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Characteristics of Water Quality in Anchialine Ponds of the Kona, Hawaii, Coast.[1]

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ABSTRACT: A study of the water quality characteristics of anchialine ponds of the Kona, Hawaii, coast suggests that groundwater is a major source of dissolved nutrients for these systems. These groundwater sources apparently show high spatial and temporal variability with respect to dissolved nutrients. Changes are apparent in the water quality characteristics of one anchialine pond system that has been subjected to considerable surrounding development. These changes are within the range of natural variability suggesting that this perturbation, at least over the short term (ca. 9 years), is not damaging since these nutrients frequently occur naturally in excess of concentrations which would control biological processes. Within an anchialine pond system that we have studied, spatial variability in water quality may be explained by a simple model of groundwater dilution with proximity to the sea.

ANCHIALINE PONDS are land-locked brackish water pools adjacent to the sea (Holthuis 1973). These pools have subterranean connections to the ocean and pond volumes respond to tidal fluctuations. Anchialine ponds are geographically restricted and are found in porous coralline or recent volcanic substrata. They are characterized by an unusual array of organisms, many of which are found only in the anchialine habitat. Anchialine ponds and their biota have only recently received attention in the literature (Holthuis 1973; Maciolek 1983; Kensley and Williams 1986). Most work has been concerned with descriptions of the biotope, taxonomy of the fauna, or hypotheses to explain observed faunal distribution; little quantitative information is available on the biota or any other component of the system. Reasons for this lack of information include the cryptic and hypogeal nature (*sensu* Maciolek 1983) of some anchialine species and the difficulty in sampling these systems.

In the Hawaiian Islands, anchialine ponds are found in the geologically young lava flows on Maui and Hawaii islands. More than 70% of the estimated 520 Hawaii Island anchialine ponds occur in a 53 km contiguous section of the Kona coast. The lands surrounding many of these Kona coast anchialine ponds have been proposed for or are undergoing resort and residential development. As a result, much of what is known regarding these anchialine systems is found not in the published literature, but rather in impact assessments written to fulfill environmental regulations.

One recently initiated development at the Waikoloa, Kona, area (between Waiulua and Anaehoomalu Bays) destroyed more than 130 anchialine ponds in late 1985; approximately 66 adjacent ponds with a combined water surface area of 1.4 ha were set aside in a 4.9 ha preserve (the Waikoloa Anchialine Pond Preservation Area–see Figure 1). Since the early 1970's, selected ponds in this Waiulua-Anaehoomalu complex (some of which are now in the preserve) were occasionally sampled for organism abundance or water quality characteristics. The literature on water quality characteristics of anchialine ponds is scant, and there are no comprehensive studies. Cox et al. (1969) reported nitrate, phosphate, and sili-

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cate levels from four Kona coast ponds; all other data are given in unpublished reports. With increasing human presence along the Kona coast, changes in anchialine pond water quality are likely. Such changes could have a profound effect on the biota. This study examines the water quality characteristics of an anchialine pond system undergoing surrounding development and tests the hypothesis that there has been no change in the water quality of this system since the commencement of development. We also propose a parsimonious hydrological model that explains the spatial variability observed in water quality characteristics of these ponds.

MATERIALS AND METHODS

Study Site

This study was carried out in the Waikoloa Anchialine Pond Preservation Area (WAPPA). The WAPPA is situated in the Waiulua Bay-Anaehoomalu section of the South Kohala District in Kona, Hawaii (Figure 1). The largest concentration of anchialine ponds on Hawaii Island was located in the Waiulua Bay area. In December 1985 more than 130 of these ponds were destroyed during the ongoing construction of a hotel complex. The WAPPA was established as a mitigative measure. Other development adjacent to and in the vicinity of the WAPPA has been undertaken over the last nine years; a golf course borders the preserve on the inland side and a road bisects it (completed in 1979, see Figure 1). About 550 m southeast of the management area is a second resort completed in 1981.

