less likely to tolerate the warmer temperatures of shallow water lo'i in full sun. Zebra mussels could have a higher temperature tolerance, but do prefer hard substrate for attachment, although in the absence of hard substrate they will attach to other hard-shelled animals (including other mollusks) and the bases of aquatic plants.
- Irrigation ditches are critical for providing water to farms around the islands; if Dreissenid densities in these waterways were reached similar to those in other states, the resulting flow reduction would be a significant concern to agricultural interests. These ditches have suitable temperature and hard substrate for mussel colonization, and also increase the risk of cross-watershed spread.
- Wahiawa Reservoir is a popular freshwater fishing lake on Oahu. It receives treated sewage from adjacent municipalities and military bases, and has elevated nutrients, bacteria, and plankton suitable for high-volume filter

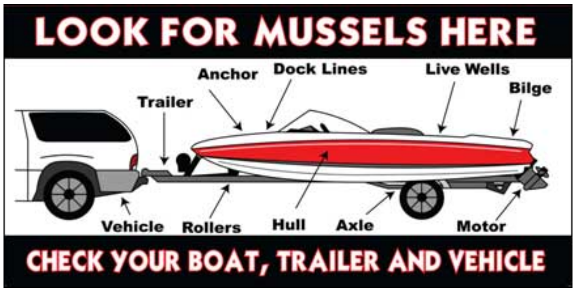
feeders. The reservoir is a haven for invasive species and was the site of a massive multiagency cleanup of *Salvinia molesta* in 2003. Its proximity to military bases, where new personnel arrive regularly with complementary moving arrangements, increases the risk of infested boats or fishing equipment contacting the lake.

- Hawaii is home to many freshwater species of special concern. The state has 5 species (4 endemic, 1 indigenous) of amphidromous fish from 5 distinct genera. These gobies (o'opu) require considerable volume of clean, fresh water. Other native species include three mollusks, and seven decapods crustaceans Any invasive species that alters benthic habitat, water composition, and flow dynamics could be detrimental to these animals, which are already threatened by habitat degradation and the presence of several non-native aquatic species.

Likely Vectors of Introduction

Dreissenid mussels could arrive in Hawaii either as waterborne larvae or as adults. In North America, adult mussels have been transported long distances when attached as biofouling to the hulls of boats, enabling the infestation of waters hundreds of miles from the mussel source. There is no risk that *Dreissena* mussels will arrive in Hawaii attached to the outside of commercial vessels. The exposure time to open ocean salinity associated with an oceanic voyage would surely eliminate any attached freshwater organisms. Ballast from those ships is not a concern, due to Hawaii's lack of any freshwater port, and the common practice of open ocean-ballast exchange. The potential risk lies in the cargo. In North America, mussels have moved over land when attached to small trailered boats, and these same boats could provide a vector to Hawaii.

The most likely pathway for introduction to Hawaiian waters is the containerized shipping of recreational boats or equipment that have larvae in water-holding spaces or directly attached adults. Incoming residents who move from the mainland often have their household goods shipped in enclosed containers. There is no record of the number of small recreational boats that arrive in this fashion, but it is considerable. There is likewise no regular inspection of small boats or fishing gear that arrive via container, and no methodical system to ensure that the gear was cleaned and dried prior to loading. It is conceivable that an infected boat from the western US could be loaded into a container and arrive in Hawaii with viable mussels attached. There is an obvious risk that larvae, which can survive in small amounts of water such as the residual pooling in kayaks, boat bilges, pumps, ballast, live wells, or anything that retains water, could then be released if the equipment is deployed upon into fresh water upon arrival in Hawaii. Adult mussels, which can survive up to 30 days in cool moist weather, might arrive in ballast tanks or attached to boats, engines, and trailers. If a new resident were to ship a small boat that had recently been in infested water in the US or Canada, and then on arrival to take the boat to one of the state freshwater fishing areas, this could well result in an unwanted introduction. Hawaii has several freshwater lakes and reservoirs in which residents enjoy boating and fishing.



California Dept. of Fish and Game

The risk is extremely small, however, that such a scenario would result in a *Dreissena* introduction. Larvae can certainly live in contained water for the time needed for ship transport to Hawaii, but there are other factors that must be considered. Containers, prior to being loaded and after being unloaded, tend to sit at port for days, often in the sun. As any frustrated new resident of Hawaii can attest, the containers often suffer temperature extremes that can warp furniture, and would easily kill both veliger and adult mussels. Of course, there are exceptions, and it is always possible that a larvae-carrying piece of equipment is loaded and unloaded quickly, on a cool day. Hawaii may be a tropical clime, but the state does have a cool wet season that would provide appropriate temperatures to keep alive a container of invading mussels. Thus, in-port delays should not be considered as a reliable risk eliminator unless standardized into a shipping biosecurity protocol with weather taken into consideration.

boatandyachttransport.com

Another pathway, although possibly less likely, is the freshwater aquarium trade. There have been many instances in Hawaii of smuggled fish being brought in for release in local streams and ponds. These invaders, usually procured to establish an exotic food source, are released with the water in which they travel, an obvious risk depending on the source location of the smuggled organism. Veliger larvae are tiny, remain planktonic for significant periods, and could be contained in water from not only smuggled fish but also legitimate pet imports. Water is often dumped directly into receiving tanks without any sort of quarantine. While there is no currently identified mussel infestation in any aquaculture facility, with the impressive rate of spread of these organisms in North America, it must be acknowledged that there is possibility of infestation in the future. Hawaii has a thriving aquarium trade, and also an unfortunate history of aquarium species establishing via the release of unwanted pets. If an aquarium contained mussel larvae or adults, and the water were dumped into one of the states reservoirs, the result could feasibly be Hawaii's first *Dreissena* invasion.

