ASSESSMENT OF FRESHWATER IMPACTS ON CORAL REEF FISHERIES OF HAWAII

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EXECUTIVE SUMMARY

Links between specific marine species, particularly native mullet *(`ama`ama*) and flagtail (*aholehole*) and freshwater input to the ocean are widely described. Although no discrete threshold has been established, juvenile *`ama`ama* appear to prefer water with salinity below 15 ppt (Blaber 1987, Dr. Ken Leber, Mote Marine Lab, Sarasota, Fla. pers. communication to Ron Englund). When salinity becomes > 15 ppt, juvenile *`ama`ama* will abandon an area and move in search of fresher water. Salinity preferences for *aholehole* are less established than that for *`ama`ama*, but the seasonal use of nursery habitat by *aholehole* is similar to that of *`ama`ama*. *Ulua* (Carangidae) and *akule* (bigeye scad) have also been linked to marine nurseries and climatic conditions in some reports, but not as specifically as linkages of *`ama`ama* and *aholehole*.

Striped mullet is a classic estuary organism. It is part of a group of fishes that must spawn in the marine high salinity sea water but whose juveniles move into bays and estuaries and up into streams (Leber Tr. 4/23/96 in Commission on Water Resources Management 1997). A major decline in Hawai`i consumer use of fresh mullet *(`ama`ama*) since 1900 and evidence that *`anae holo*, or seasonal migrations of *`ama`ama* off O`ahu have ceased, provide solid evidence of the disruption of striped mullet patterns in Hawai`i. This issue deserves far more attention from scientists.

The catch records compiled by Hawaii's Department of Land and Natural Resources (DLNR) are for commercial fishing methods only. Confidentiality of fishermen further limits the potential uses of the commercial catch data. Despite these limitations, attempts are made in the present report to compare long series of Hawai`i fishing records for marine species with peaks and valleys related to peak freshwater discharges. These efforts were ineffective, however.

One study demonstrates how changes in the growth of rates of the marine seaweed *Gracilia coronopifolia* (*limu manauea*) are affected by local changes in salinity and nutrient flow into coastal areas along the Kona coast by groundwater submarine discharge (Duarte et al. 2010)..

1.0 INTRODUCTION AND PURPOSE

The purpose of this report is to link salinity changes and freshwater flow with their possible effects on marine fish fauna in Hawai`i. Freshwater fauna and flora are excluded from the present report. Because of the diadromous life cycles of most native stream macrofauna, intact headwaters and upper stream courses with highly modified lower courses and mouths limit all but the most hardy native freshwater species (The Nature Conservancy of Hawai`i 1998).

In the U.S. Geological Survey (USGS) Pacific Islands Water Science Center list of publications, there are several reports that relate stream species assemblages to habitat characteristics (example: Brasher et al. 2003). However, there are no U.S.G.S. reports that relate freshwater flow with marine biota characteristics (USGS Pacific Islands Water Science Center, publications list website viewed Feb. 13, 2012).

Of the approximately 360 perennial streams in Hawai`i, about 20 form stream mouth estuaries (Maciolek 1981; Maciolek and Timbol 1981).  Most Hawai`i streams are small and flow over steep topography, usually entering the ocean over or through wave-formed sand or rock berms. These geological characteristics, combined with the typically rapid changes in stream discharge, have limited the formation of stable inland reaches, or estuaries, where freshwater is regularly influenced by seawater (Smith and Parrish 2002).

Salinity is a measurement in grams of salt per kilogram of solution (g/kg), which can also be expressed as parts per thousand (ppt or 0/00). Seawater contains a mixture of salts, the most abundant being sodium chloride, or table salt. The oceans contain an average of 35 grams of salt per kilogram of seawater (35 ppt). The level of dissolved salts in a fluid controls many of the processes of life. Most animals are adapted to a narrow range of salinity and cannot live in water that is outside of that range. Some animals are able to tolerate a wide range of salinities, however.

Resident fishes vary greatly in the amount of time spent in an estuary, age at entry, seasonality, habitats and reaches occupied, resources used, and degree of dependence upon the estuary.   For all of the marine species listed in Table 1, the estuary seems to serve a nursery function, although adults may occur there at least occasionally. In terms of fishery resources, this function may be quantitatively significant for *aholehole* and native mullet *(`ama`ama*) but no relationships have been established. The quantitative importance for other species is much less obvious. Because all the marine fishes are abundant in Hawai`i estuaries primarily as juveniles, they may be somewhat inconspicuous as adults and, therefore, the significance of estuaries as adult habitat may be underappreciated. All the marine species, however, have much larger nursery habitat elsewhere in marine waters (Harrison et al. 1991).

A management concern for all estuaries is the danger of habitat and water quality degradation resulting from human activities, including pollution and direct physical alteration of the stream. If such activities cause the death of juveniles in the estuary, this will lower populations of adults and reduce marine resources for exploitation, recreation, and scenic values elsewhere. Any environmental changes that persist can be expected ultimately to reduce the stocks of coastal stocks of the marine and estuary resident species affected (all ages) and result in continued reduced reproduction (Harrison et al. 1991).

For the marine and estuary resident species in Hawai`i, the fraction of the total population lost because of estuarine degradation would be different for each species. These abundances cannot be presently established because no estimate is possible of their absolute abundance in Hawai`i estuaries or of the fraction that their survivors may provide of all coastal juvenile survivors.

The extent of estuarine habitat in Hawai`i is highly variable over time, responding primarily to changes in fresh water discharge of rainfall in upland watersheds. Effects of tide on estuarine condition are much less than those of runoff. Sea condition may produce significant effects at times due to entry of salt water by wave wash over sand and berm bars at stream mouths.

As a result, fauna that require or prefer some salinity may be present a portion of the time in deeper strata rather far upstream in some estuaries. At low to moderate stream discharges, vertical temperature and salinity gradients are usually sharp, and mostly occur together, primarily in the depth range of about one to 2.5 m. This pattern tends to produce a two-layered distribution that is cool and fresh above and warmer and more saline below. High discharge increasingly distorts this pattern and at extreme discharges, all salt water is flushed out and water in the full length of the stream is cold and fresh. The full range of temperature and dissolved oxygen can probably be tolerated by all fish species present, although some of the most fully marine species might relocate to avoid the coldest temperatures, as well as the lowest salinities. In some observed streams, several marine species of the lower estuarine reaches appeared to be absent just after high freshwater discharges (Harrison et al. 1991).

Because the juveniles of marine species come from the sea and ultimately return to it, they are vulnerable to environmental degradation even if the effects are concentrated in a short length of the estuary anywhere downstream of their normal habitat. Any sources of reduced water quality in upper stream reaches will likely be felt downstream in the estuary unless diluted below harmful levels by sufficient mixing and additional runoff to the stream

It is not clear to what extent marine juveniles may survive an encounter with environmental deterioration that simply blocks them from passing through it into upstream habitats. In the least damaging case, such an environmental block near the mouth of an estuary would deprive the marine juveniles of use of the estuarine nursery. Reduced survival in other, suboptimum habitats that they may be forced to occupy would be expected, but probably no direct evidence is available for any of these species. Some of the marine species occur in these estuaries at very young stages, and their abundance is apparently correlated with large inflows of ocean water. It therefore seems likely that they would not easily leave the estuary unharmed if they entered and encountered a grossly unsuitable environment (e.g., high toxicity). Considerable mortality, as well as exclusion from upstream habitats, seems more likely in such a case (Harrison et al. 1991).

Physical alteration of the stream cross section, particularly dimensions of the opening of the mouth at the sea, can produce adverse impacts. The salinity distribution in many estuaries seems to be strongly influenced by the cross-sectional flow area. Therefore, any dredging, channel alteration or other modification can be expected to change the pattern of salinity along the channel and probably the distribution of the marine fauna in response.

Reliable prediction of the effect on salinity and other water characteristics would require thorough hydrodynamic analysis. Qualitatively, an increase in opening of the channel mouth would be expected to cause increased encroachment of salinity upstream and to shallower depths in the water column. This would favor the advance of marine species farther upstream and the retreat of freshwater species. Marine species probably could not become established year round because occasional large floods would likely flush all salt water out, as they do now. Other major effects would be expected that would require further analysis to predict even qualitatively. For example, changes would be expected in plant life and primary production within the estuary, in flow regime (e.g., current speeds), and in sediment transport and deposition (and, therefore, in stream bed substratum) (Harrison et al. 1991).

Estuaries are dynamic by nature, experiencing large changes in environmental variables, such as temperature, salinity, turbidity and discharge on several time scales. The location and nature of their sources of fresh and salt water, as well as of sediment and the geometry of the channel beds result in variability of longitudinal and vertical gradients. The horizontal and vertical distribution of salinity in estuaries is normally influenced by the height of tide and sometimes by its phasing and the amount of stream discharge. High tide levels tend to force a salt wedge farther upstream along the stream bottom. High storm discharge after rainfall tends to push salt water downstream before it. For estuaries with mouths configured like those on the north shore of Kaua`i, wave or surf height may also be a factor. When the cross section for continuous flow into and out of the stream mouth is very constricted (e.g., by a sand berm at the beach or a sill), periodic inputs of salt water in the form of high surf breaking over the bar or sill at the stream mouth may introduce significant salt water, particularly when stream discharge and tide are low (Harrison et al. 1991).

According to the U.S. Geological Survey, base flow to Hawaii’s streams is decreasing, as is the long-term annual trend in rainfall (Oki 2004). As a result, streams are slowly drying. From 1913 to 2002, base flows generally decreased in streams for which there are data (Oki 2004). The primary factor for this decrease is likely to be decreased recharge to groundwater supplies, resulting from decreased rainfall and potentially other sources. In addition, where pumping for human use has historically been important, base flows to streams may suffer from reduced groundwater storage because of human consumption.

2.0 DOCUMENT MAJOR CHANGES IN FRESHWATER FLOW AND ITS EFFECTS UPON MARINE ECOSYSTEMS

2.1 Marine Species in Hawai`i Estuaries

Section 2.1 presents a complete list of marine life that is likely to be affected by changes in freshwater flow because they live in Hawai`i estuaries, backreef areas or lagoons. This list also shows if these marine species (managed under Western Pacific Fisheries Management Council plans) are adults, juveniles and/or spawners. Freshwater fish fauna are not included in this report.

Table 2.1. Occurrence of Management Unit Species Currently Harvested in Hawai`i Estuaries and Lagoons

Management Unit Species (MUS)	**Estuarine Life Forms in Hawai`i**
Acanthuridae spp. (surgeonfishes)	Adult, Juvenile, Spawners
Yelloweye surgeonfish (*Ctenochaetus strigosus*)	Adult, Juvenile, Spawners
Orangespot surgeonfish (*Acanthurus olivaceus*)	Adult, Juvenile, Spawners
Yellowfin surgeonfish	Adult, Juvenile, Spawners
(*Acanthurus xanthopterus*)	
Convict tang	Adult, Juvenile, Spawners
(*Acanthurus triostegus*)	
Eye striped surgeonfish	Adult, Juvenile, Spawners
(*Acanthurus dussumieri*)	
Unicornfish	Juvenile
(*Naso* spp.)	
Balistidae (Triggerfish)	Juvenile
Triggerfish (*Xyrichthys pavo*)	
Carcharhinidae	
Grey reef shark	Adult, Juvenile
(Carcharhynus amblyrhnychos)	
Labridae spp. (wrasses)	Juvenile
Kuhliidae Hawaiian flag-tail (*Kuhlia sandvicensis*)	All
Carcharhinidae, Sphyrnidae, *Triaenodon obesus* (sharks)	Adult, Juvenile
Dasyatididae, Myliobatidae, Mobulidae (rays)	Adult, Juvenile
Serranidae spp. (groupers)	
Carangidae (jacks/trevallies)	Adult, Juvenile, Spawners
Decapterus/Selar spp. (scads)	Adult, Juvenile, Spawners
Holocentridae spp. (soldierfish/squirrelfish)	Adult, Juvenile, Spawners

Management Unit Species (MUS)	**Estuarine Life Forms in Hawai`i**
Scaridae (parrotfishes)	
Cirrhitidae (hawkfishes)	
Chaetodontidae (butterflyfishes)	
Pomacentridae (damselfishes)	
Scorpaenidae (turkeyfishes)	Juvenile
Hawaiian turkeyfish	
(*Pterois sphex*)	
Sabellidae (feather-duster worms)	Adult, Juvenile, Spawners
Polynemidae (threadfins)	
Threadfin (*Polydactylus sexfilis*)	Adult, Juvenile, Spawners
Priacanthidae (bigeyes)	
Sphyraenidae (barracuda)	
Barracuda (*Sphyraena helleri*)	Adult, Juvenile, Spawners
Acanthuridae (surgeonfishes) Yellow tang (*Zebrasome flavescens*) Yellow-eyed surgeonfish (*Ctenochaetus strigosus*) Achilles tang (*Acanthurus achilles*)	Adult, juvenile, Spawners
Zanclidae Moorish idol (*Zanclus cornutus*)	Juvenile
Pomacanthidae (angelfishes)	
Muraenidae Dragon moray (*Enchelycore pardalis*)	Adult, Juvenile, Spawners
Holocentridae (soldierfish/squirrelfish) Soldierfish (*Myripristis* spp.)	Adult, Juvenile, Spawners
Kuhliidae (flagtails) Hawaiian flagtail (*Kuhlia sandvicensis*)	Adult, Juvenile
Kyphosidae (rudderfishes) Rudderfish (*Kyphosus* spp.)	Adult, Juvenile, Spawners
Labridae (wrasses) Saddleback hogfish (Bodianus bilunulatus) *Xyrichthys* spp.	Juvenile

Management Unit Species (MUS)	**Estuarine Life Forms in Hawai`i**
Mullidae (goatfish) Goatfish (*Mulloidichthys* spp.) Striped mullet (*Mugil cephalus*) Yellowfish goatfish (*Mulloidichthys vanicolensis*) Goatfish (*Parupeneus porphyreus*) - *Kumu* Multi-barred goatfish (*Parupeneus multifaciatus*)	Adult
Octopodidae (octopuses) *Octopus cyanea* *O. ornatus*	Adult, Juvenile, Spawners
Opistobranchs (sea slugs)	
Bivalves	Adult, Juvenile, Spawners
Cephalopods	Adult, Juvenile, Spawners
Crustaceans	Adult, Juvenile
Shrimp	Adult, Juvenile
Crabs	Adult, Juvenile
Annelids	Adult, Juvenile, Spawners
Algae	All
Live rock	Adult, Juvenile
Helipora (blue)	Adult, juvenile, Spawners
Tubiphora (organpipe)	
Azooxanthellates (non-reef builders)	Adult, Juvenile, Spawners
Fungiidae (mushroom corals)	Adult, Juvenile, Spawners
Sm/Lg Polyped Corals (endemic spp.)	
Millepora (firecorals)	
Soft corals and Gorgonians	
Anemones (non-epifaunal)	Adult, Juvenile, Spawners
Zooanthids	Adult, Juvenile, Spawners
Sponges	Adult, Juvenile, Spawners
Hydrozoans	Adult, Juvenile, Spawners
Stylasteridae (lace corals)	Adult, Juvenile, Spawners
Solanderidae (hydroid fans)	Adult, Juvenile, Spawners
Bryozoans	Adult, Juvenile, Spawners
Tunicates (solitary/colonial)	Adult, Juvenile, Spawners
Feather duster worm (Sabellidae)	Adult, Juvenile, Spawners
Echinoderms (Sea cucumbers, sea urchins)	Adult, Juvenile, Spawners
Mollusca	Adult, Juvenile, Spawners
Sea Snails (gastropods)	Adult, Juvenile, Spawners