Three natural ponds were chosen for routine monthly sampling in the WAPPA. Sampling commenced in April 1986. The ponds were selected on the basis of their location in the system relative to nearby developments and the shoreline. The sampled ponds represent a range of situations from the inland/development margin of the preserve adjacent to the golf course to the natural shoreward/ocean border. Figure 1 presents a map of the WAPPA with existing borders and all extant ponds along with the three ponds (numbers 48, 155, and 188) that were routinely sampled; roadways and other nearby development are also indicated. Pond 48 was selected as representative of the inland location (approximately 308 m from the shoreline) that is close to development activities. Pond 155 is located in the center of the preserve (about 148 m from the ocean), and Pond 188 is situated close to the ocean (56 m away) and farthest away from direct construction activities.

Several other locations have been sampled monthly. One of these is a coastal well developed by the resort for irrigation purposes. The well is located about 1 km southeast and 850 m inland of the preserve, is well removed from coastal development, and serves as a source of natural (low salinity) groundwater for this study. As part of the permit requirements, the resort developer has dug the first of several man-made anchialine ponds (see Figure 1). These artificial ponds are designed to provide additional anchialine habitat. This first artificial water body is located just outside the WAPPA border about 50 m to the north of Pond 155. Water quality sampling of this pond commenced in July 1986 following its construction. In October 1986, water quality sampling of the irrigation water which is used on the golf course inland of the preserve was initiated. For comparative purposes, 24 anchialine ponds situated in the South Kohala–North Kona districts were sampled between November 1985 and September 1986. These ponds are representative of Kona coast anchialine systems and thus the water quality data serve as a control.

Data Collection and Laboratory Methods

In the field, replicate samples of several parameters were collected for laboratory analysis. Water samples that were analyzed for nutrients were filtered in the field through precombusted GFC (2.1 cm diameter) filters. All glassware and sample bottles were acid rinsed. With the exception of samples collected for salinity or chlorophyll analyses, all water quality parameters were sampled in triplicate. Although temperature and salinity stratification was occasionally observed in deeper (>70 cm) parts of some ponds, all

