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THE FEASIBILITY OF BRINE SHRIMP PRODUCTION ON CHRISTMAS ISLAND

Philip Helfrich, et al

Hawaii University

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16. ABSTRACT

Christmas Island, in the equatorial Pacific, was chosen as a potential site for Artemia salina culture primarily because it possesses a number of desirable attributes including some 500 hypersaline lakes and sublagoons covering more than 60 square miles. It is located in a relatively low-rainfall zone with a favorable potential for support facilities, and an inexpensive labor force. The study indicated that the imposition of proper management could result in a continuous high yield of brine shrimp and their eggs in that environment. (Sinha, OEIS)

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THE FEASIBILITY OF BRINE SHRIMP PRODUCTION ON CHRISTMAS ISLAND

by

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We are indebted to the District Commissioners of the Line Island District, Mr. Gareth Ravelle and Mr. Kitiseni Lopati, and the Manager of the Christmas Island Plantation Company, Mr. John Bryden, whose full cooperation in all aspects of the endeavor at Christmas Island contributed greatly to the success of our field studies.

We are particularly grateful to those volunteer investigators who worked very hard to execute the two expeditions to Christmas Island in March and November of 1971 and who contributed material for this report. They are: Mr. John Ball, Dr. Andrew Berger, Dr. John Caperon, Dr. Allen Cattell, Dr. Robert Clutter, Mr. Fred Farrell, Mr. Glen Fredholm, Mr. Eric Guinther, Mr. Ed Heald, Mr. Hugh Jenkins, Mr. George Krasnick, Dr. John Maciolek, Ms. Judy Meyer, Mr. Carter Pyle, Mr. Maurice Rakowicz, Mr. Mayo Ryder, Ms. Barbara Sumida, Mr. Mark Valencia, and Ms. Patricia Wagner.

In addition, Mr. Paul Bienfang, Ms. Suzanne Groet, and Mr. George Krasnick carried out continuing laboratory experiments relating to the production of Artemia on Christmas Island, and Mr. Robert Brick performed an analysis of the brine shrimp constituents.

We are indebted to Dr. Harold Webber of Groton Associates, Inc., who collaborated on the early stages of this program and contributed background material for this report.

We are extremely grateful to the late Dr. Earl Herald who gave the principal investigator valuable counsel on brine shrimp culture, and to Dr. Sarene Bowan of San Francisco State College whose impressive knowledge of Artemia biology was freely shared with us.

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INTRODUCTION

The Hawaii Institute of Marine Biology of the University of Hawaii adopted as one of its major goals a research program to develop the technology for the culture of aquatic organisms (aquaculture) in Hawaii and in other Pacific islands. Initially, this program was largely exploratory, seeking organisms that would satisfy a number of criteria established for a viable aquaculture program in the tropics. The overall objective of this research was to take advantage of those qualities of tropical environs that could be employed to increase the production of aquatic animal protein. The advantages of tropical over temperate-zone aquaculture relate to the high level of solar energy impinging upon the earth's surface in lower latitudes and the increased growth rate of organisms at the persistent higher temperatures. Thus with adequate plant nutrients, the highest possible levels of organic productivity in the natural environment might be expected, and indeed are attained in the tropics (Odum, 1971) in areas where light is not masked by heavy cloud cover. Once energy is fixed by plant organisms, an animal with a high energy-conversion efficiency, capable of thriving at elevated water temperatures, is required to convert this plant material into animal protein most economically.

The brine shrimp, *Artemia salina*, is such an animal: a truly remarkable organism from the standpoint of energy-conversion efficiency and levels of productivity, in addition to other desirable attributes upon which to base a large-scale production scheme in the tropics. Because *Artemia* thrives and produces eggs in high-salinity water, a site in the tropics was sought that would provide a large acreage of manageable, hypersaline bodies of water. Christmas Island, in the equatorial Pacific, was chosen as a potential site for *Artemia* culture primarily because it possesses a number of desirable attributes including some 500 hypersaline lakes and sublagoons covering more than 60 square miles. In addition it is located in a relatively low-rainfall zone with a favorable potential for support facilities, an inexpensive labor force, and the socio-economic benefits that might accrue from a commercial *Artemia* culture venture that are substantial.

Initial discussions on the culture of *Artemia* in the tropics were held at the conference on aquaculture at The Biologische Anstalt at Helgoland, Germany, in 1969. At this time there was a marriage of ideas: the potential of *Artemia* culture in the tropics as a mechanism to maximize protein production and the natural attributes of Christmas Island favorable to such production. Various aspects were investigated further and support was obtained from the U.S. Sea Grant Program in 1970 - 1971 and in 1971 - 1972. Two separate field studies were carried out in March and November, 1971, and laboratory investigations were conducted over the entire period.

Aquaculture has received a great deal of publicity in the popular media in recent years, often being touted as a panacea for the world's protein needs in the face of population increases. The status of world aquaculture has been thoroughly reviewed by Bardach et al (1972). It is somewhat of a paradox that Artemia per se has not been the subject of any large-scale culture schemes; however, it figures prominently in the culture of many other organisms. Bardach et al (loc sit) indicate that it is used as food, mostly for the larvae of at least 25 organisms, including carp, salmon, pompano, puffers, porgy, plaice, sole, paneid and macrobrachium shrimps, homarid and palinurid lobsters, and crab larvae. For some species of fish it is the only suitable food known to satisfy their nutritional needs during certain phases of larval life. In addition to its demand of aquaculture, Artemia in many forms, including newly hatched nauplii and live, frozen, and freeze-dried adults, is widely used by fish hobbyists. The present commercial sources are primarily from lakes in Saskatchewan, Great Salt Lake in Utah, and from San Francisco Bay, where it thrives in salterns used primarily for the commercial production of salt. Thus the principal source of this valuable product is from the harvest of largely unmanaged wild populations that are subject to major environmental perturbations. The quality of eggs from various sources differs insofar as hatchability is concerned, and undesirable levels of pesticides have been reported from the Salt Lake source (Bookhout and Costlow, 1970). The combination of factors has resulted in the San Francisco Bay Artemia being the most in demand by aquaculturalists. This latter source is harvested by the San Francisco Brine Shrimp Co. of Menlo Park, California, using relatively crude techniques to take both live adults and "eggs" (actually blastulas).

The proposed scheme to culture Artemia on Christmas Island was based upon a rapidly increasing world demand for high-quality Artemia products at a lower price than presently available to the consumer. It also proposes more sophisticated culture and management practices than have been previously employed for the production of Artemia.

GEOGRAPHY AND HISTORY

Location

Christmas Island is located in the Line Islands just north of the equator and about 1,100 miles due south of the island of Maui in the Hawaiian Archipelago. Christmas is the southernmost of the northern Line Islands, a chain of islands extending to the northwest from Christmas and including Fanning (246 km or 153 mi distant), Washington (381 km or 238 mi distant), and Palmyra (572 km or 357 mi distant). Christmas Island is 1,866 km or 1,160 miles south of Honolulu, and is located between longitudes 157° 10' W and 157° 34' W and latitudes 1° 42" N and 2° 03" N. It is only 169 km (105 miles) north of the equator. (See Figure 1.)

The Line Islands are located near the center of the vast Pacific Ocean that covers 50 million square miles, or an area equivalent to 35% of the earth's surface. The region of the Line Islands is dominated by a system of four major surface or near-surface ocean currents: the North and South Equatorial Currents, which flow to the west, and the Countercurrent and Equatorial Undercurrent, which flow to the east.

Christmas Island is the largest of the Line Islands and is sometimes referred to as the largest atoll in the world, with 321.37 km^2 (124.08 mi^2) of land area. Certainly it surpasses in size all other low coral islands, considering only land above sea level, and it exceeds the combined land area of the 36 other islands that make up the Gilbert and Ellice Island Colony (Tudor, 1972). The total area covered by Christmas, including shallow lagoons, is 639.91 km^2 (Jenkin and Foale, 1968). The greatest length, from just north of Northwest Point to Southeast Point, is 52.7 km (32.8 mi), while the maximum southwest-northeast distance is ?1.0 km (19.3 mi). (See Figure 2.)

Weather

Christmas Island is located in the Equatorial Dry Zone which is a narrow belt extending across the central and eastern Pacific (Gentilli, 1952). Rainfall normally decreases from north to south in the Line Islands with a maximum at Palmyra and a minimum at Christmas Island. A great variability exists in rainfall in the Equatorial Dry Zone, relating to the movements of the inter-tropical front which normally lies between 5° and 8° N at this longitude (Seelye, 1950).