While the risk of Dreissenid introduction is certainly low, it is worth examining the possibility of both introduction and establishment. These animals have wreaked havoc in the continental US, and are definitely not wanted here. It is important to remember that there is no natural vector for these freshwater invaders to arrive in Hawaii. Any introduction would be human-mediated transport.

Potential spread once introduced

Dreissenid mussels, unless "helped" along, have no natural mechanism for traveling upstream. They do not crawl or swim; they are passive floaters and can only colonize down-current. They can be "helped" by non-humans, however, and can be transported by birds and infested aquatic organisms such as crayfish. In Hawaii they are unlikely to move significantly up-stream. Their spread will not be limited, however, to the downstream portions of the same watershed. Hawaiian streams have been significantly altered with diversions and drainage ditches, all of which provide additional potential dispersal vectors.

Surface Water in Hawaii

The risk of zebra mussels arriving in Hawaii, while low, cannot be discounted. Likewise the majority of surface water habitats are less than ideal for establishment. However, the areas most likely to suffer an unwanted introduction, such as Wahaiawa Reservoir, do provide the islands' best habitat offerings for mussel colonization.

Hawaii's five major islands have approximately 366 perennial streams, over half of which flow continuously to the sea. By continental standards Hawaii's stream are miniscule. Hawaiian islands, over time, have developed deep and large valleys carved out by significant rainfall. Drainage basins are steep and have limited channel storage. At first glance it would seem that these discrete watersheds would severely limit potential spread of a new species. However, with the advent of large-scale agriculture in Hawaii, extensive irrigation ditches were built that provide water pathways not only between adjacent watersheds, but in some cases across islands directly through a seemingly impenetrable mountain range.

USGS began gauging surface water in Hawaii in 1909, primarily to determine the potential to serve agricultural irrigation needs. Unfortunately for this report, almost all gauging in Hawaii is to evaluate the volume (cubic feet per second) of available water, not the flow velocity. Since dreissena mussels can be dislodged at flow speeds higher than 2m/sec, it is desirable to ascertain whether that speed is achieved.

Streams in Hawaii have been often modified with dams and diversions into ditch systems. Diversions have become essential for the state's agricultural industry, and for municipal use in some areas. Channelization of streams has been a common practice to increase the land area available for development. Channelized streams have increased flow velocity, as well as increased temperature and illumination from the removal of shading vegetation. Channels lined with concrete are built oversized to accommodate storm flows, which during normal conditions results in shallow warmer water that can be inhospitable to many aquatic species. A survey done by the US Fish and Wildlife Service between 1975-1976 found that streams containing altered sections had greater means and ranges in temperature, pH, and conductivity.

Fortunately, Hawaii's larger freshwater basins do not seem to be very suitable for dreisenna mussel establishment. Data was retrieved from EPA (STORET) for Hawaii Department of Health and the City and County of Honolulu. Water quality stations surveys did not display good conditions for *Dreissena* growth and reproduction. This analysis suggests a low probability that *Dreissena* mussels will be introduced to Hawaii, and a low probability that an introduction would significantly impact human infrastructure or native freshwater biodiversity.

Limiting Factors

To characterize the suitability of Hawaii waters for establishment of *Dreissena spp.* mussels, data was sought from various sources:
STORET, USGS, USFWS, Hawaii DLNR, Division of Aquatic Resources: Stream Survey Data, and Hawaii Department of Health. Available data was sparse but covered a several decades.
Summarized data can be found in Appendix C.

Salinity

Dreissenids are freshwater species, but can tolerate very low salinities for short exposures. Tolerance to higher salinities increases with larval age in both species (though the embryos and larvae of zebra mussels have a higher degree of tolerance than to the same life stages of quagga mussels).

Dreissenid mussels generally do not tolerate salinity over 2-3ppt, but they can be acclimated up to 6ppt (quaggas) and 10ppt (zebras) when done slowly (Wright et al, 1996). Hawaii does not have systems with suitably stable low salinities, and mussels would not survive the repeated short-term fluctuations in salinities associated with estuaries and stream mouths in the islands.

Due to their steep discrete watersheds, Hawaiian streams, if unaltered, would prevent any cross-watershed spread of these mussels since the streams all end in open ocean salinity. The diversions and ditches that now crisscross the islands could allow (and have allowed) the additional spread of invasive species that might have otherwise have been naturally contained. In Hawaii, while the ocean's salinity lowers the risk of initial introduction and interisland spread, it cannot be assumed to limit the dispersal of Dreissenid mussels should they be introduced.