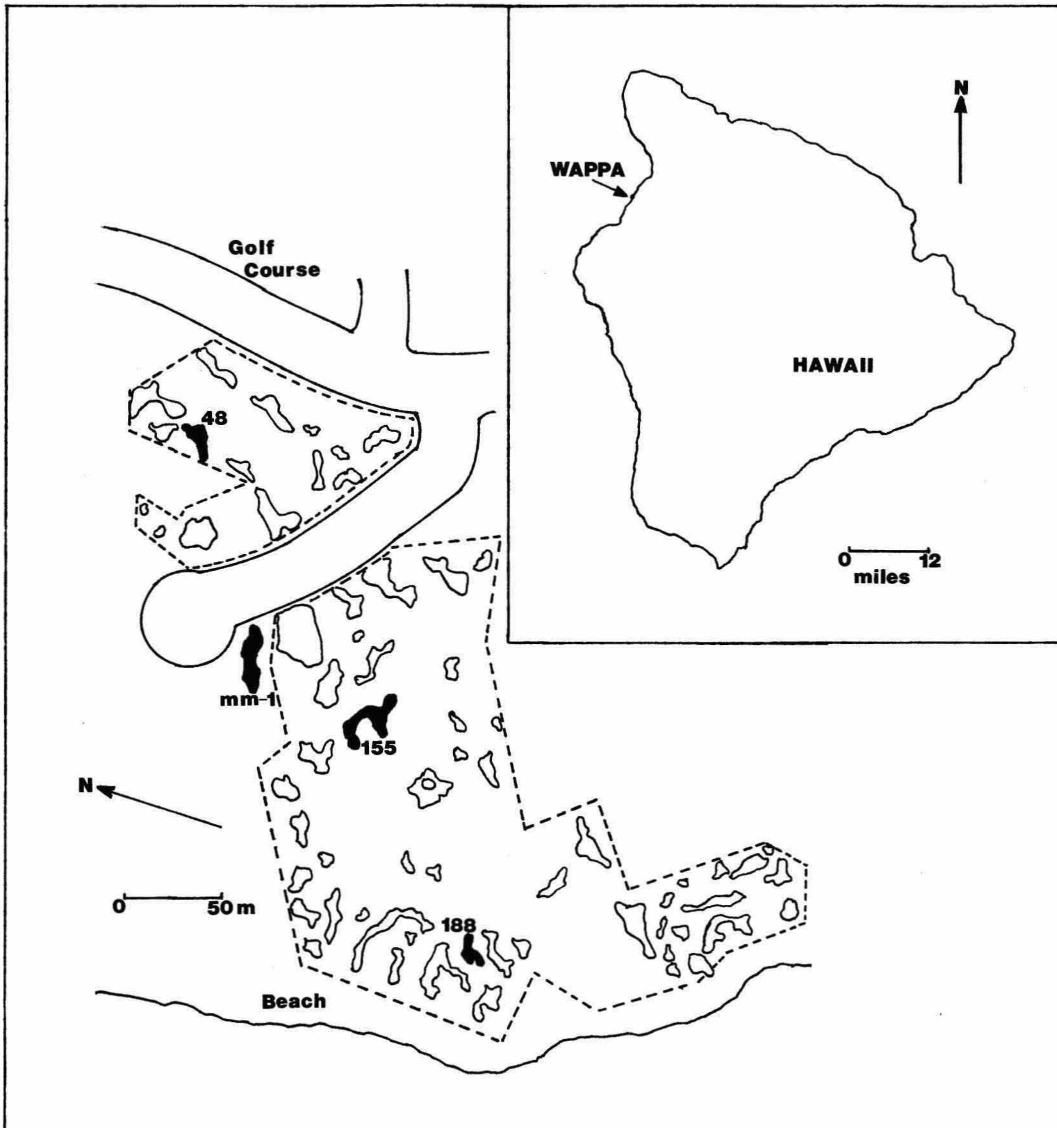

FIGURE 1. Map showing the location of four sampling sites (ponds 48, 155, 188, and mm-1) in the Waikoloa Anchialine Pond Preservation Area (WAPPA) The preservation boundary is shown as a dashed line. The location of the WAPPA on Hawaii Island is given in the inset.

samples were taken at a 15 to 20 cm depth in the water column to sample surface waters. Samples for salinity analyses were not filtered. Chlorophyll samples were collected and processed following the extraction and fluorescence procedures recommended by Jeffrey (1974), Jeffrey and Humphrey (1975), and Strickland and Parsons (1972). Salinity values were calculated from conductivity measurements obtained on a Plessey-Grundy model 6230N laboratory salinometer.

Micronutrient concentrations of samples were determined according to somewhat modified versions of the methods listed by

Strickland and Parsons (1972). The analyses were performed on a Technicon Autoanalyzer II system. Using the autoanalyzer, PO_4^{-3} (as orthophosphate) was determined following methods as outlined by Murphy and Riley (1962), $NO_2^- + NO_3^-$ by the techniques of Armstrong, Williams, and Strickland (1966), NH_4^+ following the procedures of Solorzano (1969) and SiO_2 was determined after the methods of Strickland and Parsons (1972). More detailed information on the laboratory methods are given in Smith et al. (1981).

We commenced sampling the three natural ponds (nos. 48, 155 and 188) in April 1986. In May we began sampling the coastal well and in July, following its construction, the man-made pond was added to the list of regularly sampled localities. In October 1986 we initiated sampling of the water used to irrigate the golf course inland of the WAPPA. This irrigation water is drawn from the coastal well; the well water is used to dilute treated sewage effluent from the resort which is then utilized for irrigation purposes.

Data for the water quality parameters examined in this study were compared between natural ponds (pooling data for a given pond over all surveys) and between surveys (pooling data for all natural ponds in each survey). For the above comparisons and others made in this study, the Kruskal-Wallis analysis of variance was used (SAS Institute 1985).

RESULTS

The water quality data are summarized in Table 1. These data are presented sequentially with respect to station distance from the shoreline for each survey. Thus of the locations sampled, the most inland from the shoreline is the well, followed by Pond 48, the man-made Pond 155, and Pond 188 which is in closest proximity to the sea. The results of the Kruskal-Wallis one-way analysis that compares variables between the natural ponds (pooling data for a given natural pond over all surveys) and between surveys (pooling data for all natural ponds in each survey) are presented in Table 2. The results of these ANOVAs are discussed below.