The climate of Christmas Island is summarized by Jenkin and Foale (1968) as follows:

> "On the average moderately dry, with an average annual rainfall of 873 mm (34.37 in.) but varying from very dry 177 mm (7.00 in.) to wet 2,621 mm (103.18 in.); a diurnal temperature fluctuating

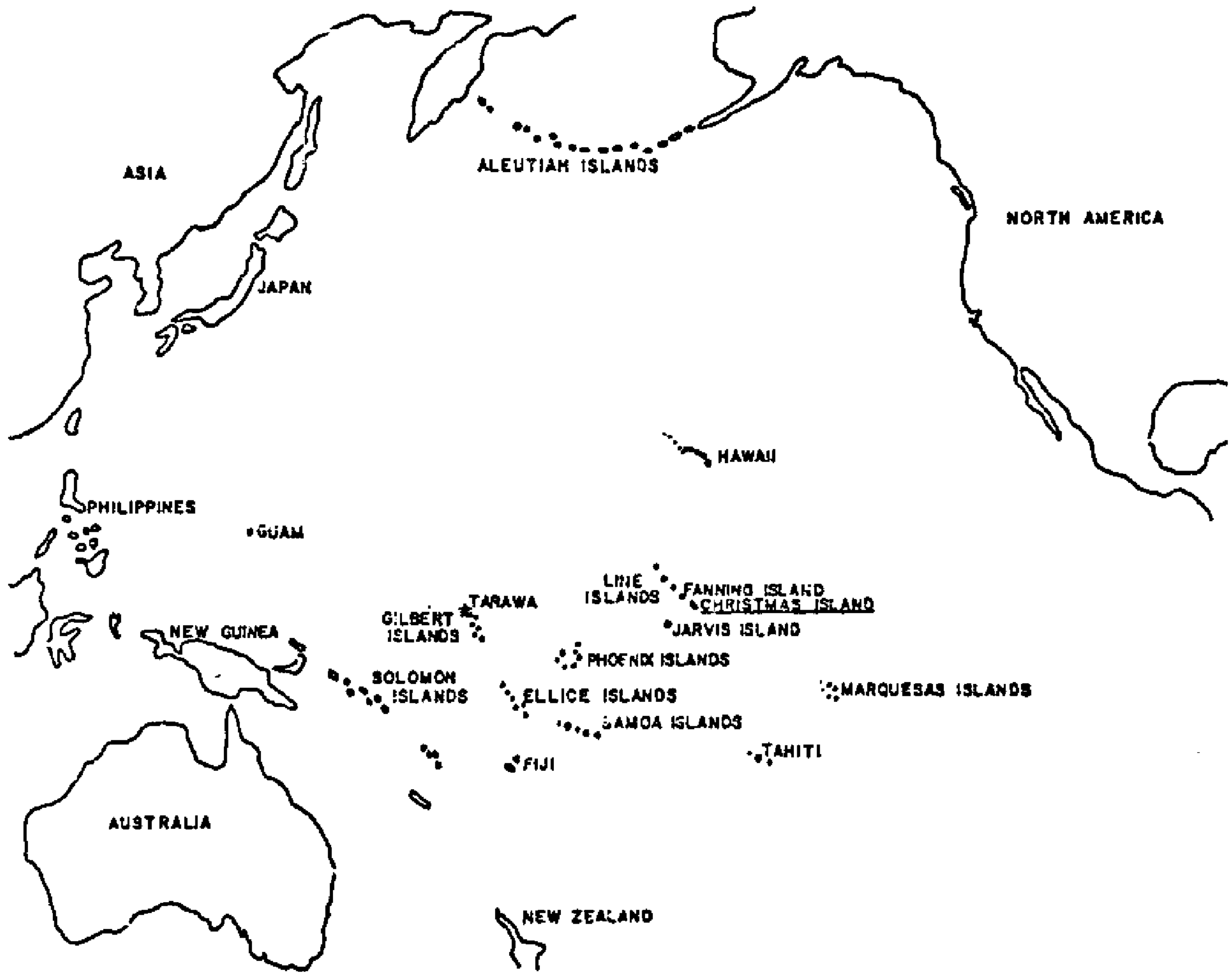

FIGURE 1. Christmas Island, site of the proposed brine shrimp culture scheme, relative to other major island groups in the Pacific. Christmas Island, in the Line Islands, is part of the Gilbert and Ellice Island Colony and is administered from Tarawa in the Gilbert Islands.

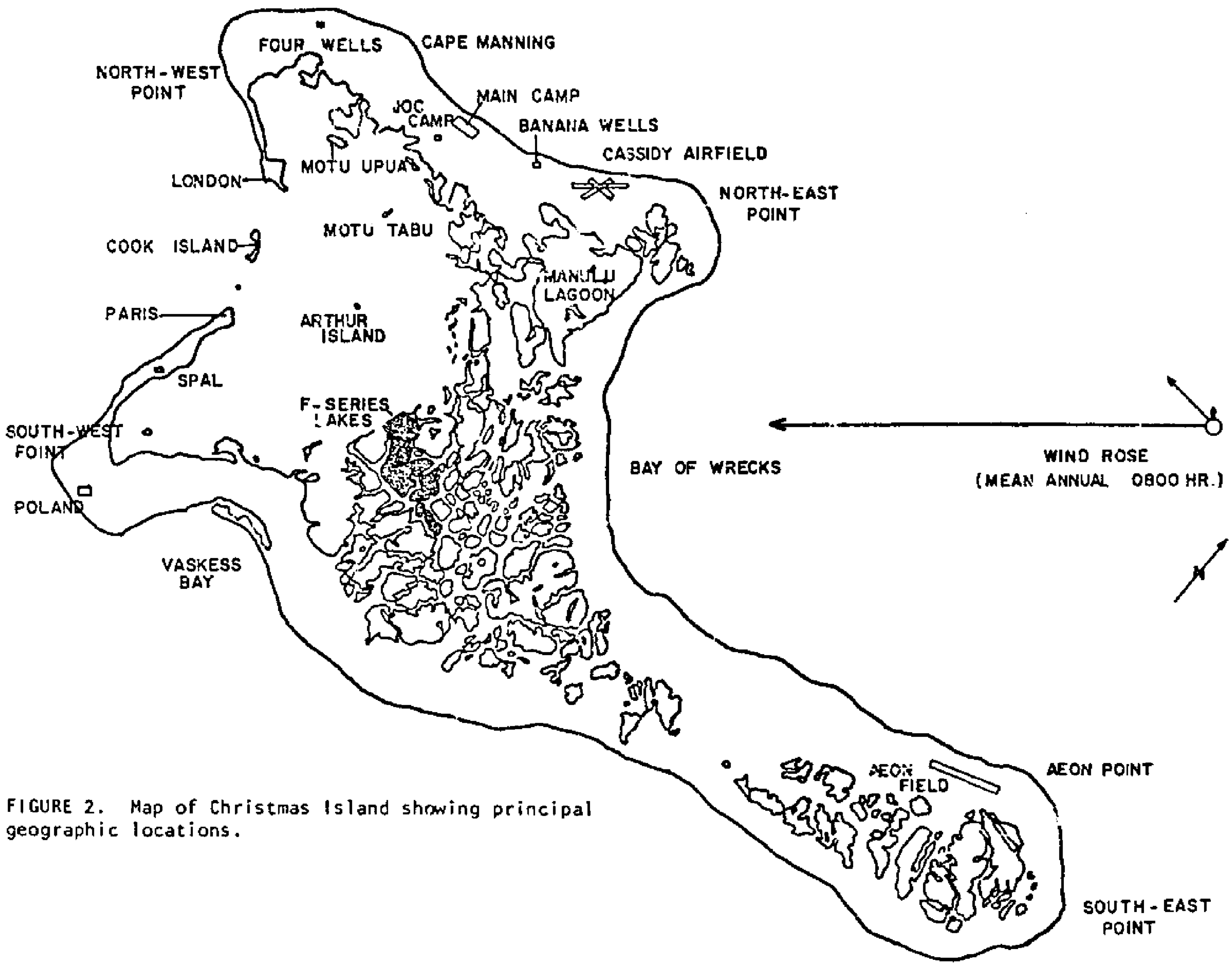

FIGURE 2. Map of Christmas Island showing principal geographic locations.

between 30°C (86°F) and 24°C (76°F), an average relative humidity of 70%, a more or less constant easterly wind of 4 m/s (8 kn) and an average cloud cover of 4 oktas (eighths). The rainfall is usually heaviest in March and April and lightest in October and November."

There is little variation in air temperature at Christmas Island; the mean annual maximum is 30.3°C (86.6°F) and the mean annual minimum is 24.6°C (76.3°F). Temperature extremes recorded are 36.7°C (98.0°F) and 20.8°C (69.4°F). The average mean relative humidity is 71.1% with a high of 80.0% and a low of 75.5%.

Winds are quite constant in regard to direction, time of year, and time of day. Winds average 8.6 knots, with the greatest velocities in January and the least in May. It is calm less than 2% of the time (Jenkin and Foale, 1968).

Evapotranspiration or open-water evaporation is summarized by Jenkin and Foale (1968) who calculated it on a monthly basis utilizing seven different formulae. Their average results were 1350 mm/yr or 53.16 in/yr. They pointed out that potential evapotranspiration is considerably higher in most months and in most years than rainfall, but their calculations did not consider evapotranspiration of soil moisture. Thus in coastal areas where infiltration and percolation into the soil is rapid, evaporation is relatively small, while on the relatively impervious lagoon flats evaporation is rapid.

The excess of evaporation over rainfall at Christmas Atoll is responsible for the high salinities produced in the isolated and semi-isolated lakes of the lagoon and it is these high-salinity lakes which constitute the primary attraction for brine shrimp culture. Periods of unusually high rainfall have a considerable effect on the lagoon lakes and, hence, predictability of occurrence of rainfall extremes would be of concern to a brine shrimp industry.

Cloud cover and sunshine are also summarized by Jenkin and Foale (1968). They found the annual average cloud cover, in tenths, at three times of day, to be as follows: 0800 - 4.7; 1400 - 5.1 and 2000 - 3.7. The mean monthly sunshine in hours per day at London village was calculated from cloud-cover data. In 13 hours from 1953 to 1965, the annual mean sunshine was 9.36 hours per day, with a range of 7.9 to 11.1 hours.

Typical of most of the earth's arid regions, the Equatorial Dry Zone is characterized by considerable variability in annual rainfall. (Compare the wettest year on record, 1941, having over 100 inches of rainfall, with the driest year, 1954, having only 7 inches.) In 35 years for which there are records, six years had over 50 inches of rainfall and five years less than 15 inches (personal communication, Ron Taylor, Hawaii Institute of Geophysics). The means and extremes of monthly and annual rainfall are summarized in Table I and illustrated graphically for 160°W in Figure 3.

TABLE 1. MEAN, HIGHEST, AND LOWEST MONTHLY AND ANNUAL RAINFALL FOR THE PERIOD 1903 - 1966, AT LONDON, CHRISTMAS ISLAND

Modified* from Table 1, Jenkins and Foale.