Temperature

The reported upper tolerance limit for temperature is 30°C, although poor growth is evident in waters above 28°C. In the lower Mississippi River, mussels exhibit depressed shell growth when temperatures reach 29-30°C. In controlled temperature tests at 35°C (95 F) all specimens of both mussel species dies within 24 hours (Spidle et al. 1995). Almost all quaggas were killed when subjected to 30°C for 7 days, although zebra mussels were fine. Zebras did not survive long-term exposure to 32°C (Claudi and Mackie 1993).

Peak spawning for both species occurs in the range of 18-24°C. In Hawaii, stream temperatures average range is 20.3-21.4°C, well within the optimum range for mussel establishment and year-round spawning, especially for shaded streams. Altered streams that have been cleared or channelized can reach a high of 30°C. There is insufficient data available to conclude which streams, if any, would regularly reach sufficient temperatures to self-control a mussel introduction.

Shipping containers, if left in the sun, can be expected to exceed the temperature tolerance for both species, which could lower the risk posed by either larvae or adults that may have hitchhiked to Hawaii.

pH

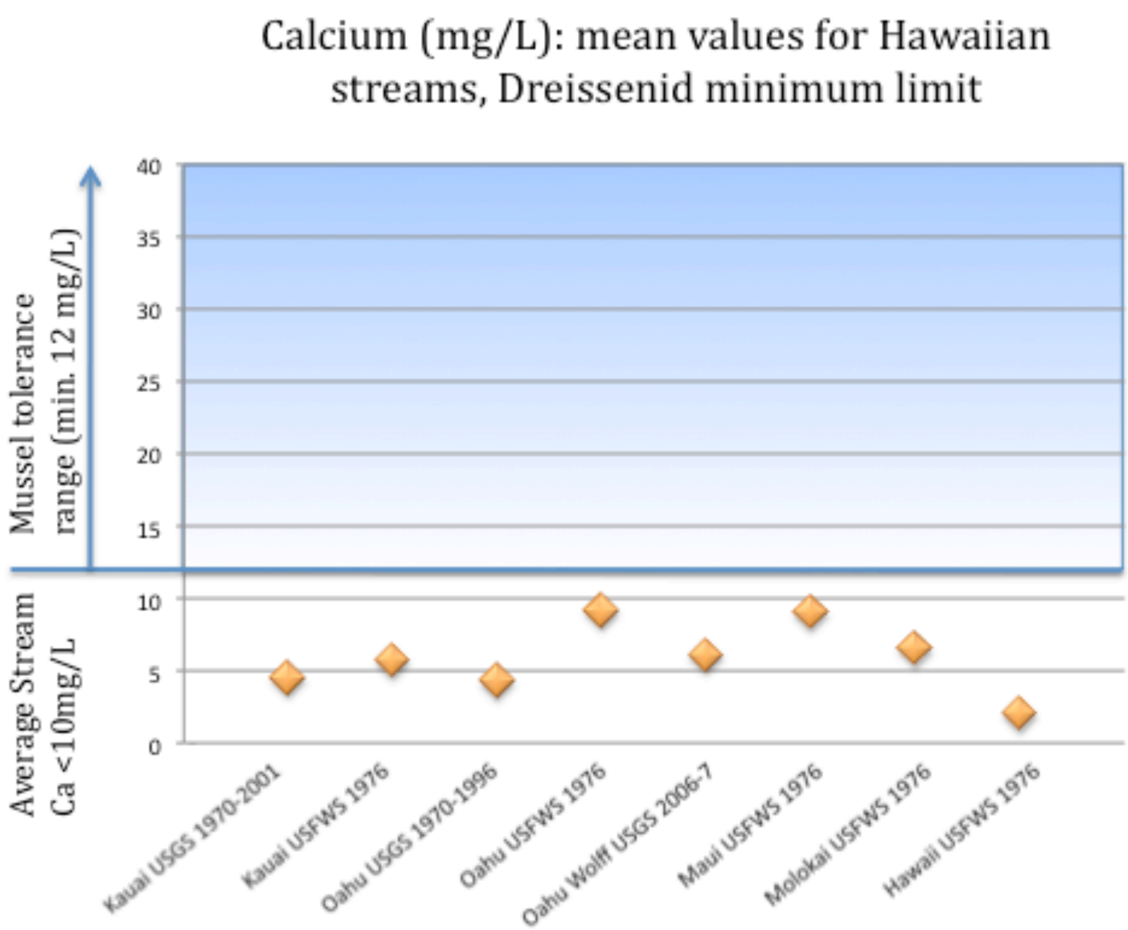
Alkalinity is a measure of water ability to neutralize acid. Most alkalinity in surface water comes from the leaching of calcium carbonate (CaCO3) from rocks and soils. The islands of Hawaii are volcanic in origin, with little to no limestone. Volcanic basalt erodes very slowly, is low in buffering minerals, and therefore has very low alkalinity.

The pH ranges for monitored sites in Hawaii falls within the lower tolerance parameters for *Dreissena* mussels. The often reported minimum for mussel development is 7.3. Hawaii's surveyed pH range is 6.2-7.5, with a statewide average of 7.14. We can thus assume that the Dreissenid risk based on pH is low.