Management Unit Species (MUS)	**Estuarine Life Forms in Hawai`i**
Tetrarogidae (waspfish)	
Caracanthidae (coral crouchers)	
Aulostomus chinensis (trumpetfish)	
Fistularia commersoni (coronetfish)	
Anomalopidae (flashlightfish)	
Clupeidae (herrings)	Adult, Juvenile, Spawners
Engraulidae (anchovies)	Adult, Juvenile, Spawners
Gobiidae (gobies)	All
Ballistidae/Monocanthidae spp.	Juvenile
Kyphosidae	Adult, Juvenile, Spawners
Caesionidae	
Cirrhitidae	
Antennariidae (frogfishes)	
Syngnathidae (pipefishes/seahorses)	
Sphyraenidae spp. (barracudas)	Adult, Juvenile, Spawners
Priacanthidae	Juvenile
Stony corals	Adult, Juvenile, Spawners
Mullidae spp. (goatfish)	Adult, Juvenile, Spawners
Acanthuridae spp. (surgeonfish/unicornfish)	Adult, Juvenile, Spawners
Muraenidae, Chlopsidae, Congridae, Moringuidae, Ophichthidae (eels)	Adult, Juvenile, Spawners
Apogonidae (cardinalfish)	Adult, Juvenile, Spawners
Zanclidae spp. (moorish idols)	
Chaetodontidae spp. (butterlyfish)	Juvenile
Pomacanthidae spp. (angelfish)	Juvenile
Pomacentridae spp. (damselfish)	Juvenile
Scorpaenidae (scorpionfish)	Adult, Juvenile, Spawners
Blenniidae (blennies)	Adult, Juvenile, Spawners
Ephippidae (batfish)	Juvenile
Monodactylidae (mono)	Adult, Juvenile, Spawners
Echineididae (remoras)	
Malacanthidae (tilefish)	
Acanthoclinidae (spiny basslets)	
Pseudochromidae (dottybacks)	
Plesiopidae (prettyfins)	

Table 2.1 does not indicate specific relationships between marine species and freshwater flow. Nor are these relationships quantitatively documented. Four marine species which are known to be associated with freshwater input are considered in Section 2.2. Even for these four species, specific relationships with freshwater flow are not quantified but observations of fishermen and scientists indicate strong associations between juveniles and freshwater inputs.

2.2 Target Marine Fish Species for this Report

Section 2.2 is focused on four marine fish species that should be examined more closely because of associations with freshwater input to the ocean. The purpose of selecting particular marine species is to test for possible influences on catch per unit of effort (CPUE), estimated from commercial catch records of the Hawaii Department of Land and Natural Resources (DLNR). Peak freshwater discharges at selected gauging stations operated by the U.S. Geological Survey are compared with the estimated CPUE of the four marine species. This analysis is summarized in Section 4 of the present report. In addition to associations with some marine fishes, salinity is known to be related to spatial patterns of native marine seaweeds. This relationship is described in Section 2.4.

There have been few directed studies of the fish fauna of Hawai`i estuaries. Many native marine species occurring in Hawaii estuaries are tolerant to freshwater to varying degrees but do not necessarily prefer or select for low-salinity conditions.  There are no adequate scientific studies that would refute or support any hypothesis that Hawai`i marine fauna require fresh water input as a factor to their survival versus other characteristics of surrounding water, such as the oceanography, morphology, pollution, introduced exotic predatory species, fishing condition or habitat condition. The association of two species of jacks (Caranx spp.), native mullet (*`ama`ama*), flagtail (*aholehole*), and *akule* (bigeye scad) with freshwater has been considered in several research projects, however.

2.2.1 Jacks

Large jacks of the genus *Caranx* (Carangidae) are predatory fish that play an important role in the ecology of tropical and subtropical estuaries. Jacks represent an important fishery resource in Hawai`i, where *Caranx ignoblis* and *Caranx melampygus* are two of the most common species (Smith and Parrish 2002). Adults and larger juveniles support a moderate commercial fishery and a popular recreational fishery of much higher overall estimated economic value

Adult jacks are found in almost all nearshore habitats, including rocky shores, reefs and bays. Juveniles inhabit-protected environments, such as backreef areas, sand flats, and lagoons. They also occur in estuaries, where their role as a component of the fish fauna is poorly understood. Utilization of estuarine habitat by juvenile jacks appears opportunistic and variable in spatial extent and duration (Smith and Parrish 2002).

Neither *C, ignoblis* nor *C. melampygus* is estuarine-dependent using the definition of Blaber et al. (1989) because viable populations occur in regions where there are no estuaries. Although jacks inhabit estuaries throughout the tropics, little research on juvenile fish fauna has been done in estuaries where *C. ignoblis* and *C. melampygus* are found. Previous studies have examined diets, distribution and abundance, but not age and growth of estuarine juveniles (Smith and Parrish 2002).

Blaber and Blaber (1980) examined various correlations between estuarine use by juvenile marine fish and biological and physical conditions found in a large Australian sub-tropical estuary. They found that increased prey availability, refuge from agitated offshore waters, and increased turbidity were more highly correlated with estuarine occupancy than were decreased salinity or refuge from potential predators.

Circumstantial evidence suggests that predation pressure on both Hawai`i jack species is much reduced in Hanalei area estuaries compared to adjacent coastal waters. Few aquatic or terrestrial predators are found to co-occur with jacks in Hanalei estuaries. This may be largely because of the lower and more variable salinity environment. The higher turbidity of the estuarine waters provides additional refuge from predation pressure (Smith and Parrish 2002). Juvenile marine fish have been shown to prefer turbid estuarine conditions (Blaber and Blaber 1980; Cyrus and Blaber 1987).

2.2.2 *`Ama`ama* (native mullet)

The striped mullet, or *`ama`ana*, is common in protected habitats, especially in Hawai`i estuaries, or *muliwai*, where stream flow is significant from surface or groundwater discharges (Nishimoto et al. 2007).

Although no discrete threshold has been established, juvenile *`ama`ama* appear to prefer water with salinity below 15 ppt (Blabber 1987, Dr. Ken Leber, Mote Marine Lab, Sarasota, Fla. pers. communication to Ron Englund). When salinity becomes > 15 ppt, juvenile *`ama`ama* will abandon an area and move in search of fresher water. During this movement, juvenile *`ama`ama* become increasingly susceptible to predation and possibly to reduced food availability.

Salinity preferences for *aholehole* are less established than that for `*ama`ama*, but the seasonal use of nursery habitat by *aholehole* is similar to that of `*ama`ama*. It is often assumed that juvenile *aholehole* also prefer water with salinities below 15 ppt (see Filbert and Englund 1995). For reference, the salinity of sea water around Hawai`i is approximately 35 ppt.

Juvenile `*ama`ama* have a relatively strong affinity for brackish water during the nursery stage of their life cycle (Major 1978, Blaber 1987). When cultured `*ama`ama* are released into habitats with lower surface salinities, the majority of individuals recaptured were caught at or near the release site (Leber et al. 1996). Small fish (45-60 mm) contributed to juvenile recruitment in Kane`ohe Bay when releases of cultured fish were made in the spring, rather than in the summer (Leber et al. 1996). Schools of striped mullet are usually aggregated according to size. Size structures of cultured and wild striped mullet suggest that schooling behavior of striped mullet may partly control the release-season effect (Leber et al. 1996).

The `*ama`ama* reach sexual maturity at about 28 cm, or about 3 years old, and migrate offshore during the winter months to spawn in the ocean. The pre-juveniles, averaging about 20 mm standard length, appear at intertidal estuarine habitats 30-45 days after hatching at sea. The recruiting fingerlings use turbidity gradients as an orientation cue, along with tidal transport as a mechanism to move into juvenile habitats. Pre-juveniles, averaging 17-35 mm SL, are very common in the shallow intertidal habitats but disappear by the end of June (Nishimoto et al. 2007). Major (1978) reported that pre-juveniles inhabit shallow areas and tolerate highly fluctuating salinity and water temperatures as a pre-adaptation to avoid fish-eating predators. The fingerlings metamorphose into juveniles at 50 mm SL, abandon the extreme conditions in the shallows, and move into deeper waters (Nishimoto et al. 2007).

Younger mullet in general seem to prefer shallower water near the shore of the estuary. Smallest estuarine mullet (about 20-50 mm SL) select the shallowest water and prefer areas with extreme temperatures and salinities, according to Major (1978), possibly a preference as a selection of a refuge from predation by larger fishes. At about 50 mm, when metamorphosis to juveniles is complete, young mullet move into somewhat deeper water (Nishimoto et al. 2007).

In Hawai`i, yearling juveniles begin to move out of the intertidal zone and out of shallow shore areas of streams by about February or March (Major 1978). Striped mullet reach advanced sexual development in fresh water but must migrate to the sea to spawn (Blaber 1987). Annual recruitment to inshore nursery habitats of young wild mullet occurs in spring in Hawai`i (Major 1978).

Commonly, ripe adults congregate densely in estuaries and move into large schools to establish spawning grounds, where they spawn in large groups, often on a predictable seasonal schedule (Blaber 1987). Predation by wading, swimming and diving birds has been shown to be responsible for a major source of mortality on mullet and a large part of the diet of some bird species (Blaber 1987).

Striped mullet is a herbivore and a detritivore, which is a key point if studying the impact of increasing plants and detritus on the food web. Striped mullet feeds directly on those items. It is also linked to the plants and detritus in the upper levels of the food web. This is a link because mullet convert plants and detritus to a food source that other fishes can use. Thus, striped mullet is a valuable indicator of ecosystem response to changes in productivity in estuaries, although productivity is only one component for study (Leber Tr. 4/23/96); KSBE FOF 1502, Waiahole case in Commission on Water Resources Management 1997).

The mullet was prized as a food fish for Hawaiian royalty. Most were collected from coastal fishponds. The Hawaiian language recognizes the different size classes of the *`ama`ama* but most intriguing is recognition of the traditional migratory route between Ewa and La`ie, Oahu. A census at the Honolulu fish market in 1900 reported that 35.6% of the fishes sold were the *`ama`ama*, however, there was no differentiation between mullet taken from fishponds or the open ocean. Mullet were the most expensive fish at the market and sold for 25 cents/lb (Cobb 1905).

In the late 1800s, many coastal fishponds were not tended and fell into disrepair, as the population migrated to the city or other crops, such as rice and taro, became more profitable. In 1900, there were 99 documented fishponds. The number of fishponds used to cultivate *`ama`ama* and other estuarine species continued declining into the 20th century, when only two ponds sold less than 1,000 lb of *`ama`ama* in 2003 (Nishimoto et al. 2007).

Fishing for *`ama`ama* was once easily recognized by the numerous, small wooden platforms, called stilt chairs, dotting the tidal flats on Kane`ohe Bay and Ala Wai Canal, that are now gone. Small skiffs now replace such platforms. Hilo Harbor, especially the Waiakea Public Fishing Area, is one of the last strongholds of stilt-chair mullet fishing (Nishimoto et al. 2007).

Observations by a longtime fisherman and Hawaii Fish and Game fishery biologist noted that the average size of mullet caught in the 1940s was 3-4 lbs but that there was a dramatic decline in average size over time. This source considered native mullet stocks overfished and the brood stocks severely depleted. He hypothesized that the losses of shallow water nursery habitat and competition from the alien *kanda* (*Valamugil engeli*) have contributed to this decline (Nishimoto et al. 2007). The population of *kanda* has exploded and invaded the native mullet habitat in many bays and estuaries in Hawai`i (Nishimoto et al. 2007).

In 1990, the DLNR and the Oceanic Institute (OI) partnered to develop a collaborative project to help restore the declining coastal stocks by using marine stock enhancement technology. Native mullet was selected for restoration because OI already had the technology to aquaculture the *`ama`ama* and there was a well-established recreational mullet fishery in Hilo, Hawai`i and a commercial net fishery in Kane`ohe, O`ahu (Nishimoto 2007).

Juvenile cultured striped mullet exceeded 20 percent of the fish collected in quantitative samples within 6-8 months after small-scale pilot releases in Kane`ohe Bay (Leber et al. 1995). A similar release impact was apparent in a recreational native mullet fishery in Hilo Bay, where small-scale hatchery releases comprised about 20 percent of the annual catch (Leber and Arce 1996). et al. 1995). The absence of 3-4 year (after tag and release) mullet from this fishery suggests that these fishes moved out of the estuary and presumably underwent an offshore spawning migration (Nishimoto et al. 2007).

2.2.3 *Aholehole*

Waiahole (lit. *ahole* water) was so named because of the teeming schools of *aholehole* that populate the location where the Waiahole Stream flows into Kaneohe Bay. *Kuhlia sandvicensis*, the *aholehole*, is a native Hawaiian fish found in both marine and freshwater habitats. In the lower reaches of streams, they are predators on stream fishes, invertebrates and insects. *Aholehole* are important food fish in Hawai`i and were often used by ancient Hawaiians in traditional ceremonies. Although *aholehole* are a part of stream ecosystems and of Hawaiian culture, little is known about their life history, specifically whether a freshwater phase is obligatory. This species' use of stream habitats is facultative. Unlike Hawaiian freshwater gobies, there is no physiological requirement of fresh water at a specific point in the life cycle of *K. sandvicensis* (L.K. Benson and J. M. Fitzsimons 2002).

Young *aholehole* are widely known to frequent the full length of estuarine waters and penetrate far into the freshwater portions of streams (Harrison et al 1991). On a small scale, distribution of various sizes of *aholehole* is likely determined somewhat by specific habitat features. Larger individuals appear to associate much more strongly with cover. At smaller sizes, they typically maintain aggregations well up into the water column, usually very close to shore (Harrison et al 1991). Recruitment to the estuaries may occur about two months after hatching. The larger size classes in the distribution suggest a fairly long residence, substantial growth, and considerable mortality and/or emigration of the estuarine population (Harrison et al. 1991).

Most *aholehole* seem to relocate to adult habitats offshore before they reach reproductive size (150-174 mm SL males; 158-189 mm SL females). Spawning is believed to be done by the larger fish that have moved farthest offshore into deeper water (Harrison et al. 1991).

Many *aholehole* enter the estuary very young and use it as a nursery habitat for between one and two years. The estuary probably offers a refuge from predation. The density and diversity of fish-eating predators seems considerably lower than in coastal marine habitat outside (Harrison et al 1991).