Surface salinity measurements of the sampled locations in the WAPPA are given in Table 1. The tide state in all ponds was near mean low tide (0.0 m) during the first three sample periods and high (+0.05 to +0.8 m) during the last three. The tide during the October sample was unusually high. The sampled ponds in the preserve have maximum depths at mean tide of less than 1 m. The three natural ponds exhibited a between-pond gradient where surface salinity increased in a seaward direction. The deeper man-made pond exhibited a departure from this trend; in three of four samples, salinity was higher than in Pond 155.

Changes in surface salinity from one survey to the next are small; both Ponds 48 and 155 show a decrease in surface salinities at high tide while this is not apparent in either Pond 188 or the coastal well. The analysis of variance using pooled salinity data for each natural pond (48, 188, 155) over all surveys showed that significant differences exist between these ponds (Table 2). This horizontal salinity gradient is apparent in Table 1 and seems to be related to pond location relative to the sea. This gradient appears to be a relatively constant feature, for no statistically significant differences were found between surveys (Table 2).

The concentrations of nitrate plus nitrite (hereafter called nitrate) in the sampled ponds is given in Table 1. The data in Table 1 suggest some patterns: nitrate values were consistently lowest in the coastal well water, which presumably is representative of natural groundwater. The highest values were found in Pond 48, the most distant from the shoreline, and a trend of decreasing values is apparent in ponds located progressively closer to the shoreline. Similar to the salinity data this nitrate gradient is statistically significant between the natural ponds in the WAPPA but it is not between surveys (Table 2). The irrigation water sampled in October had a nitrate level of 46.21 μM.

The concentration of phosphate (PO_4^{-3}) in the various WAPPA ponds from April to October is given in Table 1. The distribution of phosphate shows a trend similar to nitrate in the WAPPA system: within any one sampling

TABLE 1

MEASUREMENTS OF WATER QUALITY PARAMETERS FROM THREE NATURAL PONDS, ONE MAN-MADE POND AND THE COASTAL WELL FROM THE WAPPA MADE OVER A SEVEN MONTH PERIOD FROM APRIL THROUGH OCTOBER, 1986. The tide state of each pond at the time samples were taken is presented simply as either low (L) or high (H)

LOCATION	SURVEY	TIDE	SALINITY (‰)	NO_3^- (μM)	PO_4^{-3} (μM)	NH_4^+ (μM)	SiO_2 (μM)	Chl *a* (mg/m3)
Coastal well	MAY	—	1.7	49.8	1.9	0.09	811	—
	JUL	—	1.7	47.6	2.0	0.05	814	—
	AUG	—	1.7	46.5	2.2	0.03	778	—
	SEP	—	1.7	47.4	2.4	0.64	791	—
	OCT	—	1.7	45.5	1.8	0.13	860	—
	$\bar{X}$		1.7	47.4	2.1	0.18	811	—
	±S.D.		0.03	1.6	0.2	0.24	31	—
Pond 48	APR	L	6.3	74.7	5.1	0.90	745	0.07
	MAY	L	6.2	83.0	5.9	1.30	706	0.11
	JUL	L	6.4	79.4	4.5	1.20	705	0.09
	AUG	H	3.0	86.4	5.1	0.90	708	0.06
	SEP	H	4.1	98.1	5.7	0.91	738	0.08
	OCT	H	7.0	97.9	5.5	0.59	762	0.07
	$\bar{X}$		5.7	86.6	5.3	1.00	732	0.08
	±S.D.		2.35	4.6	0.2	0.25	21	0.06
Man-made Pond	JUL	L	9.5	64.9	4.0	0.92	657	0.42
	AUG	H	7.3	66.3	3.8	0.47	681	0.67
	SEP	H	6.3	78.8	3.9	1.02	707	0.12
	OCT	H	7.8	78.6	4.2	1.29	691	0.04
	$\bar{X}$		7.7	72.1	4.0	0.93	684	0.31
	±S.D.		1.3	7.0	0.2	0.31	21	0.29
Pond 155	APR	L	6.7	51.1	3.0	1.40	731	0.09
	MAY	L	6.5	78.3	3.6	1.03	701	0.11
	JUL	L	6.7	60.3	3.3	1.42	694	0.16
	AUG	H	5.2	60.6	3.6	1.11	708	0.09
	SEP	H	8.8	63.7	3.1	1.56	712	0.10
	OCT	H	4.1	68.6	3.2	0.71	751	0.07
	$\bar{X}$		6.4	63.7	3.3	1.21	720	0.10
	±S.D.		1.4	8.6	0.3	0.30	21	0.03
Pond 188	APR	L	8.3	55.4	2.6	0.69	703	0.05
	MAY	L	10.5	50.4	2.4	0.85	638	0.08
	JUL	L	8.9	53.4	2.6	0.77	647	0.03
	AUG	H	9.6	45.0	2.7	0.57	628	0.09
	SEP	H	8.5	48.8	2.3	1.23	658	0.21
	OCT	H	15.2	44.4	2.4	0.72	598	0.08
	$\bar{X}$		9.7	48.6	2.5	0.80	660	0.09
	±S.D.		2.3	4.6	0.2	0.22	40	0.06