Calcium

Along with temperature, calcium is likely the most important factor limiting potential dreissenid establishment in Hawaii. Much of the available literature indicates that healthy populations require calcium concentrations above 18-20 mg/L. Given the dramatic risks of invasive species, it is advisable to develop risk frameworks based on the most conservative findings. For this report, risk will be estimated based on the dreissenids' low-end reported tolerance for calcium of 12 mg/L, although it is speculated that occurrences of mussels at or below that range are sinks (i.e. non-reproducing populations). Most streams in Hawaii have levels below 12, usually well below 10 mg/L. Streams that have abnormally high calcium readings, such as Pauoa on Oahu, are channelized and likely have elevated calcium measurements resulting from the concrete linings.

Calcium concentration is not a standard measure for most stream surveys in Hawaii; the data is sparse but relatively consistent and indicates low calcium concentrations throughout the state.



Flow Velocity

Darrel Kuamo'o. Wailuku, Hawaii (DAR) Stream showing normal and flood stage

A vital limiting factor for mussels but one which has received less mention in the literature is flow velocity. From fertilization to larval settlement, zebra mussel veligers can float in the water column for up to a month as they are passively carried downstream. While ponds and reservoirs provide the slow moving water that mussels seem to prefer for dispersal and feeding, the short stream length and high-flow volumes of many Hawaiian watersheds could effectively flush the majority of larvae out to sea during the pre-settlement window. In a study of multiple environmental variables, Chen et al. (2011) found that flow velocity was the most significant variable associated with decreased settlement of veligers. The streams in Hawaii are subject to periodic and seasonal "flashing" that can not only prevent larval settlement but can easily exceed the 2m/sec flow rate that has been shown to prevent attachment and dislodge the byssal threads of settled adult mussels (Benson and Raikow 2008).

Discussion

The establishment of an invasive species is dependent on both an effective introduction and the ability of the new species to grow, reproduce, and spread. The risk of introduction to Hawaii is small but does exist. While the majority of stream environments provide less than suitable conditions for *Dreissena* mussels, the few that have a higher risk of introduction, such as Wahiawa reservoir, also have parameters approaching the mussels preferences. Given the extreme costs associated with eradicating or controlling a newly established invasive, those areas should receive additional attention in standard monitoring protocols.

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Appendix A: Management Plan

The goal of this plan is to prevent the arrival and establishment of *Dreisenna* mussels in Hawaii. The plan identifies key agencies, and recommends outreach programs, targeted monitoring, rapid response strategies, and possible eradication methods

Agencies Coordination and Leadership

Partner agencies, both federal and state, can be expected to provide a coordinated response to a suspected introduction. These agencies are all currently active on invasive species issues. At this time it is not deemed a priority of any agency to develop a distinct task force or response panel solely to deal with *Dreissena* mussel detection or response.

- The Hawaii Department of Agriculture lists zebra mussels (but not quaggas) on its list of pests designated for control or eradication (§4-69A-4(f)), and thus can be expected to respond aggressively.
- Hawaii Department of Land and Natural Resources is tasked with managing introduced wildlife in Hawaii, and has staff who have both terrestrial and aquatic expertise in invasive species management and control.
- Hawaii Department of Health is responsible for maintaining water quality, and will need to coordinate any permitting issues that may arise if using chemicals to respond to an invasion.
- US Fish and Wildlife Service can be expected to provide technical assistance, as a *Dreissena* introduction could have a serious detrimental effect on the states freshwater species of concern.
- US Geological Service conducts regular stream monitoring and has expertise in both water quality and biological parameters of Hawaiian streams.

Prevention

As is often the case with public perceptions of invasive species, attitudes in Hawaii are either fatalistic (i.e. we can't possible prevent a new invasion) or dismissive (i.e. we are so geographically isolated that we don't need to worry about accidental introductions). For many potential invasive species Hawaii provides a haven, with a moderate climate and reduced niche competition. Invasive species have arrived in the state both accidentally and deliberately, permitted and unpermitted. Indeed, invasive species have so drastically altered the habitat that one can walk for miles and not see a native species. Given the impacts that *Dreissena* or similar mussels could have in Hawaii, efforts should be made to promote the issue and its impacts. This plan recognizes that while the likelihood of dreissenid introduction is small, it should not be discounted, and a targeted outreach campaign may help further reduce the potential that *Dreissena* mussels may arrive in the state.

The target is to reduce the risk posed by newly arrived personal boating and fishing gear. Recommendations:

- Coordinate with employers, such as the military, who provide moving assistance for personnel and cover the costs of shipping containerized goods. Distribute information on invasive species, and request that gear be completely clean and dry prior to loading. Encourage new arrivals to introduce their gear to the ocean before a fresh water test.
- Test the internal temperatures of containers in port. If they have reached at least 30 C for several days there is little likelihood of any surviving larvae or adults.

The staff of each agency should review the likely import vectors and familiarize themselves with the characteristics of both *Dreissena* species.