2.2.4 *Akule*

The *akule* (bigeye scad) is generally found in inshore waters and shallow reefs. It may travel in compact groups of hundreds of thousands of fish. It supports important commercial and subsistence fisheries in Hawai`i. Observations based on current speed and direction and lunar phase indicate that these fishes school and remain in areas where abundant zooplankton are concentrated in lee eddies. Tagging experiments indicate that there is little movement between populations off northern western and southern waters of O`ahu. The larvae of these species are pelagic but the range of movement of adults is limited (Weng 1999).

Primarily a nocturnal fish, the *akule* feeds on shrimp, other invertebrates and foraminifera when inshore and on zooplankton and fish larvae when offshore. In Hawai`i, small fishes, copepods, crab megalops, stomatopods, shrimps and other planktonic crustaceans comprise the majority of the *akule*'s adult diet. The *akule* is preyed upon by tuna and billfish that are in nearshore waters (Weng 1999).

The spawning season of the akule is thought to be April through November. After a four-month larval phase, juveniles migrate inshore and recruit into the adult schools that live in nearshore waters. *Akule* is highly fecund and spawns multiple times per season. It is a predator of macrozooplankton and prey of larger pelagic fishes. As such, *akule* form a trophic link between the nearshore environment from which they feed and the offshore pelagic environment occupied by many of their predators (Weng 1999).

The *akule* carrying capacity time series calculated in one study (Weng 1999) is correlated with total precipitation. Precipitation is lagged two years behind carrying capacity. Given the one-year generation time and high growth rate of the *akule*, it is anticipated that environmental changes could be translated into changes in biomass on a one to two-year time scale. Given the two to three year life span of the *akule*, the two-year lag time would be expected if variation in precipitation affected recruitment success or early development.

Precipitation is strongly correlated with terrestrial runoff to the coastal ocean, which provides a source of fertilization to the otherwise nutrient-poor waters of the North Pacific subtropical gyre. In addition, precipitation scrubs various chemicals out of the atmosphere and deposits them in the ocean. Hence, there is a plausible mechanism of interaction between precipitation and *akule* population dynamics. This could possibly present a hypothesis to be tested in future research (Weng 1999).

2.3 EFFECTS OF SURFACE RUNOFF

Physical habitat plays an important role in structuring marine ecosystems but its contribution has seldom been well documented in the literature because of the difficulty of separating effects of habitat from other influences in the environment (McCoy and Bell 1991). Temporal physical factors include changes in temperature, salinity, turbidity, terrestrial runoff and wave energy (Friedlander and Parrish 1998).

Some streams in Hawai`i run to the sea year-long without significant diversion or stream channel modifications. These channels occur on the islands of Kaua`i, O`ahu, Maui, Moloka`i and Hawai`i. These streams have basalt basins, generally with bottoms of gravel or boulders and may range from narrow, steep-sided gorges to wide, flat-bottomed valleys with alluvial flood plains (Oki 2004).

Threats to Hawaii's continuous perennial streams include modifications of channel, changes in stream flow by diversion of water, siltation via erosion of disturbed watersheds, direct or indirect pollution of surface or groundwater and introduction of alien stream animals that either feed on or compete with native species.

The U.S, Geological Survey maintains a network of stream-gauging stations in Hawai`i, including a number of stations with stream flow records that can be used to evaluate long-term trends and short-term variability in flow characteristics. Results of this study indicate the following:

1. From 1913 to 2002, base flows generally decreased in streams for which data are available and this trend is consistent with the long-term downward trend in annual rainfall over much of the State during that period (Oki 2004).

2. Monthly mean base flows generally were above the long-term average from 1913 to the early 1940s and below average after the early 1940s to 2002 and this pattern is consistent with downward trends in base flows from 1913 to 2002.

3. Long-term downward trends in base flows of streams may indicate a reduction in ground-water discharge to streams caused by a long-term decrease in ground-water storage and recharge.

4. From 1973 to 2002, trends in streamflow were spatially variable (up in some streams and down in others) and, with a few exceptions, generally were not statistically significant.

5. Short-term variability in streamflow is related to the seasons and to the El Nino-Southern Oscillation phenomenon that may be partly modulated by the phase of the Pacific Decadal Oscillation.

6. At almost all of the long-term stream-gaging stations considered in this study, average total flow (and to a lesser extent average base flow) during the winter months of January to March tended to be low following El Nino periods and high following La Nina periods and this tendency was accentuated during positive phases of the Pacific Decadal Oscillation.

7. The El Nino-Southern Oscillation phenomenon occurs at a relatively short time scale (a few to several years) and appears to be more strongly related to processes controlling rainfall and direct runoff than ground-water storage and base flow.(Oki 2004.

Further study is needed to determine (1) whether the downward trends in base flows from 1913 to 2002 will continue or whether the observed pattern is part of a long-term cycle in which base flows may eventually return to higher levels; (2) the physical causes for the detected trends and variations in stream flow, and (3) whether regional climate indicators successfully can be used to predict stream flow trends and variations through the State (Oki 2004).

In a study of trends in stream flow characteristics at long-term gauging stations in Hawai`i (Oda 2004), the U.S. Geological Survey reports that year to year changes in stream flow are related to the El Nino-Southern Oscillation (ENSO) phenomenon, as well as the Pacific Decadal Oscillation. Not surprisingly, trends in rainfall are also linked to these phenomena. Hawaii tends to be dry during most El Nino events, but low rainfall may also occur in the absence of El Nino (Chu and Chen 2005). Similarly, rainfall tends to be low during “warm” phases of the PDO, such as Hawaii experienced from mid-1970 to 2001. The state was previously characterized by high rainfall lasting for 28 years in the preceding “cool” phase through the 1950s and 1960s. ENSO and PDO are regional climate patterns that affect the distribution of rainfall in the Hawaii Islands, and therefore exert important influence on the discharge of streams and on the recharge of groundwater from one year to the next.

ENSO is a large-scale meteorological pattern characterized by two conditions: the so-called La Nina and the El Nino. These govern temperature and rainfall trends in the Pacific Ocean, as well as exert a global influence on weather patterns. During an El Nino, the Hawaiian Islands usually experience a decrease in rainfall. This happens because El Nino causes a southerly shift in the atmospheric circulation of the north Pacific, a feature called the Hadley Cell (Hastenrath 1991).

The Hadley Cell is a large continuous belt of air that rises, moisture-laden, from the warm waters north of the equator at about 8 N latitude (Hawai`i lies between 16 and 23 north latitude), and moves north across the Hawaiian Islands, raining as it goes. During its journey to the north, the air cools, moisture condenses, and produces abundant rainfall. Eventually, airflow descends back to the ocean surface as a column of dry, cool air and creates a pressure system known as the Pacific High to the north of the islands at around 30 to 35 north latitude. Under normal conditions, the Hawaiian Islands experience a wet climate, while to the north and northeast, the Pacific High creates a dry climate. However, during El Nino, the surface waters at the equator become significantly warmer and the rising motion of the Hadley Cell shifts to the south. This brings the Pacific High south as well, and the Hawaiian Islands experience a decrease in rainfall as Hawai`i falls under the influence of the dry high pressure center (Oki 2004).

The windward or north- through east-facing sections of the islands generally have a consistent year-round supply of trade winds bringing brief showers. The wetter period of the year in windward areas depends on the individual island and the elevation, but generally occurs in the spring months. The leeward sides of the island, which are southwest through southeast sides of the islands, are more arid. In general, the wetter season is winter and the dryer season is summer. There are exceptions, such as those areas of the island of Hawai`i, which have a summer rainfall maximum induced by land and sea breeze convection.

Differences in bottom habitats along gradients of water, temperature, light, nutrients, and organic matter are associated with up-current and down-current and onshore-offshore systems. Human influences are common causes of a large number of reported ecological shifts. It is often the interaction of persistent and multiple synergistic disturbances that cause long-term ecological transitions, rather than the succession of individual short-term disturbances.

Watershed impacts in Hawaii are linked to adjacent reefs through transport processes that deliver sediments, nutrients, pollutants, as well as fresh water, to nearshore areas via surface flow and submarine groundwater discharge. Other factors, such as wave energy regimes and coastal human impacts can obscure the direct links between watersheds and coastal ecosystems. There is a weak or delayed quantitative link between land use practices and reef conditions, however

Chief among the historical uses of freshwater in Hawai`i were the enormous quantities needed to grow and process sugarcane. Between 1856 and 1920, sugar planters built miles of ditches, diverting fresh water from almost every watershed in Hawai`i. By 1920, ditches, tunnels, and flumes were diverting over 800 million gallons per day from streams and mountains to the cane-fields and their mills (Wilcox 1998).

The decline of the sugarcane industry and urbanization that has occurred since 1900 have resulted in millions of gallons of fresh water, no longer used for irrigation, to continue to flow into the sea through canals, chutes and aquaducts, even while the groundwater table falls. Some former irrigation water is used in homes and resorts, but it is eventually returned to the ocean via sewage treatment plants or injected into wells located below potable groundwater supplies. Hence, it does not replenish Hawaii`s aquifers. Water tables around the state are dropping as a result and, for no other reason than no one has changed the diversion system now that sugarcane has left most of the islands. Some former irrigation ditches have become sites for tourist inner tube adventures.

2.4 EFFECTS OF SUBMARINE GROUNDWATER DISCHARGE

There are few stream-fed estuaries in Hawai`i. The most important freshwater input to many inshore areas may well be through groundwater (Carlquist 1980). For example, on the island of O`ahu, Hawai`i, the total nutrient loading in Kahana Bay from submarine groundwater discharge (SGD) was equal to or greater than that carried by surface runoff (Garrison et al. 2003).

Submarine ground-water discharge has been recognized as a phenomenon that can strongly influence coastal water and geochemical budgets and drive ecosystem change. For example, the discharge of nutrient-enriched ground water into coastal waters may contribute significantly to eutrophication and blooms of harmful algae. Because the discharge of coastal ground water commonly occurs as diffuse seepage rather than focused discharge through identifiable springs, assessing submarine ground-water discharge has remained difficult for oceanographers and hydrologists (Swarzenski, Bratton and Crusius 2004).

Rainfall in Kona is generally so low and because of porosity and vertical permeability of the ground in the region is so high, it appears that the dominant flux of water through this sector occurs as slow, subterranean flow at about sea level. Consequently, it appeared that the reconnaissance work should be concentrated in that area where the groundwater can flow most easily. Eleven areas of discharge of brackish water, all with probable chloride concentrations greater than 1000 parts per million, were detected in one study. Although it is extremely difficult to determine the exact volume of discharge, a reasonable estimate of the volume of flow of brackish water discharges ranges from a few tens of thousands of gallons per day at nine discharge points to perhaps one million gallons per day from the two largest zones of shoreline discharge (Adams, et al. 1968).

Though the discharge of water to the ocean is a necessary part of the water/mass balance, the ecological effects of submarine groundwater discharge (SGD) have not been explicitly considered in many coastal management models (Duarte et al. 2010). SGD input to marine ecosystems decreases the salinity and increases the nutrient content of the surrounding marine waters in a way similar that of estuaries and stream systems. The organisms which inhabit these brackish environments must be able to maintain high productivity while withstanding rapid fluctuations in water column nutrients and salinity. Evidence has been accumulating in the literature that certain species of tropical marine algae have increased productivity in brackish water relative to ambient oceanic salinity (Duarte et al. 2010).

Numerous studies have shown that the growth rate, for example, of *Gracilaria* spp. increases as salinity decreases from ambient levels, with optimal conditions occurring between 20-30 ppt salinity. From such studies, it is likely that certain marine primary producers have adapted to and rely on SGD as a natural source of terrestrial nutrients and freshwater. Therefore, excessive extraction of groundwater has the potential to limit the productivity and distribution of these species as SGD flux to the coastal environment decreases.

This effect may be magnified in arid tropical regions where terrestrial runoff is minimal and SGD represents the only source of freshwater and “new” nutrients to marine ecosystems. A model has been developed and applied to the Kona coast of the island of Hawaii, where SGD is being actively studied, and where both nearshore ecology and groundwater resources are serious socio-political issues. The model incorporates standard hydrologic and economic equations. With the addition of constraints linking pumping of a basal aquifer can be kinked to changes in growth rate or productivity of a keystone marine species of macro-algae (Duarte et al. 2010).

SGD is a well-known phenomenon in Hawai`i and has been documented on the West Hawai`i coastline, which is focus of the model (Duarte et al. 2010). In addition to point sources of discharge, such as springs, groundwater may also enter the marine environment in a diffuse manner through benthic sediments. Concentrations of nutrients, trace metals, organic carbon, and methane, and CO_2 may be considerably higher than nearby surface ocean waters. The effect of SGD on marine waters may be variable over large spatial scales, as this is expected to be relative to local and regional, geologic, tidal and climatic conditions. Many studies have concluded that SGD is a significant source of nutrients to numerous coastal environments. In addition to increasing nutrient levels, SGD has been shown to decrease salinity of local waters compared to ambient oceanic conditions (Duarte et al. 2010).

Groundwater discharging from West Hawai`i into the coastal zone tends to be nearly fresh (salinity about 2-5 ppt), with reasonably good relationships between discharge, temperature and salinity (Peterson et al. 2009). Nearshore marine algae would be most affected by changes in fresh water discharge in a relatively narrow boundary layer near the ocean surface, prior to any open ocean mixing phenomena (Duarte et al. 2010).

Nutrient addition to nearshore marine ecosystems via SGD and changes in salinity due to SGD may also affect productivity as salinity is one of the most critical factors affecting the growth rate, development, and distribution of seaweeds. The distribution and abundance of heterotrophic marine fauna may also be directly affected by changes in salinity due to narrow ranges in osmotic tolerance for some organisms. Studies have suggested SGD plays a major role in large scale increases in algal biomass in Hawai`i (Smith et al. 2005) (Duarte et al. 2010).

Decreases in SGD over time could have serious implications, ranging in scale from that of individual organisms to entire ecosystems. These disturbances may significantly alter the chemical properties of coastal waters, endangering marine flora and fauna with ecological, cultural and economic value. One study was particularly interested in the effects of water quality on Hawaiian indigenous marine algae (also called *limu* in Hawaiian), which are known to be keystone species of Hawaii's coastal ecosystem (Duarte et al. 2010).

The natural growth rate of native *limu* is dependent on the aquifer's head level, as well as other ecological factors not considered in the study (light, temperature, etc). (Duarte et al. 2010). North Kona was chosen for study, in part, because of its dependence on groundwater for virtually all water supply and lack of any surface water systems to complicate the terrestrial-marine connection. The Kaupulehu-Kukio area is a particularly dry and water-limited area of the North Kona coastline (Duarte et al. 2010). More than 30% of the volume of coastal water in the Kona coastal area may be due to SGD (Knee et al. 2008). SGD is the primary source of nitrate, phosphorous and silica to this coastal environment. Salinity is a good indicator of SGD is this region. At near shore SGD sites with low salinity, nutrient concentrations may be two to three orders of magnitude greater than offshore ambient conditions (Knee et al. 2008).