Item	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual**
	Monthly and Annual Rainfall, in inches and millimeters (mm figures in parentheses)												
Mean, 23 years	2.81	3.12	4.60	6.36	3.35	2.92	2.89	1.25	1.25	.70	.82	1.64	31.71 in.
	(72)	(80)	(118)	(163)	(86)	(75)	(74)	(32)	(32)	(18)	(21)	(42)	(813 mm)
Highest monthly	22.42	26.17	18.80	21.02	11.35	11.04	7.76	6.40	7.92	3.82	4.56	13.53	102.22 in.
	(575)	(671)	(482)	(539)	(291)	(283)	(199)	(164)	(203)	(98)	(117)	(347)	(2,621 mm)
Lowest monthly	0	.04	0	.31	.04	0	0	.04	0	0	0	0	6.90 in.
	(0)	(1)	(0)	(8)	(1)	(0)	(0)	(1)	(0)	(0)	(0)	(0)	(177 mm)

* These figures differ slightly from the 33-year figures in the text because monthly data are available for only 23 years, while total annual rainfall data are available for 33 years.

** The annual figures presented in this table are sums of the monthly means.

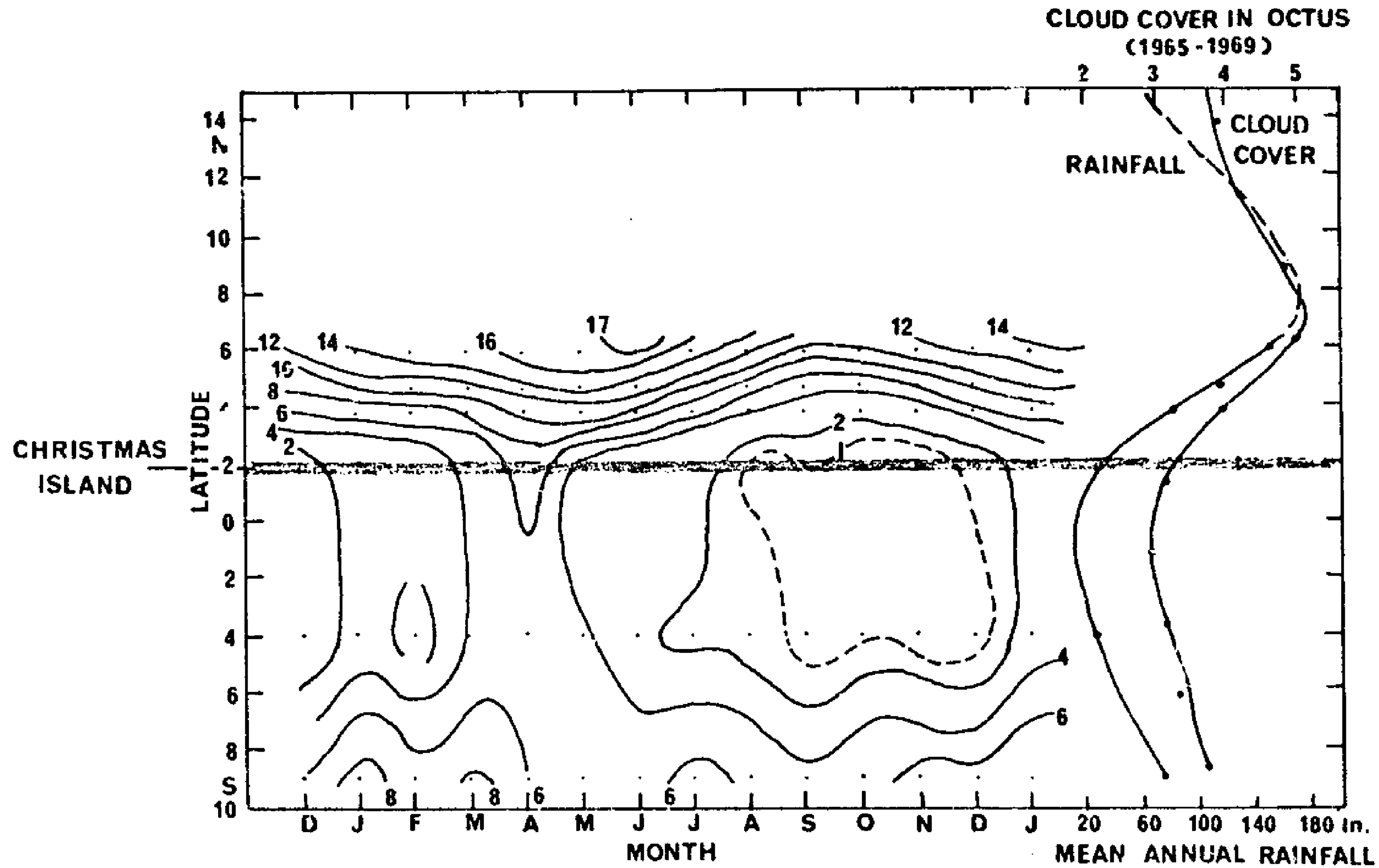

FIGURE 3. Graphic representation of mean rainfall and cloud cover in the Line Islands (160 W) by month and annual average for the period 1965 - 1969. (Courtesy of Ron Taylor, Hawaii Institute of Geophysics)

Periods of greater-than-average rainfall are associated with a southward shift in the Intertropical Convergence Zone (ITC). For reasons related to global meteorological processes, a southward shifting of the ITC will generally occur during the southern hemisphere summer. Such shifts, however, are non-periodic and may not occur in every year (Doberitz et al, 1967). Doberitz describes the rainfall anomaly-pattern of the Equatorial Dry Zone as an "interruption of very long dry periods by more or less short intervals of heavy rain which generally are connected with (a rise in) tropical sea temperatures." Intervals of high rainfall (wet anomalies) are imposed upon the annual cycle (with a wet season in March - April at Christmas Island) so that maximum monthly rainfalls during such anomalies occur in December through March. The longest and the "wettest" anomaly recorded in the Line Islands was of 36 months duration (1939 - 1941). Since that time, wet anomalies have occurred in 1957 - 1958, 1964 - 1965, and most recently, beginning in May, 1972. Rainfall for January, 1973, amounted to the greatest positive deviation from a monthly mean on record (Ron Taylor, personal communication). Although it is presently not possible to predict in advance during which years wet anomalies will occur, spectral analysis of rainfall records for nearby Fanning Atoll (Doberitz et al, 1967) indicate a somewhat unstable periodicity of around six or seven years.

Government

The Line Islands are administered by the British Gilbert and Ellice Island Government under a Resident Commissioner in Tarawa, 2,015 miles to the west of Christmas Island. The inhabited Line Islands (Washington, Fanning, and Christmas) are administered by a District Commissioner who resides in London village on Christmas Island. The government-owned Christmas Island Plantation Company until recently operated a copra plantation with contract labor from the Gilbert and Ellice Islands. The northernmost of the Line Islands, Palmyra, is under U.S. control.

Christmas Island is visited by Bank Line vessels that pick up copra annually and occasionally a colony vessel carrying supplies and personnel.

History

Christmas Island was discovered by Captain James Cook on December 24, 1777, although there is speculation that it may have been discovered in 1537 by Alvarado who called it Acea Island. The Polynesians traveling north and south across the Pacific probably visited Christmas Island. Until early in this century the island was uninhabited except for the hapless crews of ships occasionally wrecked on the island.

The United States Guano Company acquired rights to the island deposits in 1858 and worked the island for several years. In 1865 another company leased guano rights, but the lease was cancelled in 1869 because the island proved to be unproductive.

In July, 1872, the USS NARRAGANSETT took formal possession of the island for the United States. This was followed in 1888 by a formal annexation to Great Britain by Captain William Wiseman of HMS CAROLINE, despite American protests. The British leased Christmas Island to Lever's Pacific Plantations, Ltd., in June, 1902, for 99 years. They planted 72,863 coconut palms and introduced silver tip pearl shells to the lagoon. In 1913 Father Emmanuel Rougier, a catholic priest, took over the lease from Lever Brothers and in 1914 the Central Pacific Coconut Plantations acquired the island (Bryan, 1942). On November 28, 1919, Great Britain reasserted her sovereignty over the island.

In 1942 American troops landed on Christmas Island to establish a base, construct an airfield, and dredge a channel north of Cook Island that allowed ships of up to 8,000 tons to enter the lagoon. At one time as many as 10,000 American troops were stationed on Christmas Island. They maintained a farm north of London village where they kept cattle and grew vegetables by hydroponics.

In 1948 the Gilbert and Ellice Island Colony (GEIC) purchased the lease from the Rougier family and began to settle Gilbertese on the island. Since that time the government has operated the copra plantation with laborers on contract from GEIC.

In 1956 the British government established an atomic test site on Christmas and Malden Islands and devices were detonated 30,000 feet over Southeast Point, on Christmas Island. In 1962 the Americans took over the British base for a similar purpose. These operations had the code names of "Grapple" and "Dominic"; they involved over 5,000 men on the island at one time. Before leaving the island in 1964 these operations had established a number of installations and redredged the channel, which has again resilted.

In November, 1971, the population of Christmas Island included about 500 Gilbert and Ellice Islanders and three Europeans.

GEOLOGY

The developers of an *Artemia* culture scheme on Christmas Island initially proposed to involve the use of several possible combinations of saline lakes. Verying amounts of excavation, drilling, and manipulations of the substrate may be required as the program progresses. It was therefore deemed advisable to investigate the geology of Christmas Island in some detail, particularly as it relates to the saline lakes and their formation, ground water, and nutrient deposits.

Christmas Atoll crests the southeasternmost portion of a northwest-southeast trending volcanic ridge. The oceanic crust surrounding the northwest Christmas Island Ridge exhibits a broad moat and arch, with the arch crest some 240 kilometers distant from the ridge axis. An archipelagic apron forms a smooth curve grading into the insular slope (Menard, 1964). From the reef margin to a depth of 1300 meters, the slope is quite steep (Jenkin and Foale, 1968). An echosounder profile of the southwestern slope shows three "cone-like" features of probable volcanic origin (Ritchie, 1958). Coral thickness is 30 meters at Motu Tabu (Figure 4) and exceeds 120 meters elsewhere (Northrup, 1962; Jenkin and Foale, 1968; John Bryden, personal communication, 1971).