Early Detection

A great deal of research has been done in Europe and North America to determine the environmental tolerances of dreissenids. In order to fully evaluate which waters in Hawaii are at risk, the values for those parameters need to be determined. Key water bodies should be tested for calcium, pH, and high temperature to determine their suitability to establishment. Waters that satisfy the mussels' requirements should be included in routine monitoring.

Rapid Response Plan

The invasive species management community in Hawaii has effective coordination and is working towards improved management capacity. The Coordinating Group on Alien and Pest Species (CGAPS) and the Hawaii Invasive Species Council (HISC) have identified interagency coordination and rapid response as a high priority. A workshop has been held to help identify gaps and needs related to agency authorities and ability to respond. A series of future workshops is anticipated to develop an invasive species rapid response plan that coordinates notifications and response among all relevant agencies. The plan is not expected to be tailored specifically toward any one species, but rather a generic assigning and accepting of roles and responsibilities.

If mussels are seen that are suspected to be *Dreissena*, agencies must respond quickly to identify the species. The following entities can be expected to respond immediately to report of suspected mussel introduction:

- Department of Agriculture
- Department of Land and Natural Resources (DAR, Invasive Species)
- Bishop Museum (taxonomic identification)
- USFWS Pacific Islands Fish and Wildlife Office
- City and County where affected

All responders should use standardized procedures for incident management and contaminant containment to ensure that no further spread results from control efforts.

643-PEST is a 24-hour hotline for the public to call with suspected new or unidentified alien species.

Response Objectives will include:

- Identify lead agency
- Initial assessment of infestation extent
- Containment, through management of recreational use
- Obtain permits if needed, and landowner permissions as applicable
- Explore control options
- Identify necessary actions and agency capacities
- Carry out eradication measures
- Provide timely and accurate information to the public
- Monitor for recovery of natural system and additional detection
- Evaluate the mechanism for introduction, share findings with management agencies to prevent future occurrences

Control methods

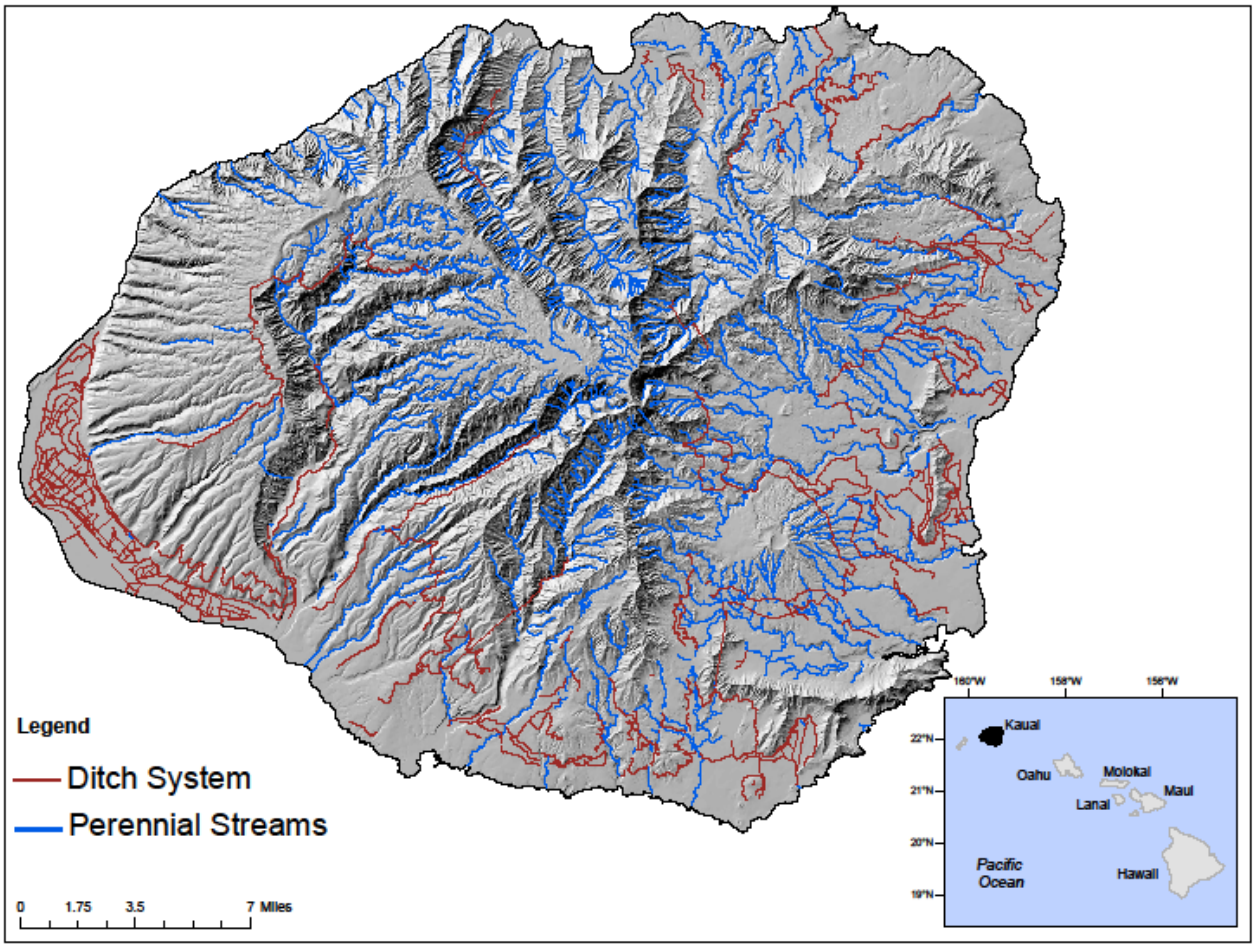
The need to control *Dreissena* mussels has fueled intense research and experimentation in the search for solutions. Chemical options are usually not applicable in open waterways, as the damage to native species is high and the likelihood of success in a self-diluting system is low. Hawaii Department of Health (DOH) recently released rules related to the use of pesticides in aquatic environments and has have approving authority for any manipulation of water quality parameters. DOH would be expected to provide guidance regarding acceptable eradication methods should *Dreissena* mussels be introduced to Hawaii. Chemical options have been used in internal and closed systems, but the majority of removal operations have been mechanical or by manipulation of environmental tolerances.