In Hawai`i, macroalgae are of major importance to the local economy, cultural practices, and reef biology. In particular, species in the genus *Gracilaria* are highly sought after as a source of fresh food. In the case study, the Hawaiian endemic red edible *limu manauea* (*Gracilaria coronopifolia*) was chosen as a keystone indicator species. *Limu manauea* is native to the Kona coast and is economically, ecologically and culturally significant in Hawaii (Duarte et al. 2010). This species is one of the three most sought after seaweeds for food in Hawaii (Abbott 1984). Its distribution and abundance in recent years has seen serious decline due to overharvesting and other factors (Duarte et al. 2010). *Limu manauea* is known to tolerate a wide range of salinity and nutrient regimes (Hoyle 1975), making it a good candidate for physiological measurements at various levels of SGD. The natural growth of native *limu* depends on the size of its own stock and water quality. Examples of water quality indicators which may affect the growth of native *limu* are salinity, nitrogen and temperature. These indicators are related to the amount of freshwater discharged. From these relationships, the natural growth of *limu* can be expressed (Pongkijvorasin et al. 2008).

When salinity is high, invasive algae can grow better than indigenous algae. Thus, the carrying capacity of the indigenous species decreases as salinity increases. Changes in native *limu* growth are affected by direct effect of salinity on intrinsic growth rate and indirect effects from the change in carrying capacity as *limu* is crowded out by competing species. Desirable ranges of salinities for species of interest in the study area are 29-33 ppt (Duarte et al. 2010).

To incorporate the ecological effect of groundwater extraction, the Duarte study (Duarte et al. 2010) imposed an ecological constraint on aquifer head level to preserve sufficient SGD leakage and thus a minimum growth rate for the marine algae of interest. In Hawai`i, on one end of the spectrum are parties arguing that groundwater wells will diminish SGD and thus seriously degrade or destroy marine ecosystems. On the other end, landowners and developers insist that the effects are small and/or insignificant relative to other activities, such as overfishing and pollution in general (Duarte et al. 2010).

An increase in salinity, caused by a decrease in freshwater discharge, may induce less growth of native algae. It is important to note that the growth of algae also depends on other factors, such as nutrients. In the Duarte (2010) study, salinity level was used as an indicator for water quality affecting algae. At the recent level of submarine groundwater discharge off Kona, the average coastal seawater's salinity around the study area is approximately 31 ppt (Duarte 2001). Studies by Hoyle (1976) and Wong and Chang (2000) indicate that the growth rate of *limu* approximately decrease by 28 percent when salinity increases from 31 ppt (salinity at status quo) to 35 ppt (ocean salinity with no discharge).

3.0 ASSESS SHORELINE CHANGES OVER TIME AND IMPACTS TO HABITAT QUALITY AND OFFSHORE PRODUCTIVITY OF THE CORAL REEF ECOSYSTEMS

3.1 General History

The histories of several Hawai`i coastal areas provide examples of shoreline changes and associated impacts to habitat and productivity. The most notable change has been to the shoreline of Waikiki, where the Ala Wai Canal was constructed in the 1920s. This project completely changed the dynamics of the fresh water flowing into Waikiki by trapping the stream runoff from Manoa, Palolo and Makiki valleys and channeling it into the ocean at the west end of Waikiki. Stopping the fresh water runoff into Waikiki impacted all of the marine species that were once so abundant, including the fish and seaweed collected by longtime residents (Clark 2009).

While no other canals like the Ala Wai have been built in Hawai`i, irrigation ditches and other projects have reduced stream water running into the ocean in many areas. In recent years, community groups have formed to clean watersheds, while others have lobbied for the return of *mauka* waters to Hawaii’s streams (Cramer 2009).

Section 3 focuses on three other areas where fisheries and habitats have changed dramatically: Maunalua Bay, Kane`ohe Bay, and southeast Moloka`i coast.

3.2 Maunalua Bay

Massive fishponds and freshwater springs at one time made Maunalua Bay a famous fishery. Wailupe Fishpond, encompassing 40 acres, is now developed as Wailupe Peninsula. Next to it was the Kupapa Fishpond at Niu, now commonly known as Niu Peninsula. The remnants of the former Maunalua Pond are what is presently known as Hawaii Kai Marina and part of the community at Hawaii Kai. In the late 1950s, Henry J. Kaiser dredged the former Keahupua-o-Maunalua (Kuapa) Fishpond, the largest in the Hawaiian Islands (523 acres), and converted it into Hawaii Kai Marina. As part of the same development, the entrance channel to the marina and the access channel to Hawaii Kai boat ramp in Maunalua Bay Beach Park were also dredged. During this massive dredging, ocean currents and the prevailing tradewinds carried huge silt plumes over the reef flats fronting Hawaii Kai and Kuliouou (Cramer 2009).

Maunalua Bay, about 8 km long with a fringing reef flat, receives discharges from nine small watersheds, each typically 10 sq. km in size. Each stream drains across the reef flat through a small, often ill-defined channel and then through a well-defined passage through the reef margin. When first mapped in 1855, the human settlements were few and the reef crest was observed to be near the ocean's surface. The same map shows that most of the peninsula separating the lagoon from the reef flat was too narrow for human settlement but it was continuous; i.e., Kuapa Lagoon was closed except during the highest spring tides, when it overtopped. During stream floods, the peninsula would have been breached (Wolanski et al. 2009).

Fishermen created permanent openings at Kuapa Pond bridged by rock walls. By 1921, these rock walls closed most of the lagoon and only a small opening existed near the mouth of the Wailupe Stream. This fish pond was later filled for a housing development. In 1900, the reef flat on the east side of the bay was sandy and extremely shallow at low tide. In 1927, Kuapa Pond was fringed by seasonal wetlands used as pastures and urbanization was still minimal. In 1930, the coast was sandy on the west side of Maunalua Bay. Large-scale urbanization occurred since the 1960s, when two navigation channels were dredged into Maunalua Bay, one on the east side of the bay and another, smaller channel in the central region near the Wailupe Stream mouth. The Kuliouou Stream that historically discharged into Paiko Lagoon was diverted to flow directly into Maunalua Bay (Wolanski et al. 2009).

All of the coastal plains and much of the surrounding hills have been urbanized. The surface of Kuapa Pond was decreased by 30 percent when it was urbanized into a marina, the streams were channelized and lined with concrete and new houses were constructed and are still being constructed on steep, highly erodible slopes with sediment protections. The degree of urbanization in 2008 varied between watersheds, examples being 33 percent of the Kamilo Nui catchment, 34 percent of the Wailupe catchment and 56 percent of the Kamilo Iki catchment, with similar high values in all of the other catchments. Runoff from these hard surfaces is directed by pipes to the channelized streams, thus reducing groundwater recharge. Invasive alien plants and a large population of feral pigs and goats inhabit upland, unbuilt areas. As a result, erosion is prevalent within the upper regions of the catchments, as well as along stream banks (Wolanski et al. 2009).

Even during dry periods and with no visible flow in the streams feeding Maunalua Bay, there is a salinity gradient in Maunalua Bay, with fresher water inshore and saltier water offshore. This is likely the result of groundwater flow from the watersheds because Maunalua Bay has a number of springs discharging freshwater below mean low tide (Hitchcock 1905). Throughout the dry season, a permanent nepheloid layer was always present along a transect on the east side of Maunalua Bay (Wolanski et al. 2009).

One major rainfall event occurred during a 6-month study on December 11, 2008. After this flood, high suspended sediment concentrations remained off Wailupe Stream for about 10 days but only for one day farther offshore. The salinity system recovered slowly over several days. Suspended sediment concentration values rose during the rising stage of the flood and remained offshore for 2-10 days. This flood event formed a river plume with a marked vertical stratification in salinity that was absent before the flood and that persisted for at least 8 days after the flood. Much of the fine sediment from the watersheds is discharged into the bay during the first flush at the rising stage of stream floods. Based on currents and suspended sediment concentrations at one stage during the first flush of the December 2008 flood, about 20 tons of terrigenous fine sediment was discharged into Maunalua Bay through the dredged channel (Wolanski et al. 2009).

Data from 1922-1925 (Pollock 1925) indicate patchy cover by live coral over the reef flat but zones of high coral cover of up to 50 percent starting near the reef crest and extending mainly on the western side of the bay. In 2008, however, coral cover was less than 5 percent over most of the reef slope, except in two localized areas and was virtually nil over the reef flat and reef slope (Wolanski et al 2009).

Coral degradation in Maunalua Bay correlates with changes in the surrounding watersheds and in the flushing rate of the bay following urbanization. At present, increasing levels of sedimentation occur in the bay, creating stagnation zones. The marina on the east side was dredged to a depth that is much deeper than the original Kuapa Lagoon. The construction of a seawall and openings to Maunalua Bay increased the residence time of water in the bay. The deeper waters in the marina and its narrow opening create a tidal jet that is topographically steered by the navigation channel deredged across the reef flat. This jet, together with currents generated by waves breaking on the reef crest, generate a quasi-permanent, re-circulating flow, causing stagnation on the east side of Maunalua Bay (Wolanski et al. 2009).

Thus, the waters on the east side are poorly flushed, having a resident time on the order of 7-10 days as demonstrated by the long retention time of the stream plume. The marina on the east coast plays a substantial role in rapping runoff water after a flood and releasing it slowly over 7 days, as evidenced by the long-duration rise in mean sea level and the low salinity near the stream discharge point. This circulation pattern helps to trap fine sediment inshore and explains the presence of a permanent nepheloid layer on the east side of Maunalua Bay. It also explains the transformation of the east coast from sandy to muddy in the last 100 years, and the on-going spread of muddy sand banks in infilling the reef flat on the east side of Maunalua Bay. The long residence time of waters in Maunalua Bay, particularly on the eastern side, facilitates degradation by high nutrient concentrations (Wolanski et al. 2009).

The groundwater recharge and storage are expected to be much smaller at present than during the history of Maunalua Bay. The Wailupe Stream flow data following the December 2009 flood showed that the thickness of groundwater storage was only 2.5 cm. This also implies that the streams now dry out much faster after rain than before urbanization occurred. The runoff water is presumably enriched in nutrients that sustain the invasive *limu* growing over the dead corals, smothering living corals and preventing recruitment of coral larvae. The filling of fishponds and parts of Kuapa Lagoon for urban developments has destroyed the halophytes and mangroves that historically trapped terrigenous sediment (Wolanski et al. 2009).

Much of the material forming the nepheloid layer is organic and likely made of algal detritus from the algal mats. As a result, the east side of Maunalua Bay is nutrient-enriched, as evidenced by the large diurnal fluctuations in dissolved oxygen concentration presumably due to algal photosynthesis during the daytime and respiration at nighttime (Wolanski et al. 2009).

In the central and western regions of Maunalua Bay, waves breaking on the reef crest are expected to be the dominant flushing mechanism as oceanic waters flooding over the crest exist through the nearest reef passage. Thus, the reef flat is those areas are well flushed, with a residence time of less than one day, precluding the formation of a nepheloid layer. Turbid plumes are present throughout Maunalua Bay following rain events and due to re-suspension of sediments accumulated within benthic algal mats that are eventually carried across the reef flat and through reef passages. These plumes are present in both wet and dry seasons on the east side, while they exist in the central and western regions only during the wet season (Wolanksi et al. 2009).

Bio-erosion of coral skeletons, coralline algae and the limestone remnant of past coral growth generated the majority of the calcareous sediment that formed the sandy beach on the west side of Maunalua Bay and that existed in the 1940s. This calcareous sand has disappeared as a result of coastal erosion, which instigated the construction of stone and cement seawalls along much of the western shore of Maunalua Bay. The disappearance of the sandy beach in the central and western regions of Maunalua Bay can be explained by the absence of coralline algae and live coral as a source of calcareous sediment (Wolanski et al. 2009). In the past, this calcareous sediment would have been produced throughout the year ar a rate of about 4 kg $CaCO_3$ m^2 per year (Kinsey 1985) and, thus, would have maintained a sandy beach.

The structure of Maunalua Bay, as well as its sources of groundwater seepage, has been altered dramatically as a result of the urbanization at Hawaii Kai and other residential communities in the hinterland. Several major fishponds were destroyed in this process. The seasonal migration of native mullet (`*ama`ama*) known to this region was disrupted for reasons that have not been fully understood.

3.3 Kane`ohe Bay

One of the best examples of reef degradation caused by runoff is that reported for Kane`ohe Bay (Smith et al. 1981; Jokiel et al. 1993). Activities near this bay led to multiple effects, including sewage pollution, agricultural runoff, increased sedimentation and freshwater runoff. The occurrence of coral reef mass mortalities during storm floods and a general decline in coral cover during a period of increasing sewage stress implicates several stressors in the degradation of Kane`ohe Bay reefs over the past several decades..

Kane`ohe Bay, at 45 km$^2$, is the largest sheltered body of ocean in the main Hawaiian Islands. This reef-dominated bay is a significant feature along the windward coast of O`ahu. The bay is approximately 8 mi (12.8 km) long and 2.7 mi (4.3 km) broad, with a mouth opening of about 4.6 mi (7.4 km) and a maximum depth of 40 feet in the dredged channel. Two navigable channels cut across the northern and southern ends of the barrier reef. The lagoon contains extensive patch and fringing reefs and its southern end is partly enclosed by the Mokapu Peninsula. This peninsula is occupied by Marine Corps Base Hawaii (from Wikipedia).

During the first half of the 20th century, the coral reefs of Kane`ohe Bay were generally healthy, supporting local fisheries and offering one of the best vistas of “coral gardens” in the Hawaiian Islands. In 1963, a large sewage outfall was installed in the bay, which had an increasing effect on corals until 1978, when the outfall was moved to the deep ocean outside the bay. Eutrophication caused by increasing sewage loads favored a growth of a bubble alga and suspension feeding and bioeroding species that combined to degrade the reef communities over a long period. Following the sewage diversion, there have been clear signs of renewed coral growth and favorable conditions for reef community renewal.

Corals started to regrow after a 1987 flooding event. Many years have passed without a major disturbance event. Urban development and pollution did considerable damage to Kaneohe Bay (Devick Tr. 02/14/96 in Commission 1997). This history illustrates a degree of resiliency to a disturbance that might have led to reef ecosystem collapse in a sewage-stressed environment (Devick 1996 in Commission 1997).

Loss of fishponds has affected the abundance of inshore fishes like native mullet at Kane`ohe Bay. There were once 30 Hawaii fishponds in Kane`ohe Bay, but now there are only 12. Because these fishponds contain much of the freshwater and productivity in specific and concentrated areas, they are excellent nursery habitats (Leber Tr. 4/23/96 in Commission 1997).