Geologic Development

The similarity of the structural trend of Christmas Island Ridge and the size and ridge position of Christmas Atoll evoke a comparison with the evolving Hawaiian Ridge to the north. Differential spreading rates and directions of the oceanic crust emanating from the East Pacific Rise produce zones of crustal weakness. During the formation of the Hawaiian ridge, volcanism progressed northwest to southeast along such a zone with the southernmost volcanically active island of Hawaii being the youngest and largest. If a similar formational mechanism applies to the Christmas Island Ridge, the volcanic complex upon which Christmas Atoll formed is the youngest of the northern Line Islands, having developed in early Cenozoic time (Menard, 1964).

The basic shape of an atoll is largely dependent on the distribution of its volcanic basement (Wiens, 1962) but the surficial detail is controlled by sea-level fluctuations and further climatic and tectonic influences. The irregular shape of Christmas Atoll is probably due to the arrangement of volcanic peaks similar to those observed on the southwest insular slope. The development of the distinctive geomorphologic features is a result of linear patch reef growth, and a progressive westward and northward infilling of the main lagoon, perhaps aided by simultaneous gradual northwestward tilting of the entire atoll. Roy and Smith (1970) speculate that Fanning Atoll, 320 kilometers to the northwest, has tilted up to the west, whereas the nearest southerly land, Jarvis Atoll, 420 kilometers to the southwest, has a filled lagoon floor eight feet above sea level. Evaporite crystals in the deepest depressions indicate recent emergence for Jarvis (Weins, 1962).

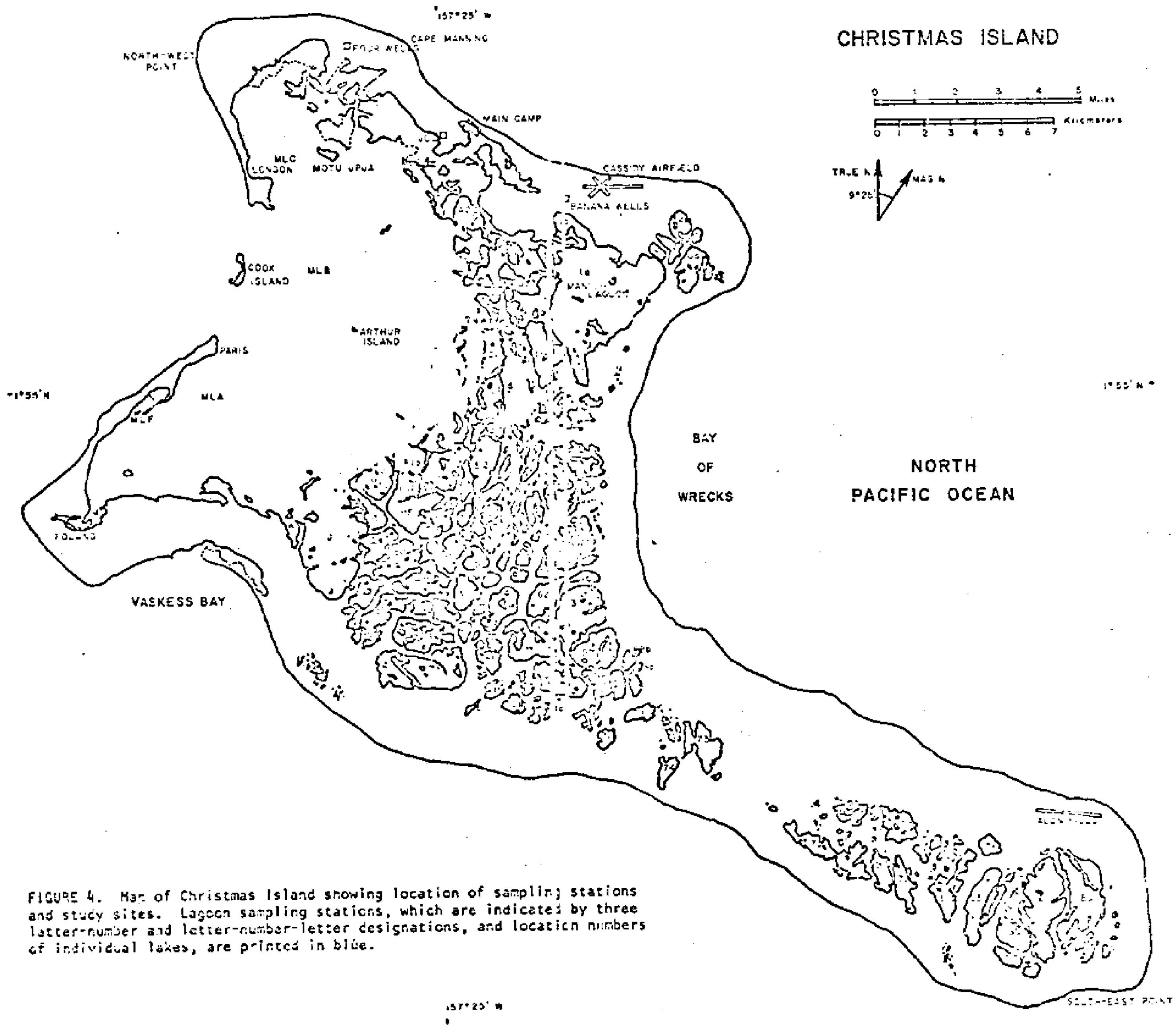

FIGURE 4. Map of Christmas Island showing location of sampling stations and study sites. Lagoon sampling stations, which are indicated by three letter-number and letter-number-letter designations, and location numbers of individual lakes, are printed in blue.

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During the post-Wisconsin eustatic rise of sea level, a rectilinear pattern of Acropora (coral) and Tridacna (giant clam) patch reefs developed on the immersed lagoon floor parallel or transverse to dominant modes of wind direction. Linear patch reef development transverse to an easterly wind mode is presently occurring in the windward lagoon and linearly arranged patch reefs oriented downward or, more rarely, transverse to the main wind direction are present in several atoll lagoons (Weins, 1962) including a rectilinear pattern in Fanning Atoll lagoon (Roy and Smith, 1970). The pattern of lake margins on Christmas Atoll presumably underlain by reefs, hints at a former dominance of northeast and southeast wind modes. Linear patch reef development was due possibly to more rapid reef growth in divergences of Langmuir cells or to a rectilinear base of sand dunes developed during the Wisconsin low stand. In the latter scheme, patch reef development would have been less in the leeward lagoon due to greater bar development nearer the sediment source. Differential growth rates of coral and coralline algae between the windward and leeward reefs, possibly aided by northwestward subsidence, resulted in the northwest Passes.

As sea level reached a maximum positive two-meter level several thousand years ago (Fairbridge, 1952) Christmas Island was nearly entirely submerged, although lagoon patch reef development kept up with the rising sea level. During the brief still stand and the subsequent eustatic fall of the sea to its present level, the reefs were planed off, supplying sediment to the emerging lakes. Beach rock formation on leveled, exposed reef tops incorporated bivalves and other biogenic debris. Aeolian sediment derived from the emerged windward coastal plain and the seaward beaches formed the coastal inland and lagoon dunes and also accumulated in the lake basins with autocthonous biogenic sediment. Wave transportation and deposition of sediment were effective in plugging breaches in lake peripheries. The lakes progressively filled and became isolated from the main lagoon, although tidal exchange maintained some ephemeral shallow channels. The increasing salinity curtailed reef and invertebrate growth, and the shells of bivalve and gastropod mollusks accumulated in berms on the leeward lake shores. The southeastern border of the main lagoon is in an incipient stage of lake isolation, whereas the interconnected lakes are indicative of the next stage of isolation. The totally isolated lakes of the Southeast Peninsula continue to shoal due to precipitation of evaporites, principally gypsum and halite.

The sedimentation rate, or at least reworking of sediment in the lakes has been extremely rapid in recent time. For example, half-meter-deep ruts in the windward nearshore of F2 were partially filled and smoothed with algal ooze and aeolian silt in the seven-month period between March and November, 1971. A core of sandy carbonate mud from the windward subaerial edge of 27A provided evidence of minimum sedimentation rate of 1.8 to 2.7 centimeters per year for the last ten to fifteen

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years, based on geiger count detection of a nuclear blast horizon (D. Knutsen, personal communication). The sedimentation in this core appeared normal and continuous for this location (27A-1, Table 2). A core (16A-1) from the windward shore of 16A shows a regressive sequence, whereas a longer core (16A-2) (Table 2) indicates cyclic variation in sediment type and presumably, lake conditions.

A further possible indication of rapid sedimentation is the presence of a reducing environment immediately below the sediment surface in all lakes. The process of burial of organic matter is apparently faster than that of decomposition. However, this prevention of total decomposition of organics prior to burial could be explained by the inhibition of decomposers in hypersaline waters without the necessity of postulating a high sedimentation rate. The possibility of "excess" productivity is excluded for most lakes by data found elsewhere in this report.

General Morphology

Reconnaissance observations on the general geology and sediments of Christmas Island were reported by Wentworth (1931) and Wentworth and Ladd (1931). A detailed analysis of landforms, soils, and hydrology was included in a report on the coconut-growing potential of the island (Jenkin and Foale, 1968). The soils have been further investigated by Hammond (1969). The presumed existence of geologic data gathered by British scientists prior and subsequent to a 1957 nuclear test ("Operation Grapple") conducted in the atmosphere above the southeast point and by private guano and phosphate rock enterprises is acknowledged, but remains largely unavailable to us.

On the basis of morphology and sediment type, the island can be classified into nine subaerial and two submarine landform units (Jenkin and Foale, 1968). The maximum elevation is 10.7 meters in the coastal dune unit along the Bay of Wrecks (Jenkin and Foale, 1968), although masses of reef rock distributed throughout the island's interior exhibit a rather uniform surface not exceeding four meters above present sea level (Wentworth, 1931).