Mechanical removal can be accomplished by scraping, brushing, or otherwise dislodging the mussel's attachment. These methods work well for clearing pipes, pilings, boat hulls, etc. Re-colonization is swift, however, so these treatments need to be repeated regularly.

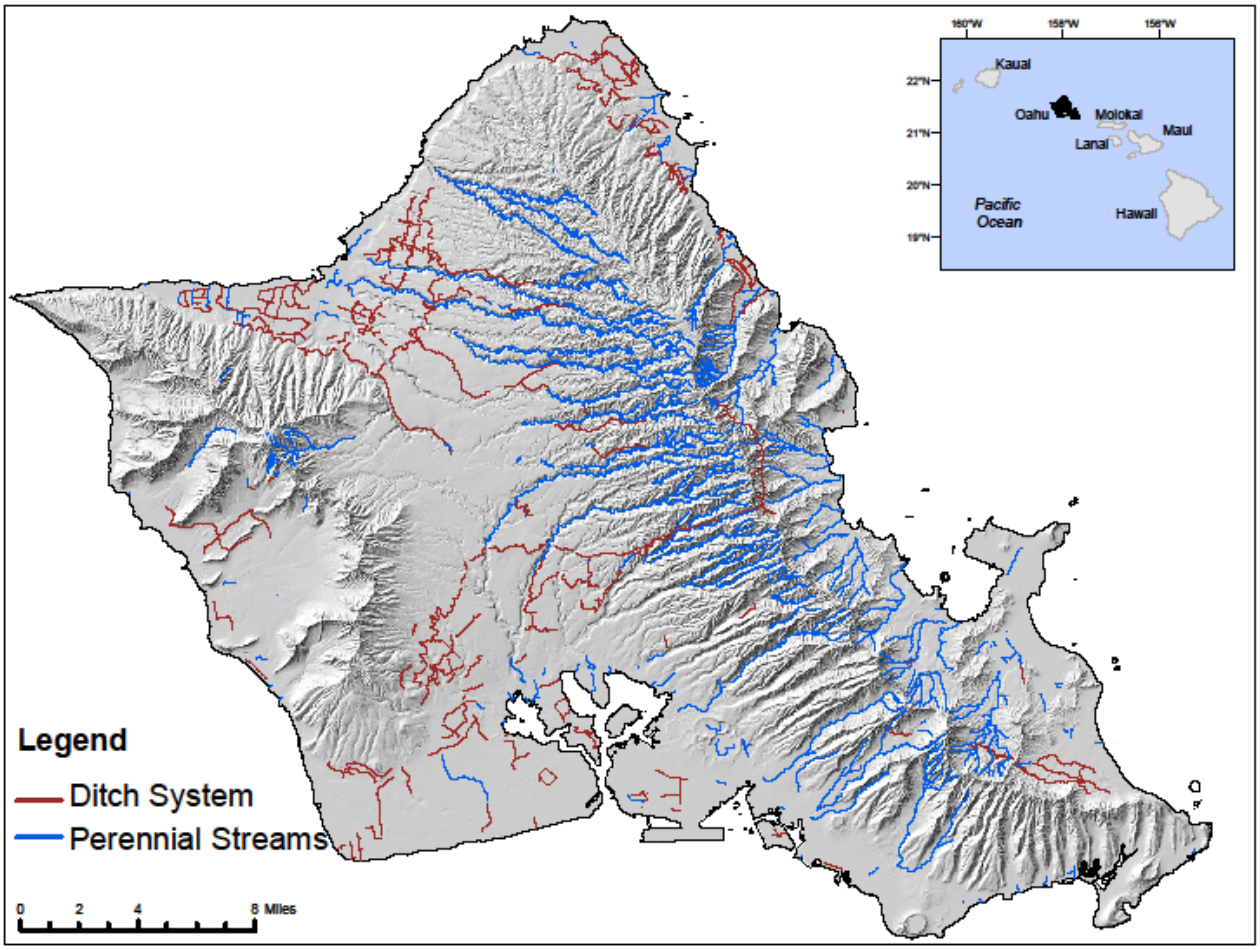
Habitat manipulation is another type of mussel control that can be effective. *Dreissena* mussels are susceptible to significant increases in temperature or flow, decreases in oxygen or pH, or dessication. Streams can be dewatered or have flow slowed enough to allow the water temperature to rise above 30°C.