Back-to-back rain events in late November and early December 2003, following a particularly dry summer, were studied (De Carlo et al. 2007). The short-term biochemical response of coastal waters and the ecosystem to runoff and physical forcing was evaluated. Dissolved N:P ratios in Kane`ohe Bay, which normally range from 2 to 4, increase to as high as >25 during storm runoff. Oder of magnitude increases in nutrients and chlorophyll in the bay shortly after the first storm that was studied and subsequent changes to the plankton community structure reflect an evolving biological response stimulated by storm discharges to the bay. Phytoplankton did not draw nutrients down to limiting levels, likely due to grazing pressure by zooplankton, yet phytoplankton were not grazed to limiting levels. As a result, a slow but steady increase of the phytoplankton standing stock was observed over time (De Carlo et al. 2007).

Low phosphate levels (<0.2 uM)) combined with very high N:P values are typical in Kane`ohe Bay water after most storms and P often becomes the ultimate limiting nutrient. Concentrations of NH_3 became elevated (8-16 uM)) following the initial storm that was studied, first in deep and subsequently in surface waters, and remained high for several months. Remineralization of organic matter transported into southern Kan`ohe Bay during the storm possibly contributes nutrients that sustain phytoplankton productivity for extended periods (De Carlo et al. 2007).

Scientists are unable to quantify the correlation between stream flow and improved fish habitat (Lowe Tr. 2/29/96). What makes Kane`ohe Bay an important habitat is not so much the salinity factor per se but involves the morphology of the sheltered areas of the bay (Lobel 4/11/96 in Commission 1997). Stream flow rates are only one factor. The number of pools, refugia, plants and the chemistry of the water when the plants dissolve should also be considered (Lobel Tr. 4/11/96 I Commission 1997).

Channelization of streams prevents high rainfall from moving up the banks of streams to collect and transport nutrients to the bay. Channelization also prevents vegetation lining the streams from filtering sediments out of the stream water. Lining of streams has greatly increased sedimentation into Kane`ohe Bay. Such increase is also likely interfering with native *limu* production (Leber Tr. 4/23/96 in Commission 1997).

During the past 75 tears, Kane`ohe Bay has experienced a large reduction in fresh water inputs as its principal tributaries have been channelized to shunt stream flow through the Ko`o;au Mountain range to the interior of O`ahu. Some of this previous diversion has been reversed. Devaney et al. (1982) estimated that these water diversions (some of which have been partially reversed) represent a decrease of over 40 percent in total stream runoff into the bay.

Some scientists attribute the current condition Kane`ohe Bay on massive nuisance exotic algae killing corals. Other scientists note that exotic species of algae are successful because they are competitively superior and they have no natural predators in the herbivorous fish that frequent the bay. Recent nutrient concentrations from across Kane`ohe Bay are reportedly below values that are considered thresholds for algal blooms (Smith et al. 2008).

3.4 Molokai's South Coast

Human activities have adversely affected much of the south coast of Moloka`i, including coastal dredging at Puko`o in the east, wharf construction and sugar cane farming in the central part of the coast, and heavy cattle grazing on the west end. Although the impact from these activities has been severe, evidence indicates that once the activities ended, water quality improved and the adjacent reef began to recover.

Many activities that occur in watersheds have a legacy. Muddy sediment introduced into gullies, stream channels and the coastal plain remains there for many years but, ultimately, it is further eroded and transported to the reefs. The greatest threats to reefs and to water quality are activities that expose upland soils to accelerated erosion and transport. Two of the principal causes of current soil loss from south Moloka`i watersheds are the stripping of vegetation by fires and the destructive grazing of feral goats. The changes visible result from the cumulative effects of many different activities over decades or, in some cases centuries.

The south Molokai reef is not the result of coral growth in the past century or even the past millennium. Nor is it the result of continuous growth. Accumulating evidence on the age and structure indicate that much of the reef originated during earlier periods of reef growth and it is quite likely that the reef was built during a number of intervals when sea level was at or near its present position (Field et al. 2007)

The reef fronting southern Molokai is a classic fringing reef, with a wide shallow reef flat, a well-developed reef crest at the seaward edge of the reef flat, and a biologically rich fore reef reaching to depths of 27 to 32 m (90 to 105 feet). Some of the activities that have caused damage by sedimentation in the past are no longer taking place. Their lingering effects, however, are still being felt in the form of excess sediment runoff.

The entire reef flat between Pala`au and Kamalo bears evidence of damage from sedimentation. The low to absent coral on the inner reef flat between Kaunakakai Wharf and Kamalo is striking, in contrast to high coral cover off other coasts of Moloka`i (Field et al. 2007.

The most dominant factor contributing to the sediment damage is the legacy of several hundred years of human activities on the island (Roberts 2008). This is evident from one area severely damaged by sediment in the 1970s. Kamalo was a prime fishing area, with extensive coral cover, prior to a series of aborted dredging operations in the area that began in the late 1960s (Roberts 2008) some of excavated material was used to alter the shape of the remains of a large fishpond and some of it was discharged onto the reef. After completion of the dredging and reshaping of the coast, these marina projects were abandoned). The dredging occurred near the Smith-Bronte landing area on the inner reef flat east of Kamalo near Kalae Loa Harbor. The prevailing westward currents carried silt from the dredge operation down the coast and well past Kamalo. The area took on the appearance of a wasteland. Everything was covered with fine silt and the fish left the area (Joe Reich, pers. communication).

Even after the company went bankrupt and abandoned the dredging operation, the fine sediments continued to remobilize whenever the wind and waves increased. Chronic turbidity and sedimentation prevented any recovery of the reefs for many years. As fine sediments were winnowed out and transported offshore, the area slowly began to improve. Reefs showed signs of recovery by the mid 1970s. Recovery was underway by the early 1980s, with full recovery by 1990. The reefs of Kamalo presently appear to be pristine but much of the area actually represents regenerated reef that was heavily damaged by siltation (Coral Reef Assessment & Monitoring Program, Molokai, Hawaii Institute of Marine Biology, undated. Read 7/13/2011 from http://cramp.wcc.hawaii.edu/Watershed_Files/Molokai/WS_Molokai-molokai-SouthMolokai)

A study by the U.S. Geological Survey during and after a heavy rainfall on November 27, 2001, Kona storm on south Moloka`i has demonstrated that such events contribute sediment and turbidity to the reef flat and fore reef, but they do it in a complex manner. The waves that accompany the weather fronts are a major factor in re-suspending both terrigenous and reef-based sediment and transporting it on the reef, where it deposits on corals and other benthic organisms and inhibits photosynthesis. Heavy rains produce floods in intermittent streams and gullies as well as overland flow at the coast. In the November 2001 storm, large amounts of terrigenous sediment were deposited along the coast and on the reef flat, where they became available as a source for later re-suspension.

The sequence of natural processes that occurred before, during, and following the November 27, 2001, Kona storm provide a solid basis for understanding the natural cycle of ridge-to-reef sedimentation in this environment. These processes are neither unusual nor extreme, and they most likely represent events that happen one or more times annually. The conditions that led to high sediment mobility and high turbidity on the reef in November and December 2001 were as follows:

- On land: A high rate of rainfall (10 cm, or 4 in, within 24 hours) led to high water and sediment runoff onto the reef. The high sediment runoff was likely exacerbated by land-use practices and a preceding dry period (~3 years). The sediment reached the coast and inner reef by means of gullies and overland flow, and much of it was deposited near the discharge points at the coast.

- On the reef: Waves were high before and during the heavy rainfall, then dropped back to normal levels. During the storm, large storm waves caused resuspension of previously deposited sediment, leading to turbidity on the fore reef. Winds were onshore; trade winds were mild to nonexistent and only slowly became reestablished in the days following the storm. The return to trade-wind conditions following the storm caused renewed resuspension and along-reef transport of flood sediment.

These conditions led to a decoupling of sedimentation on the reef flat and on the fore reef off central Moloka`i. The reef flat was characterized by initial high levels of deposition at coastal deltas and adjacent areas. Following the storm, trade winds became reestablished, leading to daily resuspension and high turbidity. Macroalgae and silt increased markedly for at least six months after the storm (Stamski and Field, 2006).

On the fore reef, the storm was characterized by high wave stresses and onshore winds, resulting in temporary high turbidity and temporary deposition. Because periodic high wave stresses subsequently re-suspended and transported the sediment, there was apparently no significant long-term storage of fine-grained terrestrial sediment on the fore reef (Field et al. 2008).

While the heaviest sediment loads are delivered to the ocean by storm events during periods of a few days, the further transport and life of the sediment may involve years to decades of interaction with the ocean environment. Annual rainfall declined in Hawaii in the second half of the 20th century (Oka 2004). It is not known, however, if this trend is part of a long-term cycle or represents a distinct change in climate. If drier weather persists over the long term, then heavy rainfall and sediment runoff would occur less frequently than in the past.

Another complicating factor is gradually rising sea level, so that the reef flat fronting south Moloka`i would become somewhat deeper than the present level. Most climate projections suggest that sea level may rise on the order of 0.5–1.0 m by 2100; it is not clear, however, how fluid flow and sediment dynamics on exposed fringing reefs might change in response to this rapid sea-level rise. Coupled hydrodynamic and sediment-transport numerical modeling is consistent with recent published results that suggest that an increase in water depth on the order of 0.5–1.0 m on a 1–2 m deep exposed fringing reef flat would result in larger significant wave heights and setup, further elevating water depths on the reef flat. Larger waves would generate higher near-bed shear stresses, which, in turn, would result in an increase in both the size and the quantity of sediment that can be re-suspended from the seabed or eroded from adjacent coastal plain deposits.

Greater wave- and wind-driven currents would develop with increasing water depth, increasing the alongshore and offshore flux of water and sediment from the inner reef flat to the outer reef flat and fore reef where coral growth is typically greatest. Sediment residence time on the fringing reef flat was modeled to decrease exponentially with increasing sea-level rise as the magnitude of sea-level rise approached the mean water depth over the reef flat. The model results presented here suggest that a 0.5–1.0 m rise in sea level will likely increase coastal erosion, mixing and circulation, the amount of sediment re-suspended, and the duration of high turbidity on exposed reef flats, resulting in decreased light availability for photosynthesis, increased sediment-induced stress on the reef ecosystem, and potentially affecting a number of other ecological processes. Perhaps, the passage of sediment presently entrained on Molokai's south reef flat would be accelerated (Storlazzi et al. 2011).

3.5 *`Anae holo*

Schools of traveling striped mullet (`*ama`ama*) once migrated seasonally from Pearl Harbor to other coasts. These schools were known as `*anae holo*. In 1900, mullet comprised about 35 percent (one million pounds) of all fish purchased at the Honolulu fish market (Cobb 1905). They presently account for only 8,000 pounds of the reported commercial catch in Hawai`i (DLNR 2009).

Winter was the time period when the `*anae holo* (traveling mullet) school in Pearl Harbor (Pu`uloa) by the thousands, prior to making an annual migration. The `*ama`ama* reach sexual maturity at about 28 cm, about 3 years old, and migrate offshore during the winter months to spawn in the ocean (Nishimoto et al. 2007).

For generations, throw-net fishermen along the leeward and windward coasts of O`ahu were synchronized to the `*anae holo* traveling cycle. The native mullet would travel east past Kalihi, Honolulu and Waikiki before turning north and hugging the windward coast all the way to La`ie (Clark 2009).

This annual migration was across shallow reefs and estuaries. Channels have been cut across the reefs at Ke`ehi Lagoon, Honolulu Harbor, Kewalo Basin and Waikiki that may be too inhospitable to the `*anae holo* and their food. Native mullet feed on native limu, which grow best where coastal springs mix fresh water with ocean water. Freshwater for agriculture and urban development was diverted from estuaries, many of which were filled for coastal development. The introduction of alien *limu* and fish has also changed the ecosystem in which the `*anae holo* thrived. Fishermen fondly remember the annual runs that occurred as late as the 1970s (Clark 2009).

Filling of the historic spawning trails that were used for centuries by the `*anae holo* cannot be reversed any time soon. However, restoration of freshwater springs along the southeastern coast of O`ahu would be beneficial for native *limu*, the diet of the `*anae holo* (Clark 2009).

Native mullet are said to eat attachments to the green seaweed `*ele`ele*, which is associated with nearly fresh water. The mullet know how to find this *limu*. This process is still observed among small groups of *aholehole* at Kanewai Pond located behind Pailo Lagoon in Kuli`ou`ou (Cramer 2009). Striped mullet is a valuable indicator of ecosystem response to changes in productivity in estuaries, although productivity is only one element of interest (Leber Tr. 4/23/96); KSBE FOF 1502, Waiahole case in Commission 2007).

A Hawaiian spirit in Pu`uloa (Pearl Harbor) was believed to supply the *anae* to answer the need for fish expressed by his sister-in-law in La`ie. After being fished on the windward coast, the remainder of the mullet returned by the same path until they reached Honouliuli in Pearl Harbor, where the spirit resided.

The mullet was prized as a food fish for royalty. The Hawaiian language recognizes the different size classes of the *`ama`ama* but most intriguing is recognition of the traditional migratory route between Ewa and La`ie, Oahu. A census at the Honolulu fish market in 1900 reported that 35.6% (one million pounds) of the fishes sold were the *`ama`ama*, however, there was no differentiation between mullet taken from fishponds or the open ocean. Mullet were the most expensive fish at the market and sold for 25 cents/lb (Cobb 1905). The 1900 census shows that 485,531 pounds of mullet were from ponds on the island of O`ahu (Cobb 1905), but the overlap with the total Honolulu market sales is unknown.

In the late 1800s, many coastal fishponds were not tended and fell into disrepair, as the population migrated to the city or other crops, such as rice and taro, became more profitable. In 1900, there were only 99 documented fishponds. The number of fishponds used to cultivate *`ama`ama* and other estuarine species continued declining into the 20th century, when only two ponds sold less than 1,000 lb of *`ama`ama* in 2003 (Nishimoto et al. 2007).

One of the principal harvests in the old fishponds was native mullet because of the combination of freshwater and shallow sand or mud flats that the ponds created were ideal for growing the *limu `ele`ele* and other seaweeds that mullet consumed. In addition to the loss of fishpond areas, toe concept of interconnection between the fishponds and estuaries has been lost. In some cases, there were said to be underground connections between the ponds. A fish warden noted in the 1930s that there was an underwater lava tube connecting Kaelepulu Pond and Kuapa. When the mullet would leave one pond, they would reappear in the next pond (Editorial Board, Lawai`a No. 2, 2009).

Fishing for *`ama`ama* was once easily recognized by the numerous, small wooden platforms, called stilt chairs, dotting the tidal flats on Kane`ohe Bay and Ala Wai Canal, that once marked the daily migratory path of the mullet. Small skiffs now replace such platforms. Hilo Harbor, especially the Waiakea Public Fishing Area, is one of the last strongholds of stilt-chair mullet fishing (Nishimoto et al. 2007).