Soil development is very slow and generally uniform on dry atolls due to the scarceness of organics and the common chemical nature of the parent mixed calcareous debris. Thus lateral soil differences result mainly from variations in the size and depositional mode of shell and coral fragments, whereas incipient soil profiles develop only as a response to increased compaction and a decrease of organics with depth.

Up to a meter -- but more commonly less than 10 centimeters -- of beach rock (biosparudite, Folk, 1965) caps extensive areas of reef rock (coral biolithite and intrasparudite) and unconsolidated medium calcirudite on the lagoon flats. The thick beach-rock sections were exposed along walls of

TABLE 2. SEDIMENTATION IN CORE SAMPLES

Lake	Core	Interval, cm	Sediment
16a	16a-1	0-2	Pebble-size halite crystals in ground mass of green algae-carbonate-halite mush with some pebble-size pelecypod fragments.
		2-10	R. .dal sediment; whole pebble and cobble size shells in ground mass of sand size shell fragments.
		10-15	Coarse sand-size orange gastropods (40%); rounded and subangular pebble-size shell fragments and silt-size shell fragments partially cemented with calcium carbonate.
		16-30	Scattered coarse sand-size orange gastropod in white carbonate mud matrix
		30-59	Occasional gastropods and pelecypod fragments in pink carbonate mud matrix.
16a	16a-2	0-2	Brown alga ooze
		2-9	Pink alga ooze
		9-10	Pelecypod shell-fragment layer
		10-84	Laminated tan clay; occasional pebble-size pelecypod fragments; whole pebble-size pelecypod halves.
27a	27a-1	0-6	Sand and silt-size fragments partially cemented together with calcium carbonate; occasional large, circular benthic foraminifera.
		6-63	Same; abundant rounded beach-rock pebbles with black algae on exterior.
		63-120	Carbonate mud with occasional aeolian uprated pebble.

collapsed spring channels which feed many of the enclosed lakes (e.g., lakes 19e and 27b) and on the edge of islets in lake 27a. These exposures indicate cycles of deposition and beach-rock formation. Incipient beach-rock formation was observed in evaporated areas of Manulu Lagoon (lake 1a) and at 30 centimeters below the floor of an inactive spring channel entering lake 19e. *In situ* *Acropora* and *Tridacna* reef complexes are exposed along some lake margins. Repeated attempts at deep probing of the interlake margins between I4 and F7 and on the southeastern shore of 27a met with an impenetrable horizon at approximately 6.5 meters below land level.

Lagoon and Lagoon Lakes

The physical parameters of the lagoon and particularly those of the lagoon lakes are dependent upon the relationship between precipitation and evaporation that has existed over some several months prior to an observation period. Observations presented in this report were made mostly in March and November of 1971. Rainfall records from Christmas Atoll reveal that the preceeding four years were all below average in total annual rainfall. In fact, considering annual totals for the years 1967 through 1971, only the rainfall measured in 1969 exceeded one-half the 33-year mean of 31 inches (800 mm) annually. Additional direct observations were made during August of 1972 during a seven-day period spent on Christmas Island. Beginning in July, 1972, Christmas Atoll received exceptionally heavy rains which resulted in significant changes in the physiography of the lagoon-lake complex. Rainfall records for the months prior to the 1971 and 1972 observation periods are as follows:

Monthly Rainfall, in inches

Year	Jan	Feb	Mar	Apr	May	June
1971	0.39	0.39	1.21	5.25	0.66	5.30
1972	0.02	0.94	1.57	7.43	0.71	3.56
	July	Aug	Sep	Oct	Nov	Dec
1971	0.63	0.91	0.14	0.39	0.00	0.51
1972	8.85	5.68				

Unless otherwise indicated, descriptions and data presented in this section are based on the 1971 observations. Amendments to these observations, applicable during "wet" years (see page 9), are inserted where appropriate.

Nearly 50% of the total area of Christmas Atoll is occupied by saline lagoon lakes and lagoons. The semicircular main lagoon, covering 160.55 km^2 (61.99 mi^2) (Jenkin and Foale, 1968), comprises half of the total area of lagoon lakes and lagoons. Much of the main lagoon is quite shallow and its maximum depth is only 7 meters. Extensive tidal flats border the lagoon on all sides except in the vicinity of the two passes. Both passes are on the western side of the atoll; separated by Cook Island, they are each about 2 km wide.

Contrary to the impression obtained from maps of Christmas, including Figure 4, the shoreline of the main lagoon is not readily located in the field. Tidal sand-shoals and flats, peninsulas and islands separated by flats and channels, all tend to obscure any definite shoreline encompassing the main lagoon as a unit. Linear reefs, coral knolls, peninsulas, and small islets dot particularly the eastern portion of the lagoon, making navigation even in shallow-draft vessels uncertain. The shoal nature of the lagoon is evident in aerial photographs in which submerged and subaerial features are difficult to distinguish (Plates 1 and 2).

Mixing of lagoon and oceanic water is probably restricted to the region of the passes where the lagoon is open to the ocean along less than 25% of its leeward side. Evaporation generally exceeds rainfall received by the atoll, which contributes to the establishment of a salinity gradient increasing from the passes across the lagoon in all directions. Surface water just north of Cook Island had a measured salinity of 35.9 o/oo on March 23, 1971 -- the salinity of oceanic water around the atoll. Salinities measured along the north, east, and south shores of the lagoon on August 30, 1972, were: 34 to 35 o/oo in the vicinity of London; 36 o/oo in the northern part; and 37 o/oo just west of "Little Plantation" (B-series lakes).

Approximately 25% of the total surface of Christmas Atoll is occupied by some 500 interconnected or isolated lagoon lakes distributed both east of the main lagoon and along the center of the Southeast Peninsula. These lagoon lakes vary in size from Manulu Lagoon (1A), covering 15.98 km^2 (6.17 mi^2), to small salt pans several meters across and a few centimeters deep.

Reconnaissance sampling indicates lakes of two basic types, sub-evaporite phase and evaporite phase, dependent upon the degree and duration of isolation in regard to water exchange. Most lakes lacking evaporite deposits are connected by shallow, narrow channels to the main lagoon. Interconnected series of lakes open at one end of the series to the lagoon ("open" lakes) have salinity gradients which reflect their proximity to the main lagoon. These gradients may be explained entirely in terms of restricted exchange with lagoon water and evaporation, although springs entering some lakes undoubtedly have an effect upon salinity. There is also an apparent north-south-oriented salinity gradient of the "open" lakes fronting on the lagoon.

Plate 1. Aerial photograph illustrating shoal nature of the lagoon.

Plate 2. A view of Christmas Island taken from approximately 500 feet (150 meters) above lake 24 looking northeast. Lake F3 is in the foreground with lake F2 in the center. The F2-F3 channel clearly shows.

A north-south gradient in salinity suggests a possible influence by the fresh water from Ghyben-Herzberg lenses within the island structure. (For a discussion of freshwater lenses on atolls, see Cox, 1951, and Arnow, 1954.) According to Charles (1960) and Jenkin and Foale (1968) permanent or semi-permanent underground freshwater lenses are most likely to occur on the coastal plains along the northern portion of the atoll, in the Poland and New Zealand Airfield areas (southwest), and along the north to northeast portion of the Southeast Peninsula. Jenkin and Foale (1968) estimate the volume of fresh water in all of the northern sites on Christmas Island to be 4.3×10^9 gallons (19×10^6 kl) and of the southern sites to be 2.06×10^9 gallons (9.4×10^6 kl). The relatively low salinities measured in "open" lakes along the northeast lagoon shore such as lakes A1 to A4, as compared with those salinities measured in open lakes closer to the center of the atoll (e.g., F1-F7), possibly result from the close proximity of the former lakes to low-salinity groundwater. In addition, there are fewer shoaling linear reefs between the passes and the A-series lakes than between the passes and the F-series lakes, suggesting that the residence time of lagoon water in the north may be somewhat less than the residence time of lagoon water near the eastern shore.

Springs entering lake A1B through two "streams" had salinity values of 24 o/oo and 16 o/oo in March, 1971. Paradoxically, the heads of these and two other streams entering lake A1B contained water at salinities between 20 and 32 o/oo on August 25, 1972. Direct association with the Ghyben-Herzberg lens is not indicated by the 1972 data.(In addition to salinities being higher than expected under the conditions prevailing in 1972, no flow of water was observed issuing from the "springs" at a time when fresh water in the groundwater body should have been expanding toward the island margins.)

Figures 5 through 8 show salinity gradients along the northeast lagoon shore based on surface water samples taken in March, 1971, and August, 1972. Sampling stations are indicated by triangles. Although the isohales are drawn across the land to separate lakes of differing salinities, groundwater salinities may in fact be radically different and are not indicated on the maps. Salinities of a few isolated (closed) lakes are indicated by their value. Isohales are drawn in parts-per-thousand steps only where space permits Water flowing between lakes in August, 1972, is shown by arrows indicating the direction of flow.