TABLE 2

CHI-SQUARE VALUES FROM THE KRUSKAL-WALLIS ANOVA OF WATER QUALITY PARAMETERS. Analyses were performed with each response variable pooled across surveys (Pond analysis) and across ponds (Survey analysis). Significant differences at the $P < 0.01$ level are denoted with an asterisk

CLASS	SALINITY	NO_3	PO_4	NH_4	SiO_2	Chl *a*
Pond	14.80*	43.46*	47.16*	15.72*	12.85*	2.84
Survey	1.14	2.40	1.29	21.26*	7.53	5.54

period, phosphate concentration was lowest in the low salinity coastal well, highest in the most inland pond (48) and decreased in ponds located closer to the shoreline. These differences in phosphate levels between ponds are statistically significant (Table 2). This trend is apparently stable through time for there are no statistically significant differences between surveys (see Table 2). The phosphate concentration of the single irrigation water sample was 19.7 μM, over three times the concentration found at any other location.

Ammonium (NH_4^+) concentrations in the sampled ponds through the April–October period are also given in Table 1. The low salinity coastal well ammonium levels are an order of magnitude lower than the concentrations seen in the ponds. Although highest values were found in the central part of the preserve (Pond 155), the trend of decreasing ammonium concentrations with proximity to the shore persists. These differences are statistically significant between ponds as well as between surveys (Table 2) suggesting considerable fluctuation in concentration through time. The single irrigation water sample provided the highest ammonium concentration recorded in this study (9.4 μM), almost six times the concentration observed at any other location.

As with the other nutrients, silicate levels were highest inland and they decreased towards the sea (Table 1). The differences in the level of silicate between ponds are statistically significant but no significant differences exist between surveys (Table 2) suggesting that the seaward gradient in silicate is temporally stable. The silicate concentration from the single irrigation sample was 887 μM.

Chlorophyll *a* (Chl *a*) concentration in the sampled ponds did not exhibit any obvious trend; these data are given in Table 1. In the natural ponds (48, 155, and 188) mean Chl *a* concentrations are similar with no statistically significant differences apparent either between ponds or surveys. The highest Chl *a* values were found in the man-made pond.

Twenty-four anchialine ponds well removed from the Waikoloa pond preserve along the Kona coast were sampled for comparative purposes. Other than one pond with nearby hotel construction, these pools have been subjected to little or no surrounding development. The results of water quality sampling in these ponds are as follows ($\bar{X} \pm$ S.D.): salinity ranged from 1 to 14 ppt (6.3 $\pm$ 3.0 ppt), nitrate values were between 0.5 to 62.4 μM (38.1 $\pm$ 19.6 μM), phosphate concentrations were between 0.5 to 6.6 μM (2.0 $\pm$ 1.9 μM) and ammonium ranged from 0.3 to 14.8 μM with a mean of 3.1 $\pm$ 3.6 μM.