Observations by a longtime fisherman and Hawaii Fish and Game fishery biologist noted that the average size of mullet caught in the 1940s was 3-4 lbs but that there was a dramatic decline in average size over time. This source considers mullet stocks overfished and the brood stocks severely depleted. He hypothesized that the losses of shallow water nursery habitat and competition from the alien *kanda* (*Valamugil engeli*) in the same estuaries as native mullet have contributed to this decline. The population of *kanda* has exploded and invaded the native mullet habitat in many bays and estuaries in Hawai`i (Nishimoto et al. 2007).

In 1993, by using stock enhancement experiments, it was discovered that many nursery habitats in Kane`ohe Bay are actually below carrying capacity. Even degraded habitats like Kahalu`u, which has been channelized and diverted, have shown major increases in recruitment of mullet due to release of hatchery fishes. In other words, despite the degraded nursery condition at Kahalu`u, the hatchery fish did not displace the wild fish because there is enough food and space for these animals (Leber Tr. 4/23/96 in Commission 2007).

The current nursery habitats are capable of supporting large increases of juvenile mullet even during good recruitment years like 1993. Thus, the current levels of natural productivity are not being fully utilized (Leber Tr/ 4/23/96 in Commission 2007). Oceanic Institute studies have shown that the limits of inshore fish abundances in Kane`ohe Bay are largely due to lack of recruitment, rather than food limitations. Unless recruitment limitations are overcome, increasing food and habitat would not necessarily increase fish abundances (Leber Tr. 4/23/96 in Commission 2007).

3.6 Summary

Coastal waters that receive large stream discharges may change, not necessarily in direct response to runoff but over the long term with increasing development and eutrophication in and around Hawai`i coastal waters. This is evident from the previous description of major damage to Maunalua Bay. Other areas may actually recover after damage from flood runoff and sedimentation. Examples are described in Kane`ohe Bay and along the south Moloka`i coast. It is often the interaction of persistent and multiple synergistic disturbances that cause long-term ecological transitions, rather than the succession of individual short-term disturbances.

4.0 ANALYZE AND INTERPRET STREAM FLOW DATA TO DETERMINE IMPACTS TO MARINE SPECIES AND ECOSYSTEMS

There are two sections of Section 4. The first section assesses available data to determine if there may be relationships between long-term commercial catch records compiled by the Hawaii Department of Land and Natural Resources (DLNR) for O`ahu and Kaua`i and long-term reports of peak stream discharge at selected stations gauged by the U.S. Geological Survey (U.S.G.S.).

The second section examines possible relationships between the growth of native seaweeds (*limu*) and submarine groundwater discharges along the Kona coast of the island of Hawai`i.

4.1 Possible Relationships Between Estimated Commercial CPUE of Selected Nearshore Fish Species and Surface Stream Discharges on O`ahu and Kaua`i

Data records were summarized by DLNR to assess four nearshore reporting areas (Nos. 403, 407, 409 and 503) that have been consistent producers of selected fish species that are known to be associated with freshwater as juveniles: *aholehole*, *akule*, native mullet (*`ama`ama*) and jacks. The proposed method for these assessments was to try to associate changes in commercial catch records of these species at the selected sites listed above with long-term records of peak stream discharge in the areas of Maunalua Bay, Kane`ohe Bay, Waianae on the island of O`ahu and the Hanalei region on the island of Kaua`i. The catch reporting areas are "nearshore," which, under the DLNR definition, are ocean waters to two nautical miles offshore.

DLNR commercial catch reports are withheld for reporting areas where fewer than three fishermen make reports. An attempt to calculate time trends in estimated catch per unit of effort (CPUE) for individual areas 403, 407, 409 and 503 was abandoned because confidentiality issues prevented availability of almost 70 percent of the landings records compiled in DLNR's commercial catch reports (R. Kokubun, DLNR, personal communication to P. Dalzell, Council, January 26, 2012). This high level of unavailability was not adequate to search for possible connections with long-term stream discharge.

A second DLNR summary was made of commercial catch records by combining reporting areas 403, 407, 409 and 503. About half of the compiled commercial catch records had to be purged from this attempt due to data confidentiality (R. Kokubun, DLNR, personal communication to Mark Mitsuyasu, Council, February 3, 2012). The data for these four nearshore areas was combined to improve the available database by reducing the level of confidentiality (i.e., less than three fishermen reporting per area). Even so, only 49 percent of the commercial catch data base could be used because of confidentiality problems. Nevertheless, this result represents an attempt to search for possible linkages with long-term peak fresh water discharge at selected U.S.G.S. stations.

This effort is also weakened because the DLNR does not record non-commercial catch statistics. Alternative sources of such data are inadequate. Non-commercial catches of some fish species, including the four considered in this section, are substantial. Therefore, when estimating CPUE for the selected species, emphasis was placed on fishing methods that are more likely to have had commercial purposes (e.g., lay gill net) than on methods that are more likely to be non-commercial (e.g., throw net).

With these constraints in mind, long-term commercial catch summaries for four combined nearshore catch reporting areas (403, 407, 409 and 503) were compared with long-term peak stream discharges for four separate U.S.G.S. gauging stations to search for possible relationships between the two sets of data. It was possible that long-term relationships might be evident in the highs and lows of relationships between commercial fish species (four nearshore areas combined) when they are strongly influenced by fresh water discharge.

CPUE is estimated annually by dividing the pounds caught from commercial fishermen’s reports for a lengthy time period by the number of commercial fishing trips they reported. A major weakness of the DLNR data base is that only commercial fishermen (who sell catch) are required to report data. Fishing trips for subsistence or recreation are not required to report their catch to this data base.

Only a few of the commercial catch data bases made available through the DLNR were of sufficient length to examine for possible changes in CPUE. The longest data base for *aholehole* (four nearshore reporting areas combined) was CPUE caught by lay gill net estimated for the period 1952-2007. *Aholehole* catch data for a few years in the 1960s were not available for this analysis. The peak effort reported during this period was from 1978-1984, ranging from 24 to 63 trips per year. CPUE using this gear peaked in 1957 (40.8 lb/trip) and in 1965-1967 (25.8-43.1 lb/trip), 1974 (29.1 lb/trip) and 1978 (30.2 lb/trip). Additional peaks in CPUE occurred in 1990 (62.3 lb/trip) and 1995 (47.7 lb/trip). The ten highest years of CPUE using this method occurred mostly before 1978, whereas the ten lowest years of CPUE occurred mostly after 1999 to 2007. This result suggests that commercial *aholehole* CPUE with lay gill nets in more recent years was significantly reduced in comparison to earlier years for the four nearshore areas combined. In 2007, the State of Hawaii banned lay gill nets in some areas and imposed time and tagging restrictions on gill net use in other areas. The new rules obviously have changed the lay gill net fishery since 2007.

DLNR maintains a long, continuous data base for commercial *akule* lay gill net from 1965 through 2010 (four nearshore reporting areas combined). The peak effort reported during this period was between 1971 to 1975, ranging from 46 to 84 trips/year; from 1980 to 1985, ranging from 112 to 67 trips per year; from 1996 to 2001; ranging from 67 to 88 trips per year; and from 2006 to 2010, ranging from 54 to 75 trips per year (except 35 in 2009). Commercial CPUE reported for these areas ranged from highs in 1966 (712.5 lb/trip), 1967 (657.1 lb/trip), 1970 (635.9 lb/trip), 1972 (689.8 lb/trip), 1975 (655.2 lb/trip), 1976 (911.8 lb/trip), 1977 (639.8 lb/trip) and 1978 (683.9 lb/trip). Lower CPUE per trip was reported during the 1980s: 214.3 lb/trip (1982), 319.2 lb/trip (1984), 300.05 lb/trip (1986), 203.2 lb/trip (1987), 105.4 lb/trip (1988), 69.9 lb/trip (1989). Average CPUE per trip has generally recovered to higher levels more recently: 1998 (950.3 lb/trip), 2000 (739.4 lb/trip), 613.5 lb/trip (2004), 675.7 lb/trip (2005), 629.9 lb/trip (2007), 837.4 lb/trip (2008). In 2007, the State of Hawaii banned lay gill nets in some areas and imposed time and tagging restrictions on lay gill nets in other areas. The new rules obviously have changed the lay gill net fishery since 2007 (Hawaii DLNR 2007).

Lay gill net harvest of native mullet (*`ama`ama*) has a long, continuous history in DLNR commercial catch records dating back to 1949. Commercial fishing effort (i.e., annual commercial trips) reached highest levels in the period 1955 (98 trips), 1952 (96 trips), 1962 (96 trips), 1963 (113 trips), 1964 (108 trips), 1965 (94 trips), 1967-1975 (99-154 trips), 1978 (104 trips), 1980 (92 trips), 1981 (120 trips), 1982 (150 trips), 1983 (199 trips), 1984 (117 trips). Annual commercial trips to lay net for mullet reached 86 in 1985, 90 in 2002 and 83 in 2006. The CPUE of this commercial method reached the highest levels in 1952 (424.3 lb/trip), 1953 (237.6 lb/trip), and 1979 (239.1 lb/trip). The lowest average commercial CPUE for this method occurred during the 1980s and early 1990s: 1981 (44.1 lb/trip), 1982 (31.8 lb/trip), 1983 (18.0 lb/trip), 1984 (16.5 lb/trip), 1985 (19.9 lb/trip), 1986 (12.04 lb/trip), 1987 (18.2 lb/trip), 1988 (13.04 lb/trip), 1989 (16.4 lb/trip), and 1991 (8.8 lb/trip). A project sponsored by the Oceanic Institute and Hawaii Department of Land and Natural Resources tagged and released native mullet in 1990, 1992-1993 in Kane`ohe Bay and in 1990 in Maunalua Bay. These efforts no doubt inflated the CPUE of commercial mullet reported in those areas for a period of time.

Commercial CPUE of *ulua* (jacks) is difficult to estimate for long periods from the DLNR commercial catch reporting system because the nomenclature has been changed over time and records do not consistently refer to the same species. Commercial catch records for the inshore handline *omilu* date back to 1949, however. The years of greatest commercial effort (i.e., total trips) are from 1949 to1957 (7 to 19 trips per year), 1987 to 1991 (11 to 32 trips per year), and 2005 (14 trips per year). The average estimated CPUE per trip for this method has ranged from lows of less than 10 lbs/trip (in 1972-1975, 1982-1986, 1993, 1996, 1999 and 2006 to levels over 18 lb/trip in the period 1957-1972 2003-2005; 35-39 in 2008-2009 and 101 lb/trip in 2010.

Trends in commercial catch CPUE (four DLNR nearshore reporting zones combined) were compared with long-term trends in peak stream flow for four separate gauging stations maintained by the U.S.G.S. and reported in the U.S.G.S. national water information system web interface for Hawai`i. Unfortunately, many of the gauging stations that were once reported have been discontinued, so the number of sites that could be utilized was reduced.

Long-term data on peak stream flow are available for the period 1958-2010 for U.S.G.S. gauging site 16247500, Wailupe Gulch at Aina Haina, Oahu. This is a reasonable site for estimation of annual peak stream discharge into Maunalua Bay. Peak discharges in this data set are not correlated with the estimated commercial CPUE of *aholehole* caught by lay gill net from 1952 through 2007. Rather, the estimated CPUE has declined substantially in this fishery in the four nearshore areas since about 1966.

Peak discharges do not appear to be correlated with the estimated commercial CPUE of native mullet from the four nearshore areas. No obvious correlations are apparent between estimated commercial CPUE for four combined DLNR reporting zones and peak stream discharges reported by the U.S.G.S. for site 16097900, Puulumu Stream, near Kilauea, Kauai. This site is a poor substitute for a stream flow gaging site closer to Hanalei Bay but it provides a much longer site set of stream flow information compared to the Hanalei sites.

The estimated commercial lay gill net catches of *akule* from 1965 to 2010 have two major trends: generally high levels of annual commercial CPUE from 1965-1980 and between 1990-1993 and 1996-2010; and generally lower annual commercial lay gill net catches of *akule* during other periods for which commercial catch data are available. Long-term data on peak stream flow are available for the period 1958-2010 for U.S.G.S. gauging site 16212300, Nanakuli Stream, near Nanakuli, Oahu. This station is a reasonable site for estimating annual peak stream discharge into the Waianae region. The stream discharge data do not support any apparent correlations with estimated commercial lay net CPUE of *akule*.

The estimated commercial lay gill net catches of native mullet (`*ama`ama*) changed from low levels between 1981-1991 to higher levels in 1995-1997 and 2007-2010. Long-term data on peak stream flow are available for the period 1958-2010 for U.S.G.S. gauging site 16247500, Wailupe Gulch at Aina Haina, Oahu. This is a reasonable site for estimating annual peak stream discharge into Maunalua Bay.

Long-term data on peak stream flow are available for the period 1963-2011 for U.S.G.S. gauging site 16283480, Ahuimanu Stream near Kahalu`u, Oahu. This is a reasonable site for estimation of annual peak stream discharge into Kaneohe Bay. Peak stream flow is reported by the U.S.G.S. for site 16097900, Puulumu Stream, near Kilauea, Kauai. This site is a poor substitute for a stream flow gaging site closer to Hanalei Bay but it provides a much longer site set of stream flow information compared to the Hanalei sites. Peak stream discharge recorded at this location does not appear to be correlated with the estimated commercial CPUE of native mullet reported by the DLNR from the four nearshore areas.

At none of the four stations that recorded peak stream discharge does the estimated commercial inshore handline catch of *omilu* appear to be correlated with peak stream discharge in the four combined DLNR commercial catch reporting zones.

The previous section compared estimated commercial CPUE for four marine species combined with estimates of peak stream flow discharge at four separate locations monitored by the U.S.G.S. Remembering all the limitations on data availability, no apparent correlations were evident. There are several problems with the two data sets that may have constrained the present attempt to correlate DLNR commercial catch reports with U.S.G.S, peak stream discharge reports. These include:

- Due to confidentiality of fishermen's reports, four nearshore catch reporting zones in the DLNR catch reporting system had to be combined. Even so, confidentiality problems prevented 49 percent of fishermen's reports from being considered in the present report.
- Four <u>combined</u> DLNR nearshore zones (further limited by confidentiality problems) are compared with four <u>separate</u> records of peak stream discharges recorded at U.S.G.S. gauging stations.
- DLNR reports from fishermen are limited to commercial catch reports. Many types of nearshore fishing do not catch fish for commercial purposes and these are not included in the present analysis.
- A tag and release project for native mullet in 1990, 1993 and 1994 probably inflated the commercial mullet catch recorded in Kane`ohe Bay for a period of time.

Table 3 reports on the comparison of CPUE estimated from fish catch reports for four DLNR nearshore reporting zones with four separate reports of peak stream discharge recorded by the U.S.G.S.