Springs flowing into both open and closed lakes are common features of the lagoon-lake complex. In some cases these springs arise two or three meters above the lake-water level and feed streams flowing over beds cut deeply into the flat between the lakes. These stream cuts often have the appearance of collapsed underground caverns, and the elevational difference between the stream bed and the hardpan surface of the interlake flat may be as much as two meters. (See Plate 3.) In all cases investigated

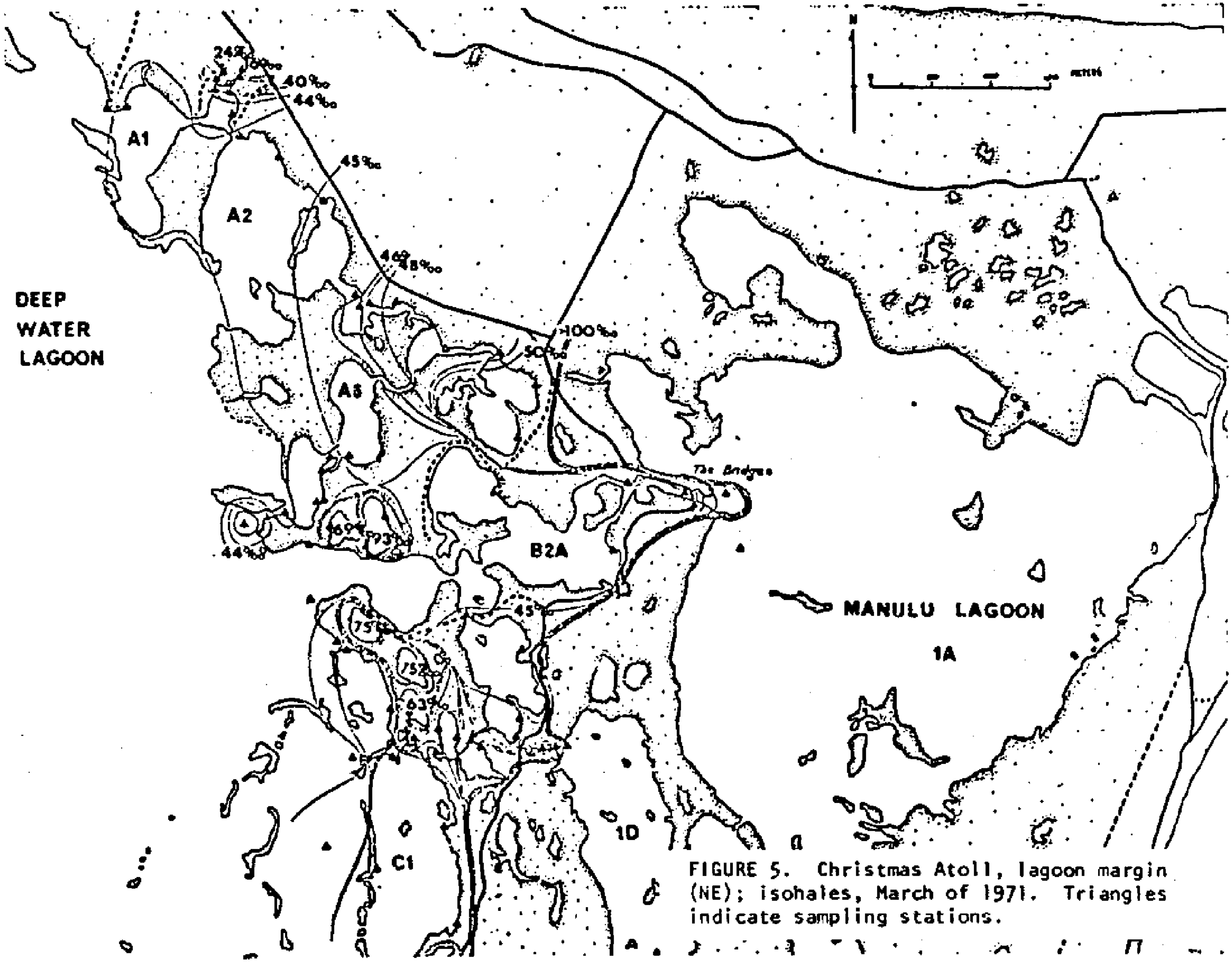

FIGURE 5. Christmas Atoll, lagoon margin (NE); isohales, March of 1971. Triangles indicate sampling stations.

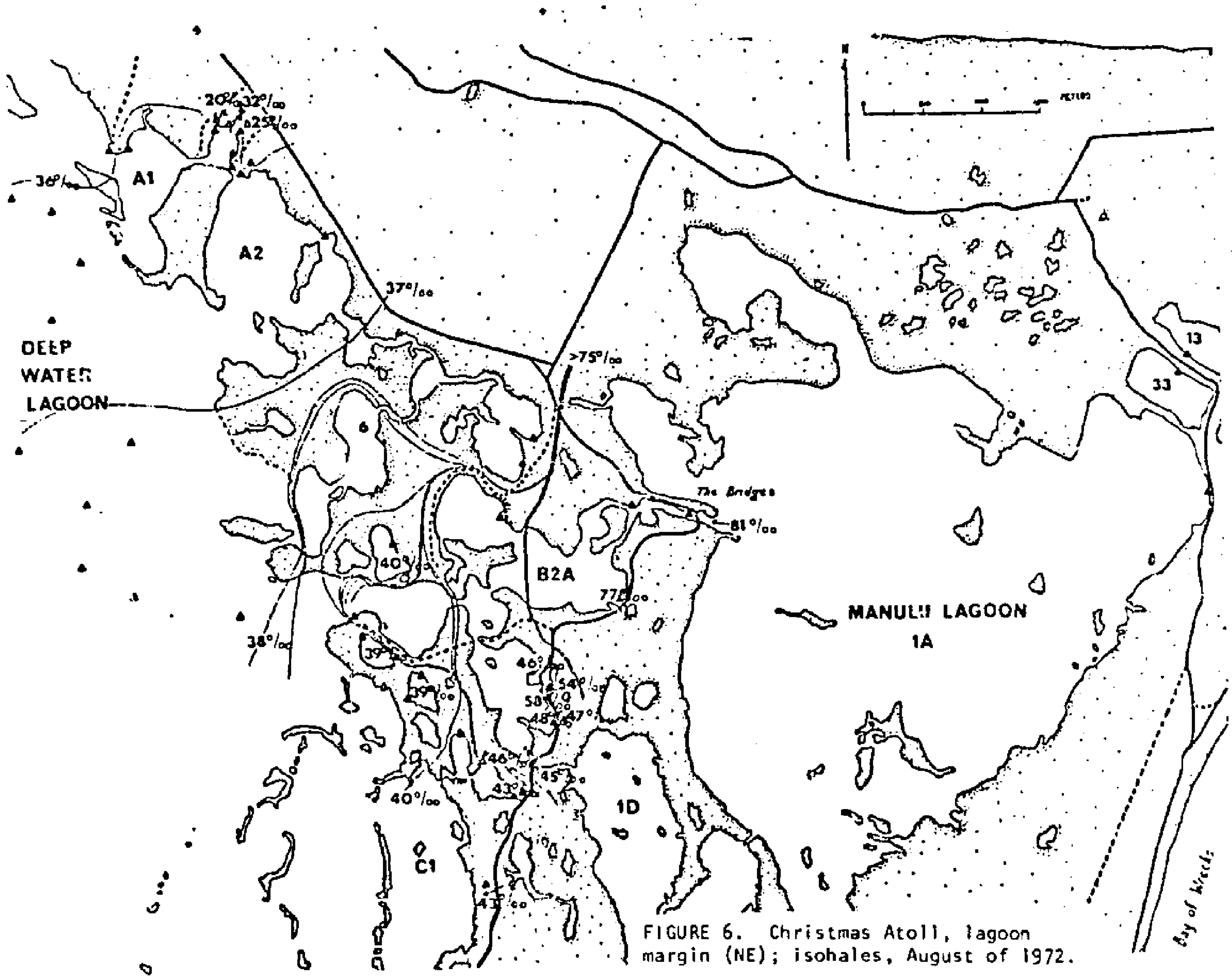

FIGURE 6. Christmas Atoll, lagoon margin (NE); isohales, August of 1972.

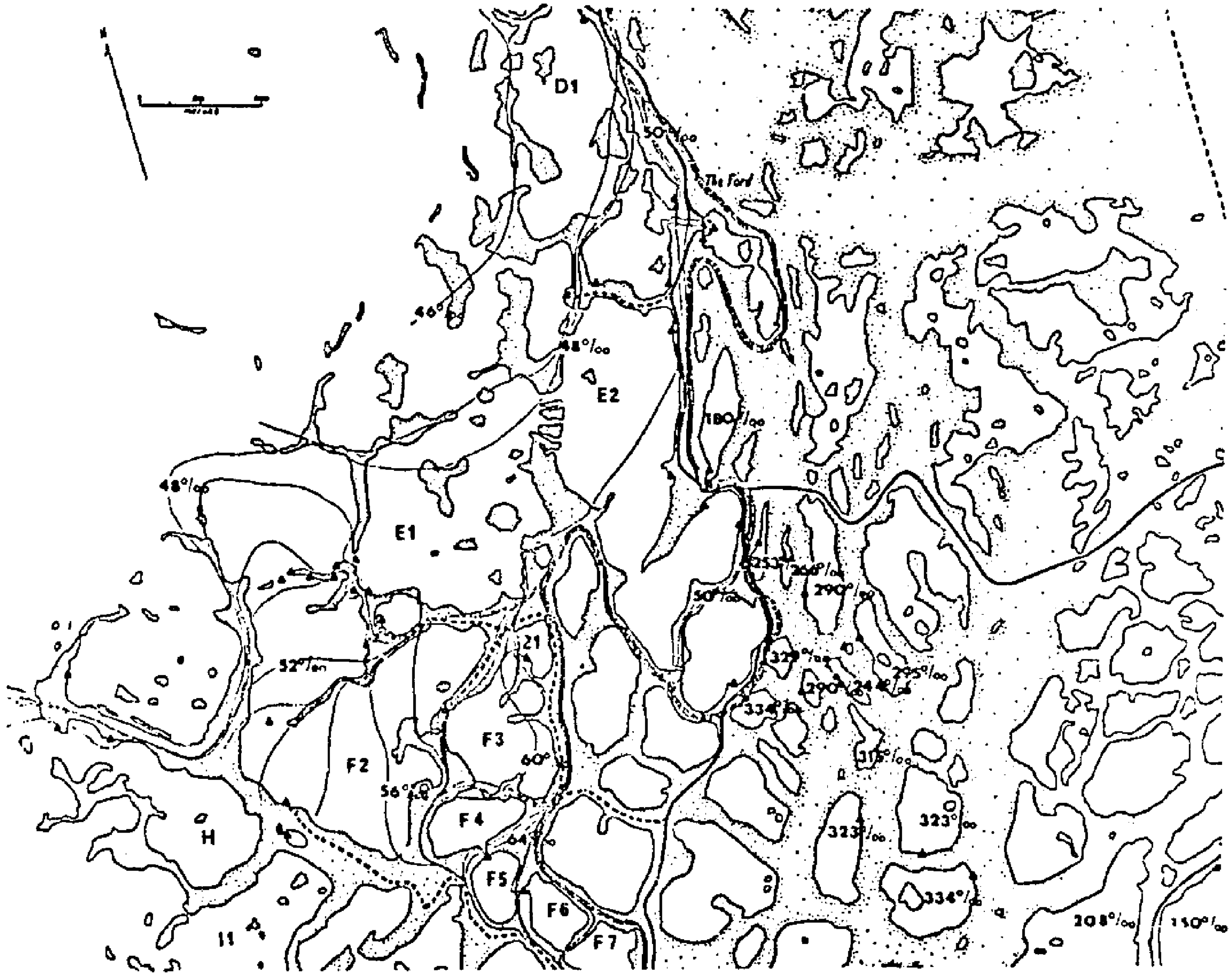

FIGURE 7. Christmas Atoll, lagoon margin (SE); isohales, March of 1971.