Appendix B: Waterway Maps

Kauai

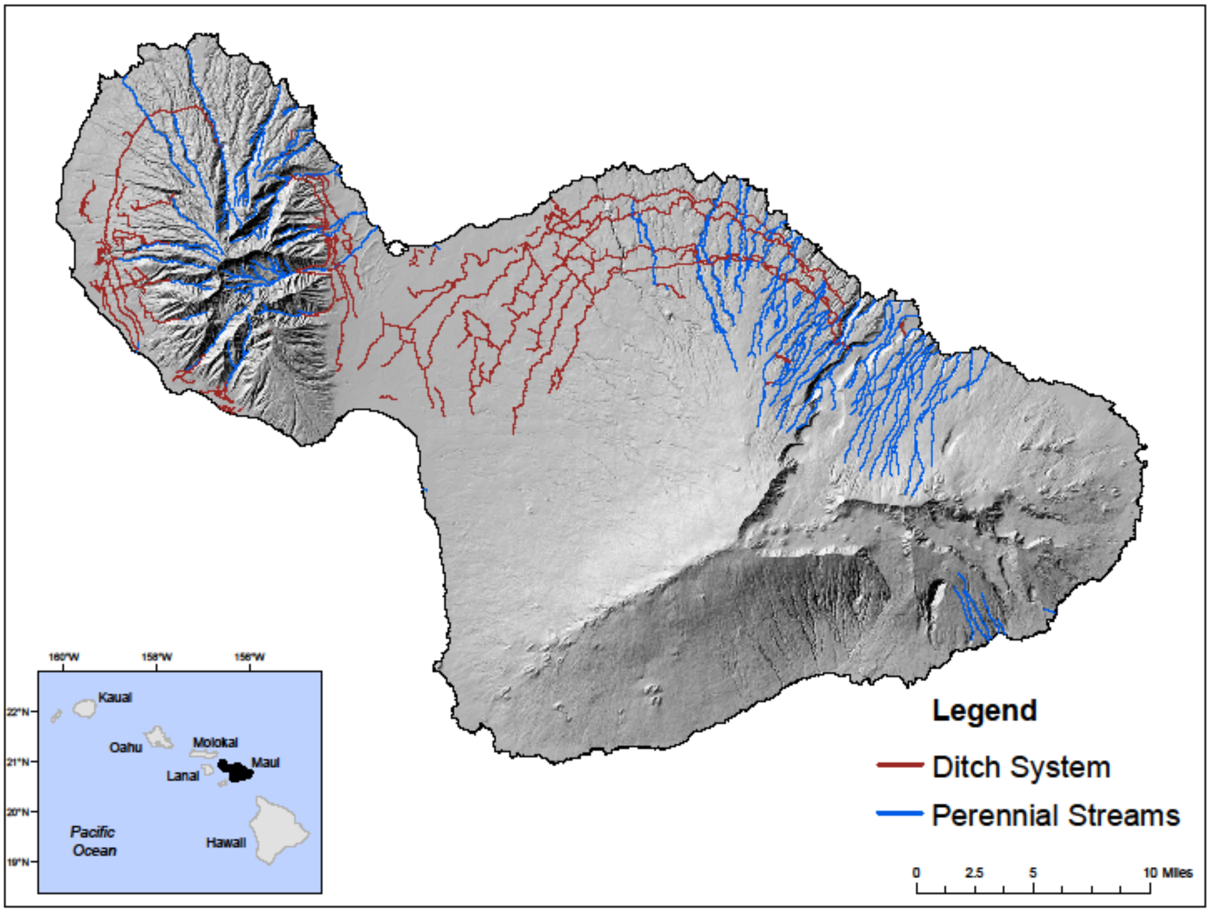


Oahu

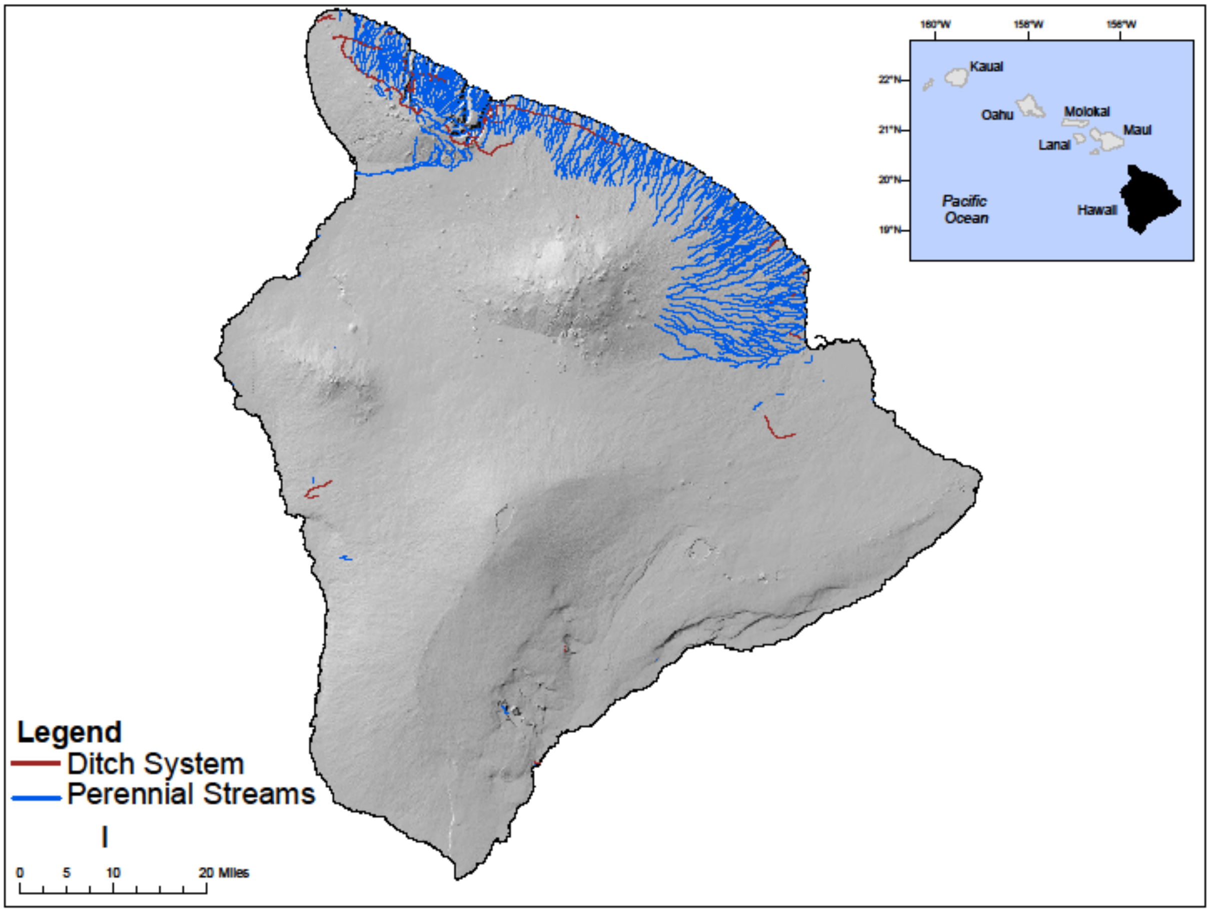


160°W
158°W
156°W
22°N
21°N
20°N
19°N
Kauai
Oahu
Molokai
Maui
Lanai
Pacific Ocean
Hawaii
Legend
Ditch System
Perennial Streams
0
2
4
8 Miles

Maui


160°W
158°W
156°W
22°N
21°N
20°N
19°N
Kauai
Oahu
Molokai
Maui
Lanai
Pacific Ocean
Hawaii
Legend
Ditch System
Perennial Streams
0
2.5
5
10 Miles

Hawaii Island



Appendix C: Water Quality Data

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pH

Year(s)	Source	Mean	Min	Max	StDev
2005-2010	DAR	7.4	4.99	9.1	0.55
1970-2001	Kauai USGS	7.07	4.7	8.6	0.517
1970-1996	Kauai USFWS	7.3			
2006-2007	Oahu USGS	6.88	5.4	8.5	0.49
1976	Oahu USFWS	7.2			
1976	Oahu Wolff USGS	7.5	6.51	9.45	0.5
1976	Maui USFWS	7.5			
1976	Molokai USFWS	7.2			
1976	Hawaii USFWS	6.2			

Temp C

Year(s)	Source	Mean	Min	Max	StDev
2005-2010	DAR	20.43	11.94	31.52	2.12