Table 3. Estimated CPUE of Target Fish Species Compared to Records of Peak Stream Discharge

Marine Species	Fishing Method	10 Years of highest CPUE[1]	10 years of lowest CPUE[2]	Peak Stream Discharge			
				Aina Haina, O`ahu[3]	Kahalu`u, O`ahu[4]	Nanakuli, O`ahu[5]	Kilauea, Kaua`i[6]
Aholehole	Lay gill net	1957 (40.7)		No record	No report	No record	No report
	(1954-2007)	1965 (43.1)		High (1470 cfs)	High (6610 cfs)	No record	Low (170 cfs)
		1967 (42.0)		Medium (1070 cfs)	No report	No record	Low (161 cfs)
		1974 (29.1)		Low (436 cfs)	High (2030 cfs)	Medium (570 cfs)	Low (84 cfs)
		1978 (30.2)		Low (648 cfs)	Low (650 cfs)	Low (30 cfs)	No report
		1987 (28.7)		Low (215 cfs)	Low (900 cfs)	Medium (700 cfs)	Low (182 cfs)
		1990 (62.3)		Low (496 cfs)	Low (890 cfs)	Low (350 cfs)	Low (220 cfs)
		1994(29.6)		Medium (1120 cfs)	High (2320 cfs)	Low (300 cfs)	Low (120 cfs)
		1995 (47.7)		Low (511 cfs)	Low (298 cfs)	Low (200 cfs)	Low (20 cfs)
		1996 (28.6)		Low (308 cfs)	Low (642)	Low (300 cfs)	High (1240 cfs)
			1982 (6.8)	Low (666 cfs)	High (3500 cfs)	High (2470 cfs)	High (963 cfs)
			1984 (6.8)	Low (250 cfs)	Low (150 cfs)	Low (50 cfs)	Low (30 cfs)
			2000 (6.2)	Low (no record)	Low (375 cfs)	Low (21 cfs)	Low (40 cfs)
			2001 (4.8)	Low (no record)	Low (389 cfs)	Low (1 cfs)	Low (49 cfs)
			2002 (5.5)	Low (no record)	Low (509 cfs)	Low (39 cfs)	Medium (456 cfs)
			2003 (4.9)	Low (257 cfs)	Low (432 cfs)	Low (50 cfs)	Low (75 cfs)
			2004 (3.2)	Low (562 cfs)	Low (940 cfs)	Medium (770 cfs)	Low (126 cfs)
			2005 (4.6)	No record	Low (486 cfs)	No record	Medium (336 cfs)
			2006 (7.9)	No record	High (1720 cfs)	No record	High (823 cfs)
			2007 (7.1)	No record	Low (507 cfs)	No record	Low (68 cfs)

Marine Species	Fishing Method	10 Years of highest CPUE[1]	10 years of lowest CPUE[1]	Peak Stream Discharge			
				Aina Haina, O`ahu[2]	Kahalu`u, O`ahu[3]	Nanakuli, O`ahu[4]	Kilauea, Kaua`i[5]
Akule	Lay gill net	1954 (2260.7)		No record	No report	No record	No record
	(1954-2010)	1966 (712.5)		High (1370 cfs)	High (2630 cfs)	No record	Medium (478 cfs)
		1972(689.8)		Medium (801 cfs)	Low (942 cfs)	High (1060 cfs)	Low (44 cfs)
		1976 (911.8)		Low (370 cfs)	Low (800 cfs)	High (3320 cfs)	No record
		1978 (683.9)		Low (648 cfs)	Low (650 cfs)	Low (30 cfs)	No record
		1998 (950.3)		Low (no record)	Low (220 cfs)	No record	Low (20 cfs)
		2000 (739.4)		Low (no record)	Low (375 cfs)	Low (21 cfs)	Low (40 cfs)
		2005 (675.7)		No record	Low (486 cfs)	No record	Medium (336 cfs)
		2007 (629.9)		No record	Low (507 cfs)	No record	Low (68 cfs)
		2008 (837.4)		Low (552 cfs)	Medium (1260 cfs)	No record	Low (49 cfs)
			1979 (321.6)	Low (676 cfs)	High (1720 cfs)	High (1300 cfs)	No record
			1982 (214.3)	Low (666 cfs)	High (3500 cfs)	High (2470 cfs)	High (963 cfs)
			1984 (319.2)	Low (250 cfs)	Low (150 cfs)	Low (50 cfs)	Low (30 cfs)
			1986 (300.1)	Low (319 cfs)	Low (1,000 cfs)	High (2500 cfs)	Low (25 cfs)
			1987 (203.2)	Low (215 cfs)	Low (900 cfs)	Medium (700 cfs)	Low (182 cfs)
			1988 (105.4)	Medium (949 cfs)	Medium (1100 cfs)	Low (375 cfs)	Medium (400)
			1989 (69.9)	Low (574 cfs)	Low (890 cfs)	Low (450 cfs)	Medium (330 cfs)
			1994 (286.9)	High (1120 cfs)	High (2320 cfs)	Low (300 cfs)	Low (120 cfs)
			1995 (285.5)	Low (511 cfs)	Low (298 cfs)	Low (200 cfs)	Low (20 cfs)
			2002 (191.7)	Low (no record)	Low (509 cfs)	Low (30 cfs)	Medium (456 cfs)

Marine Species	Fishing Method	10 Years of highest CPUE[1]	10 years of lowest CPUE[1]	Peak Stream Discharge			
				Aina Haina, O`ahu[2]	Kahalu`u, O`ahu[3]	Nanakuli, O`ahu[4]	Kilauea, Kaua`i[5]
Native mullet	Lay gill net	1952 (424.3)		No record	No record	No record	No record
(*`ama`ama*)	(1949-2010)	1953 (237.6)		No record	No record	No record	No record
		1954 (113.1)		No record	No record	No record	No record
		1957 (123.7)		No record	No record	No record	No record
		1969 (133.6)		Low (499 cfs)	High (7300 cfs)	High (2070 cfs)	No record
		1995 (133.7)		Low (511 cfs)	Low (298 cfs)	No record	Low (20 cfs)
		1997 (128.6)		Low (200 cfs)	Low (642 cfs)	Low (450 cfs)	Low (30 cfs)
		2007 (165.3)		No record	Low (507 cfs)	No record	Low (68 cfs)
		2008 (186.9)		Low (552 cfs)	Medium (1260 cfs)	No record	Low (49 cfs)
		2009 (169.9)		Low (335 cfs)	Low (578 cfs)	Medium (826 cfs)	Low (148 cfs)
			1982 (31.8)	Low (666 cfs)	High (3500 cfs)	High (2470 cfs)	High (963 cfs)
			1983 (18.0)	Low (400 cfs)	Low (650 cfs)	Medium (cfs)	Low (213 cfs)
			1984 (16.5)	Low (250 cfs)	Low (150 cfs)	Low (50 cfs)	Low (30 cfs)
			1985 (19.9)	Low (319 cfs)	Medium (800 cfs)	Low (300 cfs)	Low (285 cfs)
			1986 (12.0)	Low (319 cfs)	Medium (1000 cfs)	High (2500 cfs)	Low (25 cfs)
			1987 (18.2)	Low (215 cfs)	Medium (900 cfs)	Medium (700 cfs)	Low (182 cfs)
			1988)13.0)	Medium (949 cfs)	Medium (1100 cfs)	Low (375 cfs)	Medium (400 cfs)
			1989 (16.4)	Low (574 cfs)	Medium (890 cfs)	Low (450 cfs)	Medium (330 cfs)
			1990 (42.2)	Low (496 cfs)	Medium (890 cfs)	Low (350 cfs)	Low (220 cfs)
			1991 (8.8)	High (2250 cfs)	Medium (960 cfs)	Low (80 cfs)	Low (54 cfs)

Marine Species	Fishing Method	10 Years of highest CPUE[1]	10 years of lowest CPUE[1]	Peak Stream Discharge			
				Aina Haina, O`ahu[2]	Kahalu`u, O`ahu[3]	Nanakuli, O`ahu[4]	Kilauea, Kaua`i[5]
Omilu	Inshore handline	1977 (33.8)		Low (150 cfs)	Low (600 cfs)	Low (300 cfs)	No record
	(1949-2010)	1988 (41.2)		Medium (949 cfs)	Medium (1100 cfs)	Low (375 cfs)	Medium (400 cfs)
		1989 (62.8)		Low (574 cfs)	Medium (890 cfs)	Medium (450 cfs)	Medium (330 cfs)
		1990 (75.8)		Low (496 cfs)	Medium (890 cfs)	Low (350 cfs)	Low (220 cfs)
		2003 (115.2)		Low (257 cfs)	Low (432 cfs)	Low (50 cfs)	Low (75 cfs)
		2004 (102.8)		Low (562 cfs)	Medium (940 cfs)	Medium (779 cfs)	Low (126 cfs)
		2005 (74.0)		No record	Low (486 cfs)	No record	Medium (336 cfs)
		2007 (39.7)		No record	Low (507 cfs)	No record	Low (68 cfs)
		2009 (35.6)		Low (335 cfs)	Low (578 cfs)	Medium (826 cfs)	Low 148 cfs)
		2010 (101.2)		Low (253 cfs)	Low (336 cfs)	No record	No record
			1956 (7.6)	No record	No record	No record	No record
			1973 (8)	Low (370 cfs)	Low (650 cfs)	Low (200 cfs)	No record
			1974 (6)	Low (436 cfs)	High (1930 cfs)	Medium (570 cfs)	Low (84 cfs)
			1982 (8)	Low (666 cfs)	High (3500 cfs)	High (2470 cfs)	High (963 cfs)
			1983 (5.75)	Low (400 cfs)	Low 650 cfs)	Medium (500 cfs)	Low (213 cfs)
			1986 (7.5)	Low (319 cfs)	Medium (1000 cfs)	High (2500 cfs)	Low (25 cfs)
			1993 (4.5)	Low (385 cfs)	Low (415 cfs)	Low (400 cfs)	Low (223 cfs)
			1996 (6.8)	Low (308 cfs)	Medium (900 cfs)	Low (300 cfs)	High (1240 cfs)
			1999 (3)	Low (no record)	Low (298 cfs)	No record	Low (52 cfs)
			2006 (5.08)	No record	High (1720 cfs)	No record	High (823 cfs)

Table 3 Notes: [1] CPUE for various fishing methods estimated annually where data available from report by R. Kokubun, DLNR, to M. Mitsuyasu, Council, providing DLNR commercial catch reports for four nearshore reporting zones combined (No. 403, 407, 409, 503). Ten highest years of estimated CPUE included in Table 2.

[2] CPUE for various fishing methods estimated annually where data available from report by R. Kokubun, DLNR, to M. Mitsuyasu, Council, providing DLNR commercial catch reports for four nearshore reporting zones combined (No. 403, 407, 409, 503). Ten lowest years of estimated CPUE included in Table 2.

[3] Long-term data on peak stream discharge are available for the period 1958-2010 for U.S.G.S. gauging site 16247500, Wailupe Gulch at Aina Haina, O`ahu. Some values estimated.

[4] Long-term data on peak stream discharge are available for period 1963-2011 for U.S.G.S. gauging site 16283480, Ahuimanu Stream near Kahalu`u, O`ahu. Some values estimated.

[5] Long-term data on peak stream discharge are available for the period 1968-2011 for U.S.G.S. gauging site 16212300, Nanakuli Stream at Nanakuli, O`ahu.

[6] Long-term data on peak stream discharge are available for the period 1965-2009 for U.S.G.S. gauging site 16097900, Puukumu Stream near Kilauea, Kaua`i..

4.2 Submarine Groundwater Discharge off Kona Coast, Hawai`i

Submarine groundwater discharge (SGD) is a well-known phenomenon in Hawai`i and has been documented on the West Hawaii coastline, which is the focus of a model (Duarte et al. 2010). In addition to point sources of discharge, such as springs, groundwater may also enter the marine environment in a diffuse manner through benthic sediments. Concentrations of nutrients, trace metals, organic carbon, and methane, and CO_2 may be considerably higher than in surface ocean waters. The effect of SGD on marine waters may be variable over large spatial scales, as this is expected to be relative to local and regional, geologic, tidal and climatic conditions. Many studies have concluded that SGD is a significant source of nutrients to numerous coastal environments. In addition to increasing nutrient levels, SGD has been shown to decrease salinity of local waters compared to ambient oceanic conditions (Duarte et al. 2010).

The model by Duarte et al. (2010) correlates submarine groundwater discharge along the Kona coast with the growth of native seaweeds (known as *limu*). When salinity is high, invasive algae can grow better than indigenous algae. Thus, the carrying capacity of the indigenous species decreases as salinity increases. Changes in *limu* growth are affected by direct effect of salinity on intrinsic growth rate and indirect effects from the change in carrying capacity as *limu* is crowded out by competing species. Desirable ranges of salinities for seaweed species of interest in the study area are 29-33 ppt (Duarte et al. 2010).

The natural growth of *limu* depends on the size of its own stock and water quality. Examples of water quality indicators which may affect the growth of *limu* are salinity, nitrogen and temperature. These indicators are related to the amount of freshwater discharged (Pongkijvorasin et al. 2008).

To incorporate the ecological effect of groundwater extraction, the Duarte study (Duarte et al. 2010 imposed an ecological constraint on aquifer head level to preserve sufficient SGD leakage and thus a minimum growth rate for the marine algae of interest. In Hawai`i, on one end of the spectrum are parties arguing that groundwater wells will diminish SGD and thus seriously degrade or destroy marine ecosystems. On the other end, landowners and developers insist that the effects are small and/or insignificant relative to other activities, such as overfishing and pollution in general (Duarte et al. 2010).

North Kona was chosen for this model for its dependence on groundwater for virtually all water supply, lack of any surface water systems to complicate terrestrial-marine connection, availability of field data, and local political attention focused on both water resource scarcity and marine ecosystem degradation. It is reasonable to only model the coastal, basal aquifer when investigating SGD phenomena (Duarte et al. 2010). Recent research in Kona, employing a variety of techniques, has revealed more than 50 point-source and diffuse discharge sites, which primarily occur or are amplified in coastal embayments. At nearshore SGD sites with low salinity, nutrient concentrations may be two to three orders of magnitude greater than offshore ambient oceanic conditions (Johnson et al. 2008).

In Hawai`i, macroalgae are of major importance to the local economy, cultural practices, and reef biology. In particular, species in the genus *Gracilaria* are highly sought after as a source of fresh food. In the case study, the Hawaiian endemic red edible *limu manauea* (*Gracilaria coronopifolia*) was chosen as a keystone indicator species. *Limu manauea* is native to the Kona coast (Duarte et al. 2010). This species is one of the three most sought after seaweeds for food in Hawaii (Abbott 1984). Its distribution and abundance in recent years has seen serious decline due to overharvesting and other factors (Duarte et al. 2010). *Limu manauea* is known to tolerate a wide range of salinity and nutrient regimes (Hoyle 1975), making it a good candidate for physiological measurements at various levels of SGD.

Two replicate experiments were conducted with *Gracilaria coronopifilia* using a highly controlled unidirectional algae growth chamber that allows simultaneous variation of nitrate, phosphate and salinity in order to simulate varied levels of SGD (Duarte et al. 2010). Four treatments were chosen using empirical relationships on SGD from the Kona coast (Johnson et al. 2008) to determine nutrient and salinity levels. The treatments ranged from low salinity/high nutrients to high salinity/low nutritens. The results suggest that moderate levels of SGD influx to a nutrient-poor environment may increase the growth rate of *Gracilaria coronopifloa*.