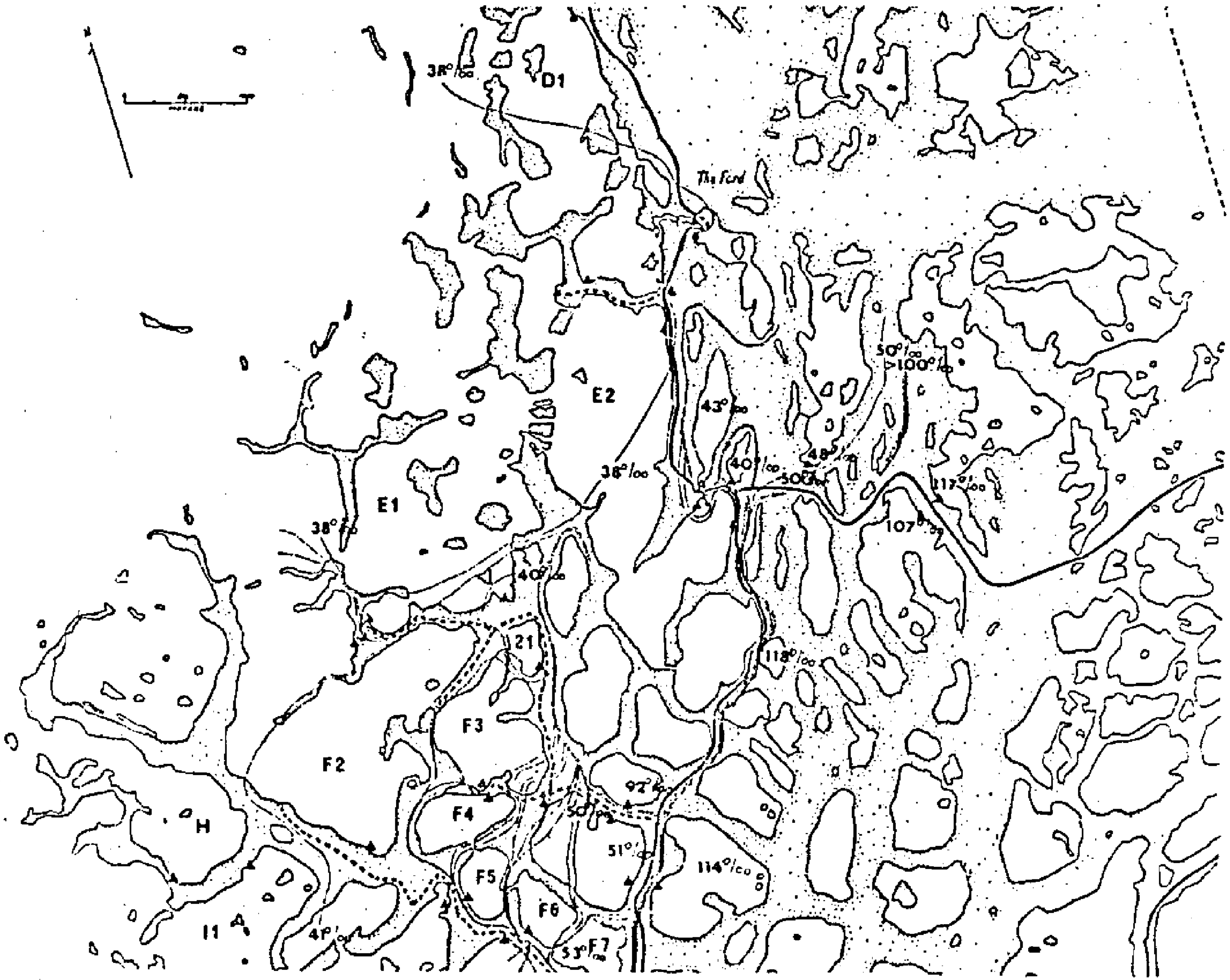

FIGURE 8. Christmas Atoll, lagoon margin (SE); isohales, August of 1972.

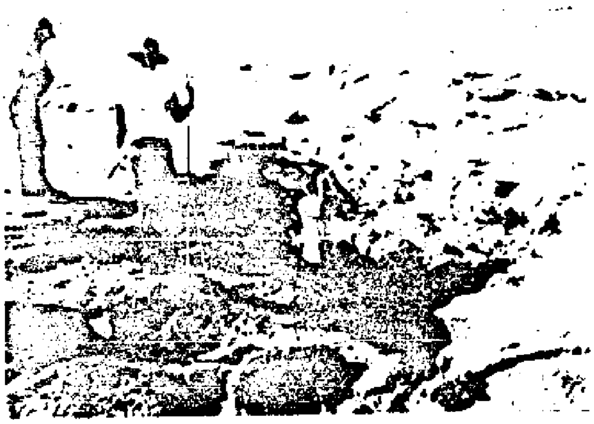

Plate 3. Stream cut showing elevational difference between stream bed and hardpan surface of the interlake flat.

in March, 1971, with the exception of water entering lake A1B, the salinity of the spring water was between 36 and 41 o/oo. These values are considerably less than the salinities of the lakes in the areas adjacent to the springs. Moreover, the salt content of the spring water is less than that of the lagoon surface water. The total input of water from the several springs at the northern end of lake 16A was estimated at less than 0.01 cubic meters per second (9,510 gallons per hour).

Continuous long-term flow from one particular spring was indicated by the presence of a peculiarly sharp inverse temperature gradient previously noted by Northrup (1962).

Frequently differences of a meter or more between adjacent lake-water levels were observed; e.g., E2 was 1.2 meters higher than 16A (November, 1971). These differences may be explained by variations in lake-water budgets. Successive rings of shell berms or a border of evaporite crystals, either gypsum and halite or gypsum only, indicated past higher shorelines around most lakes. Large fluctuations in surface area result from elevation changes of less than a meter, due to the generally gently sloping and shallow configuration of the lake basins. The lakes appeared to be at their lowest recent level in November, 1971. Manulu Lagoon (lake 1A) was partitioned into smaller interconnected lakes in contrast to maps constructed by Jenkin and Foale (1968) from aerial photographs taken in the 1950's. Asymmetric basin profiles with recently exposed windward shores indicate active aeolian deposition in some lakes (e.g., 27A and 16A).

Lake levels in August, 1972, appeared to be near maximum. The water levels in lakes located some distance from the main lagoon inundated high shoreline vegetation. In most cases this represented an increase in depth of at least one meter and possibly as much as 2.5 meters;

these increases in water level must have resulted from the heavy rains in July and August of 1972. Lakes located near the lagoon but previously isolated from the lagoon were connected by channels which exhibited strong unidirectional water flow into the lagoon or into open lagoon-lakes. Manulu Lagoon was no longer partitioned into smaller lakes. Water flow under "The Bridges" was observed over several days in August to be always out of Manulu (into B2 and the main lagoon). The level of water in 16A was above that in the adjacent open lake, E2, and water was flowing over the low lip separating the two lakes. Water flowing between the open lakes, D3 and D2, at a place called "The Ford" inundated the road to a depth of nearly one meter, making it all but impassable to vehicles.

Springs flowing into closed lakes could not be investigated in August, as the water levels in these lakes were above the elevations of the springs. In most cases it was difficult to locate the cuts in the beach rock flat made by these springs. By way of example, the stream cut shown in Plate 3 could be located, but lake-water covered the inter-lake flat by several centimeters at that time.

During periods when long-term evaporation predominates over precipitation, lakes actively depositing chemogenic sediments can be classified according to the nature of the evaporite. Key indicators of lake types are bottom morphology, sediment type, and the presence or absence of a red gelatinous alga, apparently associated with a range of hypersalinity, i.e., in 1971, approximately 200 to 300 o/oo.

Relatively isolated lakes, e.g., 19d, 19e, 33a, are less than two meters deep and have salinities greater than 300 o/oo. Bottoms are rough due to a network of polygonally arranged ridges exhibiting nearly one meter of relief from ridge top to basin floor. The gypsum and halite crust is only five centimeters thick in 33a and overlies red gel interspersed with halite crystals. A peripheral ring approximately one meter wide around lakes lacking evaporites, or containing only a thin crust of gypsum, indicates relatively low-salinity seepage at the water-shore contact. One can determine lakes actively receiving shoreline seepage by the presence or absence, in the evaporite ring, of halite crystals which are rapidly dissolved by contact with low-salinity water.

The spring-fed evaporitic lakes are also less than two meters deep but exhibit a smooth bottom consisting of a one-centimeter-thick crust of halite cubes overlying at least one meter of red gel mixed with halite crystals.