1970-2001	Kauai USGS	20.3	10	30	2.51
1970-1996	Oahu USGS	21.41	16.5	31	2.18

Calcium

Year(s)	Source	Mean	Min	Max	StDev
1970-2001	Kauai USGS	4.44	0.5	13	2.75
1976	Kauai USFWS	5.7			
1970-1996	Oahu USGS	4.25	0.5	27	5.99
1976	Oahu USFWS	9.1			
2006-2007	Oahu Wolff USGS	6.06	0.815	20.56	3.77
1976	Maui USFWS	9			
1976	Molokai USFWS	6.5			
1976	Hawaii USFWS	2			

Spec Conductance

Year(s)	Source	Mean	Min	Max	StDev
1970-2001	Kauai USGS	87.26	21	320	33.35
1976	Kauai USFWS	131			
1970-1996	Oahu USGS	84.18	22	384	53.72
1976	Oahu USFWS	180			
2006-2007	Oahu Wolff USGS	131.37	43.93	283.5	56.63
1976	Maui USFWS	107.4			
1976	Molokai USFWS	93			
1976	Hawaii USFWS	43			

Data From:

DAR	Division of Aquatic Resources. Stream Surveys
USFWS	Timbol & Maciolek (1978) Statewide inventory of streams
USGS	waterdata.usgs.gov
Wolff USGS	Wolff & Kock (2009) Ecol. Assessment of Wadeable Streams on Oahu