DISCUSSION

A characteristic feature of west Hawaii is its diffuse groundwater discharge at the shoreline (Cox et al. 1969). Estimates range from 2300 to 9400 $m^3\,day^{-1}\,km^{-1}$ of coastline in the vicinity of the WAPPA (Kanehiro 1977). This discharge is a result of the island's geologically young lavas. The high porosity of these lavas will not support water contained above sea level near the shoreline (Cox et al. 1969). Thus, anchialine ponds are restricted to depressions in the lava that extend down into the water table. Anchialine ponds are defined as having brackish water; this mixohalinity is the result of seaward-flowing groundwater moving through the porous substratum and mixing with warmer, more saline waters below. Typically the residence time of water in anchialine ponds is on the order of hours and is related to high substratum porosity (Kanehiro 1977). Because of the subterranean connection, anchialine ponds are tidally influenced; groundwater mixes with seawater and the water quality of the ponds reflect this interaction. Since groundwater and seawater show distinct differences in the water quality characteristics we measured, the pond characteristics are expected to display variability compatible with relative influence of a given water type prevailing at a given tidal condition. Thus tide state and the resulting variable degree of mixing contribute to the extant chemical conditions in anchialine ponds. These conditions may be further altered by other physical (e.g., solar radiation, basin permeability, and location, etc.) and biological processes (e.g., nutrient assimilation by plants).

Along the Kona coast, the greatest natural contribution of nutrients comes from groundwater rather than surface seawater (Bienfang, 1980). This author noted nearshore ocean water nutrient concentrations from a location 35 km south of the WAPPA as follows: nitrate 0.3 μM, phosphate 0.1 μM and ammonium 0.3 μM. Swain (1973) reported groundwater nitrate concentrations ($\bar{X} = 55.7$ μM, n = 2) and silicate concentrations ($\bar{X} = 1550$ μM, n = 2) from an upland well. Kay et al. (1977) noted Kona coast groundwater nitrate levels ranging from 27 to 108 μM ($\bar{X} = 57 \pm 15.3$ μM, n = 8) and phosphate concentrations from 1 to 3.9 μM ($\bar{X} = 2.1 \pm 0.3$ μM, n = 8). In the present study, groundwater nitrate, phosphate, and silicate, as represented by the coastal well samples, are all relatively high. Reported natural groundwater nutrient levels in other localities may be greater. Johannes (1980) reported groundwater nitrate levels between 115 and 380 μM from Perth, Australia, and Marsh (1977) noted nitrate concentrations in Agana, Guam groundwater of 178 μM.

The subterranean flow of the low-salinity, high-nutrient water towards the shoreline at Waikoloa is driven by the hydrostatic head developed inland; because of low rainfall and high substratum permeability this water table gradient is only about 19 cm km^{-1} (Kanehiro 1977). This suggests that the water chemistry of the WAPPA ponds is controlled by the net seaward flow of groundwater. The data for nitrate, phosphate, and silicate show a statistically significant gradient relative to pond location, decreasing with proximity to the shoreline. Salinity shows an opposing statistically significant gradient with respect to distance from the sea. These gradients appear to be relatively stable features (no statistically significant changes through time) and are probably caused by the dilution of groundwater with seawater on its movement towards the sea, as well as by modification due to biological activity (assimilation) in the ponds. Ammonium does not seem to follow the trend described for the other nutrients. The statistically significant spatial (between ponds) and temporal (between surveys) differences in ammonium concentrations are probably reflective of rapid turnover of this nutrient. Most of the plant biomass in these anchialine systems is comprised of benthic (attached) algae; phytoplankton which our Chl *a* samples measure comprises a small proportion of the total. Phytoplankton response to the nutrient gradient as measured by Chl *a* was low and not significant suggesting that pond water residence time is short relative to phytoplankton turnover.