Numerous studies have shown that the growth rate of *Gracilaria* spp. increases as salinity decreases from ambient oceanic levels, with optimal conditions occurring between 20-30 ppt salinity. From these studies, it is likely that certain marine primary producers have adapted to and rely on SGD as a natural source of terrestrial nutrients and freshwater. Therefore, excessive extraction of groundwater has the potential to limit the productivity and distribution of these species as SGD flux to the coastal environment decreases. This effect may be magnified in arid tropical regions, where terrestrial runoff is minimal and SGD represents the only source of freshwater and “new” nutrients to marine ecosystems. The model is applied to the Kona coast of Hawai`i, where both nearshore ecology and groundwater resources are serious socio-political issues (Duarte et al. 2010).

This model incorporates standard hydrologic and economic equations, with the addition of constraints linking pumping of a basal aquifer to changes in growth rate or productivity of a keystone marine seaweeds. Based on the results, it seems clear that for very wet, windward sides of the islands, it would take a tremendous amount of pumping to significantly affect SGD fluxes and net impact on the nearshore water quality. For drier, leeward areas, there is a greater chance of nearshore effects. However, it is possible that the impact could be on the order of or less than that of naturally occurring weather pattern and seasonal fluctuations.(Duarte et al. 2010).

A study of groundwater recharge has been conducted on the island of Hawai`i using the most current data and accepted methods. For this study, a daily water-budget model for the entire island was developed and used to estimate mean recharge for various land cover and rainfall conditions, and a submodel for the Kona area was developed and used to estimate historical groundwater recharge in the Kona area during the period 1984-2008 (Engott 2011).

5.0 COMPREHENSIVE REPORT THAT PROVIDES THE COUNCIL WITH AN ASSESSMENT OF THE CORAL REEF FISHERY ECOSYSTEM OF HAWAI`I

5.1 Summary of Present Report's Findings

Links between specific marine species, particularly native mullet *(`ama`ama*) and flagtail (*aholehole*) and freshwater input to the ocean are described in several references. No discrete threshold has been established, but juvenile *`ama`ama* seem to prefer water with salinity below 15 ppt. When salinity becomes > 15 ppt, juvenile *`ama`ama* will abandon an area and move in search of fresher water (Blaber 1987, Dr. Ken Leber, Mote Marine Lab, Sarasota, Fla. pers. communication to Ron Englund). Salinity preferences for *aholehole* are less established than that for *`ama`ama*, but the seasonal use of nursery habitat by *aholehole* is similar to that of *`ama`ama*.

Striped mullet (*`ama`ama*) is a classic estuary organism. It is part of a group of fishes that must spawn in the marine high salinity sea water but whose juveniles move into bays and estuaries and up into streams (Leber Tr. 4/23/96). A major decline in Hawai`i consumer use of fresh mullet *(`ama`ama*) since 1900 and evidence that *`anae holo*, or seasonal migrations of *`ama`ama*, have dropped substantially, provide solid evidence of disruption of the seasonal native mullet run. Landings of *`ama`ama* at the Honolulu fish market in 1900 totaled about one million pounds. Only about 8,000 pounds of striped mullet were landed statewide in the year 2009. Yet, this issue has not received the same attention as others concerning management of entire *ahupua`a*, or complete watersheds in Hawai`i.

The catch records compiled by Hawaii's Department of Land and Natural Resources (DLNR) are for commercial fishing methods only. Confidentiality of fishermen further limits use of these data. Despite these limitations, attempts are made in the present report to search long series of Hawai`i nearshore commercial fishing records for possible evidence of peaks and valleys that could be related to the histories of freshwater discharges. These efforts were ineffective.

A study of submarine groundwater discharge, however, demonstrates how changes in the growth of rates of *Gracilia coronopifolia* (*limu manauea*) are affected by local changes in salinity and nutrients flow into coastal areas along the Kona coast by groundwater submarine discharge.

5.2 Effects on Coral Reef Ecosystem

Possible effects on the coral reef ecosystem from changes in freshwater discharge into the ocean are summarized in the following sub-sections.

Effects of modified freshwater volume from streams

Input of freshwater can be altered by diversions of water to or from contributing streams. Freshwater input may be deliberately modified for several reasons: 1) to protect human and property safety; 2) to control salinity; 3) to divert pollutants; or, 4) to control nutrient additions.

Increasing freshwater input into an area, through stream channelization for example, will have four principal physical effects during peak discharges. First, mean salinity will be lowered. Second, mean flushing rate will be increased. Third, the water body's tendency to stratify, both vertically and horizontally, will be increased. Fourth, more seawater input will occur, particularly if vertical stratification is enhanced. In general, increased freshwater input will cause marine water body hydraulics to move toward those of drowned river valley estuaries, particularly in the vicinity of the inlet streams (Miller et al. 1990).

Effects on the abiotic environment

The principle hydrologic effects of increased freshwater flow are to temporarily increase the volume and increase the mean residence time of peak freshwater discharges. Other effects upon surface runoff production are related to the water quality of the outflow into marine water bodies (Miller et al. 1990).

Unless large volumes of freshwater enter the marine water body differ markedly in quality, including pollutants, increasing freshwater input will generally have little immediate effect on the overall abiotic environment of most areas. This is partly because increasing freshwater input reduces the mean water residence time, and partly because the abiotic environment (temperature and oxygen) is coupled so tightly to the atmosphere.

On the other hand, cumulative effects, of nutrient additions for example, may be substantial. Or, if enough freshwater is introduced so as to cause the water body to stratify vertically, then the hydraulic characteristics of the water body can be altered, with widespread effects. Frequently, inlet streams are sources of inorganic turbidity. Increasing freshwater input may decrease light penetration and increase thermal stratification, especially in the vicinity of inlet streams (Miller et al. 1990).

The most intense effects will occur in the area(s) of the marine water body that receive input(s) of fresh water. Temperature variation will increase because most freshwater input streams are slightly warmer in dry months and slightly cooler in wet months. Mean salinity will decline, but the primary effect will be to create a more extensive salt wedge, and to further isolate bottom waters from the atmospheric influences (Miller et al. 1990). Urbanization of many areas in Hawai`i has accelerated changes that increase fresh water flow temporarily after high rainfall, although long-term stream flow has declined in recent decades.

Effects on marine colonization

Very little is known about the nearshore physical processes that move offshore larval stages of marine biota toward stream channels. Long-shore currents are sometimes strong inshore and their variation is likely to be a major determinant of the entry of marine larvae. Increased freshwater input will have little effect on the numbers of fish reaching channels, unless they are actively migrating and cued by odors or other stimulants. If marine larvae are cued by odors, the lower salinity of estuaries may have considerably greater impacts on the colonization process than normal.

Although low stream discharges are probably the most important determinant of the numbers of marine larvae entering a marine water body through stream channels, the effects on marine fish entering the channel depend on the degree of stratification and the volume of freshwater input. If flow through the channel is turbulent, as is probably most often the case during flooding, increased freshwater input may potentially reduce passive colonization. The effect on retention of marine larvae also depends on stratification, but in general, increased freshwater input will reduce the fraction of new seawater entering on a flood tide which remains in the water body. In general, increasing freshwater input will reduce colonization, at least by passively moved stages of marine larvae (Miller et al. 1990).

Effects on primary production

The principle hydrodynamic effects of increasing freshwater input on marine biota, through stream channelization for example, are local. There may be an increasing tendency to stratify, flush surface organisms and entrain more demersal forms.

With few exceptions, increasing freshwater input will negatively impact marine planktonic primary production in the immediate vicinity of the inlet stream, owing to the increased local flushing rate. Other direct effects of increased freshwater input on primary production of marine species depend mainly on the water quality and temperature of the input. Usually, however, turbidity will increase, which may decrease primary productivity. The residence time of marine biota in the upper layers, at least, will be decreased. The tendency for water body stratification will increase, which may isolate bottom waters, and, if organically rich, may induce anoxic conditions.

Benthic marine primary production may be depressed as well, but, unlike marine phytoplankton or attached marine algae, will not be flushed from the system more quickly. While the above effects may occur in the vicinity of the inlet stream, other, sometimes opposite, effects may occur elsewhere in the marine water body.

The overall response of the marine water body to increased freshwater input will respond to the increased flushing rate, lower salinity, and probably increased vertical stratification, turbidity and nutrients. The response depends upon the nature of the marine primary producers. In general, a local reduction in marine phytoplankton productivity and a shift toward more benthic primary production should be expected, with increased low turbidity freshwater input. Elsewhere in the marine water body, increases in overall primary productivity of some marine species may accompany increased freshwater input because of additional nutrient loading. The overall response can be negative, however, if nutrients are not already limiting (Miller et al. 1990). Hawai`i streams discharge rapidly, so long-term effects on primary productivity are probably more important than short-term effects.

Secondary marine productivity

Perhaps the main impact of increased freshwater input will be to temporarily expand the region of low and varying salinity, thus potentially decreasing predation by marine predators temporarily. The effect will certainly occur in the vicinity of the inlet stream if a pronounced salt wedge forms after storm flow of freshwater. Furthermore, marine species which migrate actively in response to odor cues, for example, may increase.

The potential negative effects of increased freshwater discharge on marine secondary production include a decreased residence time for zooplankton, and possibly decreased benthic secondary production by depressing oxygen in the impact zone. If a shift toward marine benthic primary production occurs, a shift toward marine benthic secondary production may be expected (Miller et al. 1990).

5.3 Future Directions for Coral Reef Fisheries Management

Stream flow impacts on the marine environment need to be perceived in terms of the resilience of marine species and ecosystems to the changes in the intensity of these pressures. Because of complexities of the links to marine ecosystems, it is difficult to quantify the relative contribution of each land-based human activity to freshwater changes and to develop policies that integrate across the land-sea boundaries. .Some studies have attempted to demonstrate and quantify the processes leading to reef degradation as the result of urbanization (Wolanksi et al. 2009).

The frequency and intensity of disturbances, whether caused by weather, pollution or other factors, produce a regeneration niche that will be occupied by marine species that have regeneration times that fit the period of disturbance. Because of the high species diversity in coral reefs, there are a large number of associated regeneration times, raging from days to decades (Hatcher et al. 1987; Nystrom et al. 2000, McClanahan 2002). Turf algae have the fastest regeneration times, of the order of 20 days, followed by fleshy algae and coralline algae and, lastly corals. Corals have regeneration times ranging from a few years to decades, depending on the species, depth, type of reef and growth form (Done 1997; Ninio et al. 2000). The fast-replacing organisms increase organic to inorganic carbon production ratios relative to the slow-replacing species. In addition to regeneration times, there are fundamental physiochemical limits or a fundamental niche that will restrict the success and recovery of marine species (Hutchinson 1965).

Summary of Recommendations

- Some marine species, particularly native mullet *(`ama`ama*), *aholehole* and native seaweeds, are linked to reduced salinity. Few studies have shown this relationship quantitatively, however. Estuary as nursery habitat has long been ignored in Hawai`i. Most management efforts have focused on adult life stages of marine life. The estuary continues to connect the portions of the traditional Hawaiian resource management unit known as the *ahupua`a* (Nishimoto et al. 2007).

  Further studies should focus on placed-based fisheries research to emphasize linkages between environmental conditions and specific places.

- Current efforts in nearshore marine resources management emphasize the definition of "best management practices" for various types of marine species and ecosystems. Maintaining this direction would be especially important if management aims to keep abreast of changes induced by rising sea temperature and sea level in Hawaii's ocean waters.

  Continue to emphasize place-based solutions to coastal fisheries problems that could be addressed by local communities.

- Submarine groundwater discharge can have impacts to nearshore marine areas via changes in nutrient loads, temperature and salinity (UNESCO 2004). These impacts may significantly alter the coastal ecosystem, changing its fitness for plant and animal species with ecological, cultural and economic value. One study has emphasized the effects of salinity on native macroalgae species (called *limu* in Hawaiian language), which are regarded as keystone species of Hawaii's nearshore ecosystem (Abbott 1978). This type of *limu* thrives where freshwater entering the ocean comes from submarine groundwater discharge (Kay et al. 1977). Changes in SGD have had a major impact on the ecosystem of Maunalua Bay with increasing urbanization and associated eutrophication of coastal waters in east Honolulu.

  A high priority for future research should be continued modeling of the effects of submarine groundwater discharge on the survival and growth of native macroalgae and other marine species that could be affected by changes in outflow to the ocean.

- A high priority for further study would be an investigation of why the annual runs of *`anae holo*, or native striped mullet, have apparently ceased off the island of O`ahu.

  The cessation of the centuries-old runs of native mullet represents a major change that has not been adequately explained, despite all of the current interest in watersheds, marine habitats and possible overfishing. Various hypotheses, ranging from possible habitat alteration, decline of fishponds, the history of Hawaii's urbanization, and even possible overfishing need to be examined thoroughly. This effort will require consultation among former fishermen, historians, Hawaiian cultural experts and scientists.

- Studies connecting land use conditions in Hawai`i with the status of selected marine species should be emphasized. For example, analysis of stranded Hawai`i green sea turtles has shown that elevated disease rates (tumor formation) in this species were clustered in watersheds with high nitrogen footprints, an index of natural and anthropogenic factors that affect coastal eutrophication. Land use onshore of where the turtles feed may play a role. These turtles forage on invasive macroalgae, which can dominate nutrient rich waters and sequester environmental N in the amino acid arginine (Van Houtan et al. 2010).

  Further research that connects marine biota with changes in land use conditions need to be conducted at specific places and corrective actions need to be recommended for implementation.

- Potential concerns are that 1) resource management agencies are losing sight of ecosystem-based research and may potentially overlook many essential calcifying organisms (e.g., crustose coralline red algae, foraminifera and Halimeda) that should be closely researched in order to better understand the effects of ocean acidification and warming, 2) unrealistic perceptions of what constitutes a healthy reef (e.g., that high coral cover is always necessary) may permeate the public and resource management agencies and will be perpetuated indefinitely, and 3) resource management agencies might try to restore ecosystems to non-natural states where essential elements of reef systems become lost because too much emphasis was placed on only a single type of organism (e.e, stony coral) (Vroom 2011).

Most of the primary production is achieved by reef algae, and most of the recovery rate of these algae is usually less than one month for the microscopic filamentous turfs to a few months for the larger erect frondose and calcareous algae. The recovery of heterotrophic organisms is usually slower, ranging from years to decades, and the recovery of the reef structures themselves, from massive coral heads to platform reefs, ranges from decades to millennia (McClanahan 2002).

It may be that there is self-organization of marine ecosystems around novel events or organisms. Once this new diversity becomes a non-pathogenic part of the ecosystem, it can become part of the ecosystem's diversity and, therefore, its resilience. This new state, however, may, be undesirable to humans.

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