The seaward flow of high nutrient groundwater and its dilution by nutrient-poor seawater provides a simple model that explains the observed trends in water chemistry of the Waikoloa anchialine ponds. Nutrient levels other than silicate in the natural groundwater (as represented by the coastal well) are, however, consistently lower than concentrations found in the inland ponds. Thus, if this model is correct, there must be additional nutrient input occurring between the coastal well and the inland border of the WAPPA (Pond 48). One possible source is the Waikoloa golf course situated about 30 m inland of the preserve. Water used to irrigate the grounds is enriched with treated sewage effluent. We obtained the following nutrient concentrations (in μM) from this irrigation water: nitrate 46.2, phosphate 19.7, ammonium 9.4, and silicate 887. Dry fertilizers (21–7–14, N : P : K ratio) are also applied to the golf course at an approximate rate of 276 kg ha^{-1} yr^{-1}. Nitrogen and phosphorus from these sources may be entering the WAPPA groundwater although Chang and Young (1977) found no leaching to groundwater beneath a golf course on Oahu receiving a similar nutrient subsidy. This (1977) study however was carried out on older, much less permeable substrate than is present at Waikoloa. Autochthonous input of nitrogen is also possible through nitrogen fixation by the kiawe tree (*Prosopis pallida*) which is present in the pond preserve. If significant autochthonous nutrient production was occurring throughout the preserve, one might expect a gradient of increasing nitrate levels towards the shoreline. This is not the case.

Comparative anchialine pond nutrient data are available from Cox et al. (1969). These authors noted nitrate, phosphate and silicate levels in four anchialine ponds adjacent to the

TABLE 3

COMPARISON OF MEAN SALINITIES (‰ ±SD) AND MEAN NUTRIENT CONCENTRATIONS (μM ± SD) TAKEN IN 1977 FROM FIFTY PONDS LOCATED IN OR NEAR THE WAPPA (BIENFANG 1977) AND THE THREE NATURAL WAPPA PONDS SURVEYED IN THIS STUDY. Significant differences exist between the means of the two studies for nitrate and phosphate ($P < 0.01$, Kruskal-Wallis ANOVA)

SOURCE	N	S (‰)	NO_3^-	PO_4^{-3}	NH_4^+
Bienfang (1977)	88	6.6 ± 1.8	17.81 ± 9.52	1.17 ± 0.33	0.94 ± 0.84
Present Study	18	7.4 ± 2.8	66.33 ± 17.70	3.70 ± 1.26	0.99 ± 0.30

WAPPA prior to any development. Mean concentrations (μM ± SD) are as follows: nitrate 54 ± 3.4, phosphate 1.5 ± 0.4, and silicate 609 ± 100. Other than phosphate which is low relative to the present study, these values are similar. More water quality data for the Waikoloa anchialine system prior to any development are available from Bienfang (1977). This author reported water quality data for 50 anchialine ponds overlapping with and in the vicinity of the WAPPA. The grand means for Bienfang's (1977) data as well as those from the present study are given in Table 3. A Kruskall-Wallis ANOVA of these data point to statistically significant positive differences in the concentrations of nitrate and phosphate between the two studies. These significant increases may be related to the use of enriched irrigation water (i.e., sewage effluent diluted with coastal well water) and fertilizers on the Waikoloa golf course constructed subsequent to Bienfang's (1977) survey.

In conclusion, this study documents statistically significant increases in nitrate and phosphate concentrations in the Waikoloa anchialine ponds since 1977. Although statistically greater, nutrient concentrations in the WAPPA presently fall into the range of values observed in the groundwater or other anchialine ponds along relatively undeveloped sections of the Kona coast. Periodic sampling of the biota in these ponds from 1972 (Maciolek and Brock 1974) to present has yielded no obvious changes, suggesting that the biota of anchialine pond systems are insensitive to the increased nutrient concentrations observed in this study. It appears that these nutrient species are in excess and thus are not limiting. Possible mechanisms to this apparent biotic insensitivity are the characteristic short water residence time of ponds and the usual presence of large numbers of endemic herbivorous crustaceans. Through their grazing these crustaceans appear to keep many macroalgal species from dominating the system. Any perturbation affecting these mechanisms could result in major shifts in the structure of anchialine pond communities.

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