Lakes lacking gypsum and halite deposits, e.g., E-, F-, and I-series lakes, are interconnected by narrow channels to the main lagoon. Channel morphologies for lakes in the F series appeared to represent stages in a developmental cycle. Incipient channel development was occurring between F6 and F7, where a steady flow two meters wide and a few centimeters deep transported water over the beach rock crust from F6 to F7 during spring tides. Perhaps during and after infrequent heavy rains, water of low salinity and under-saturated with respect to calcium carbonate initiates dissolution of the hardpan while flowing between lakes. Once the crust is weakened, the silt and clay would be eroded by the water flow, leaving a sediment dominated by pelecypod and Acropora fragments. A more advanced stage in this process is represented by an inactive channel between F2 and F4. At the F2 end, the beach-rock crust is absent along 20 meters of the channel length and the channel is filled with pelecypod shells. Once the channel bottom is eroded below the water table (0.5 to 1 meter on the lagoon flat), extensive widening may occur from lateral seepage and undercutting as evidenced by blocks of beach rock tens of meters in diameter slumped into one channel. An example of the initiation of the final stage in this cycle is found in an inactive channel between F4 and F5. A hypersaline puddle is bounded by a shell shoal at the F4 end and a shell berm at the F5 end. As the puddle water evaporates and through capillary evaporation elsewhere, beach rock is forming to stabilize the unconsolidated shells.

Nearshore bottom sediment type varies considerably in these "open" lakes, but the dominant type for F-series lakes is a sandy, pelecypod and Acropora fragment gravel. The berms around the lake margins consist of well-sorted pelecypod and gastropod shells and shell fragments. A core in windward nearshore Fla penetrated 16 centimeters of pink organic "fluff" to an extinct pelecypod bed. Windward sedimentation for reworking is fairly rapid in these open lakes, as evidenced by five-month-old ruts partially filled and smoothed by "fluff" and aeolian silt.

A reducing environment indicated by hydrogen sulfide odor was present immediately below the surface sediment in all lakes sampled. A semi-diurnal increase in foam reported previously by Wentworth (1931) was observed along the leeward shores of many enclosed lakes, and in the larger interconnected bodies, linear arrangements of foam extending from leeward to half the lake breadth indicated active Langmuir cells.

Some elements of the biota of lakes reflect the salinity and degree of isolation from the lagoon. Table 3 illustrates the distribution of selected organisms in lakes of increasing salinity. The basis for the discontinuous distribution of some organisms (Tridacna and Acropora) is other than just salinity. 53 o/oo appears to be the upper limit of salinity for the organisms listed.

TABLE 3. DISTRIBUTION OF SELECTED ORGANISMS IN SALINE LAKES, ARRANGED BY INCREASING SALINITY

Data obtained during March, 1971, expedition.

		Organism											
Lake No.	Salinity, o/oo	"Gambusia"	*Uca* spp.	*Planaxis sulcatus*	*Nerita reticulata*	*Natica marochiensis*	*Spondylus* sp.	*Cerithium breve*	*Rhinoclavis asper*	*Fragum fragum*	*Ostrea* sp.	*Acropora* cf. *grandis*	*Tridacna maxima*
A1B creeks	16-37	x	x										
A1B	37-43												
A1A	43-45		x	x	x	x	x						
A6A	43.5		x										
B2B	43.5-45.5			x									
A2	44-45		x										
B1	44			x									
B2A	44							x					
B3	44.5-45.5			x				x					
A6B	45			x									x
A3	45-48		x	x									
C1A	45-46												
D1	46							x					
E2A	46		x					x					
1A (part)	47			x									
D2	47-48			x				x					
G	47			x									
A4	48		x	x				x					
E1B	48-50			x									
E2B	48-49			x									
E3	49			x									
F1A	49-50												
A5	50		x					x					
C1B	50-52							x					
C2	51-52							x					
E4	51												
H	51-52											x	x
F1B	51-53		x							x	x		
D3	52-55												
C3	52.5												
F2	53-58												
21	61												
7D	63												
F4	63-75												
7A1	69												
7B	74.5												
7C	75												
7A2	93												

PHYSIOGRAPHY OF THE F-SERIES LAKES

A detailed study of the F-series of lakes at Christmas Island was undertaken because they seemed to offer a mechanism for *Artemia* production that would allow the use of natural empoundments requireing a minimum of alteration and of tidal flow to aid in water movement. An important aspect of the *Artemia* culture scheme being proposed is in the production of eggs, which normally float and are blown to the downwind shore where they are harvested. The slope and composition of the substrate along the downwind shoreline therefore recieved special attention in our consideration of the F-series of lakes.

The Nine F-Series Lakes

The F-series of lakes consist of nine interconnected bodies of water that lie along an approximate north-south axis adjacent to the main lagoon (Figure 4). For purposes of identification these lakes were numbered F1a. F1b, F2, F3, F4, F5, F6, F7, and 21 (Figure 9). The distance from the roughly defined mouth of F1a to the southern shore of F7 is 3-1/2 miles (5.6 km). These lakes are all interconnected and subject to some tidal influence. There is a salinity gradient from about 48 o/oo at the mouth of F1a to 101.5 o/oo in F7 (Figure 9). The total surface area of the lakes was estimated, using a plinometer, to be 384.5 acres (155.6 hectares) and the volume of the lakes was calculated to be 853×10^6 ft^3 (24.14×10^6 m^3).

The depth of the lakes was surveyed utilizing a Raytheon Model DE-F19 Fathometer Depth Recorder, battery powered and mounted on a skiff. Tracks and positions were located on charts enlarged from Christmas Island Chart #2 published by the Directorate of Overseas Surveys, scale 1:50,000. A magnetic compass, a mariner's sextant, and an engineer's level on shore were used to determine locations. The figures that follow have depth contours plotted in 5-foot intervals; solid lines indicate areas in which fathometric recordings were then taken, while dotted lines are approximations based upon the data from adjacent areas and features on an aerial photograph made by the Royal Air Force (scale -- approximately 1:29,000). North is oriented to the top of the paper.

In lakes F1a and F1b insufficient tracks were run with the fathometer to attempt a reconstruction of depth contours (Figure 10).

Due to limitations in time, not all shorelines and bottom material were studied in detail. Photographs and notes were taken along the downwind (western) shorelines of the F-series of lakes, as well as along the channels connecting the lakes.

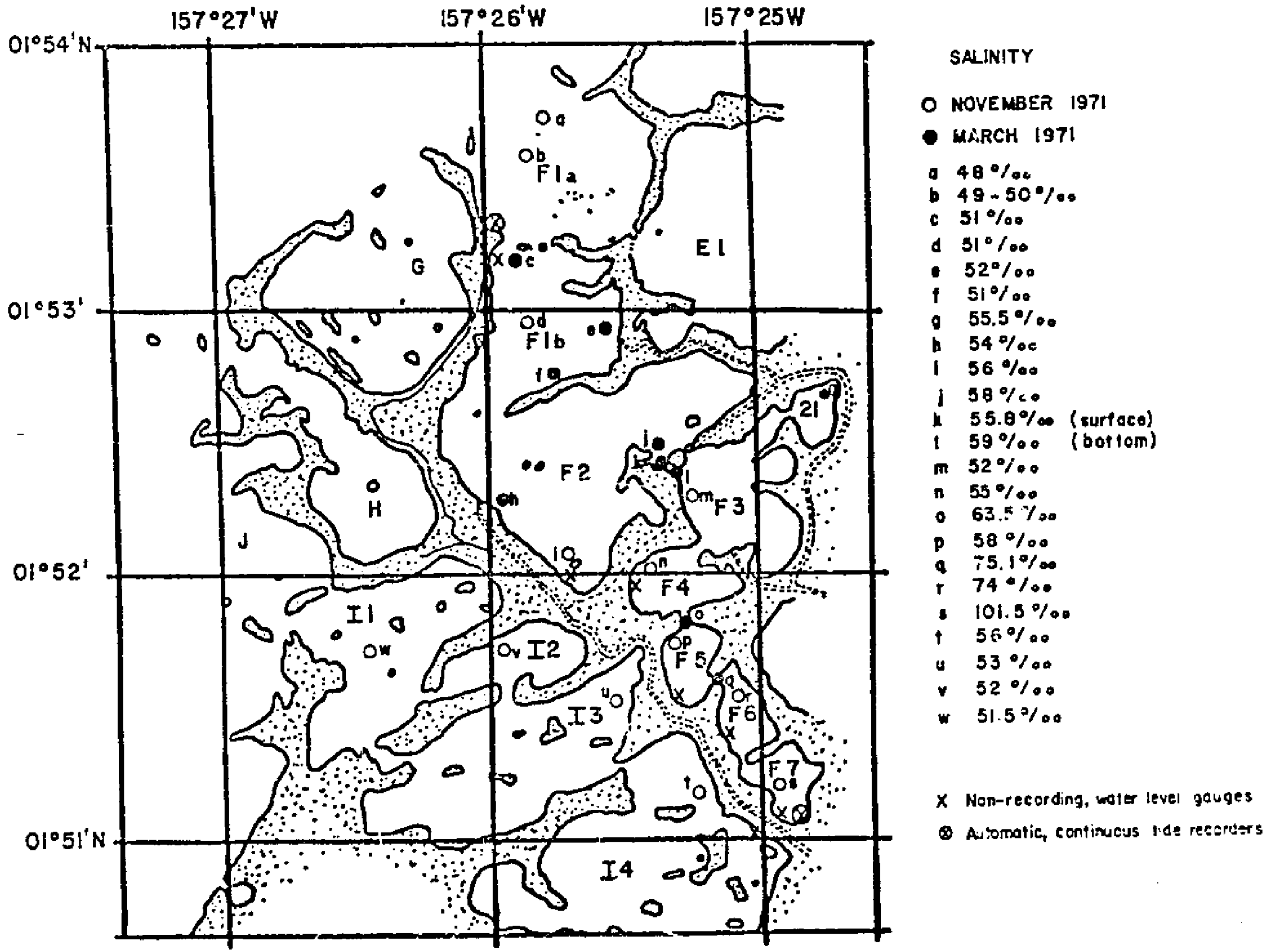

FIGURE 9. F-series of lagoon lakes, showing salinity determinations and tide gauge sites.

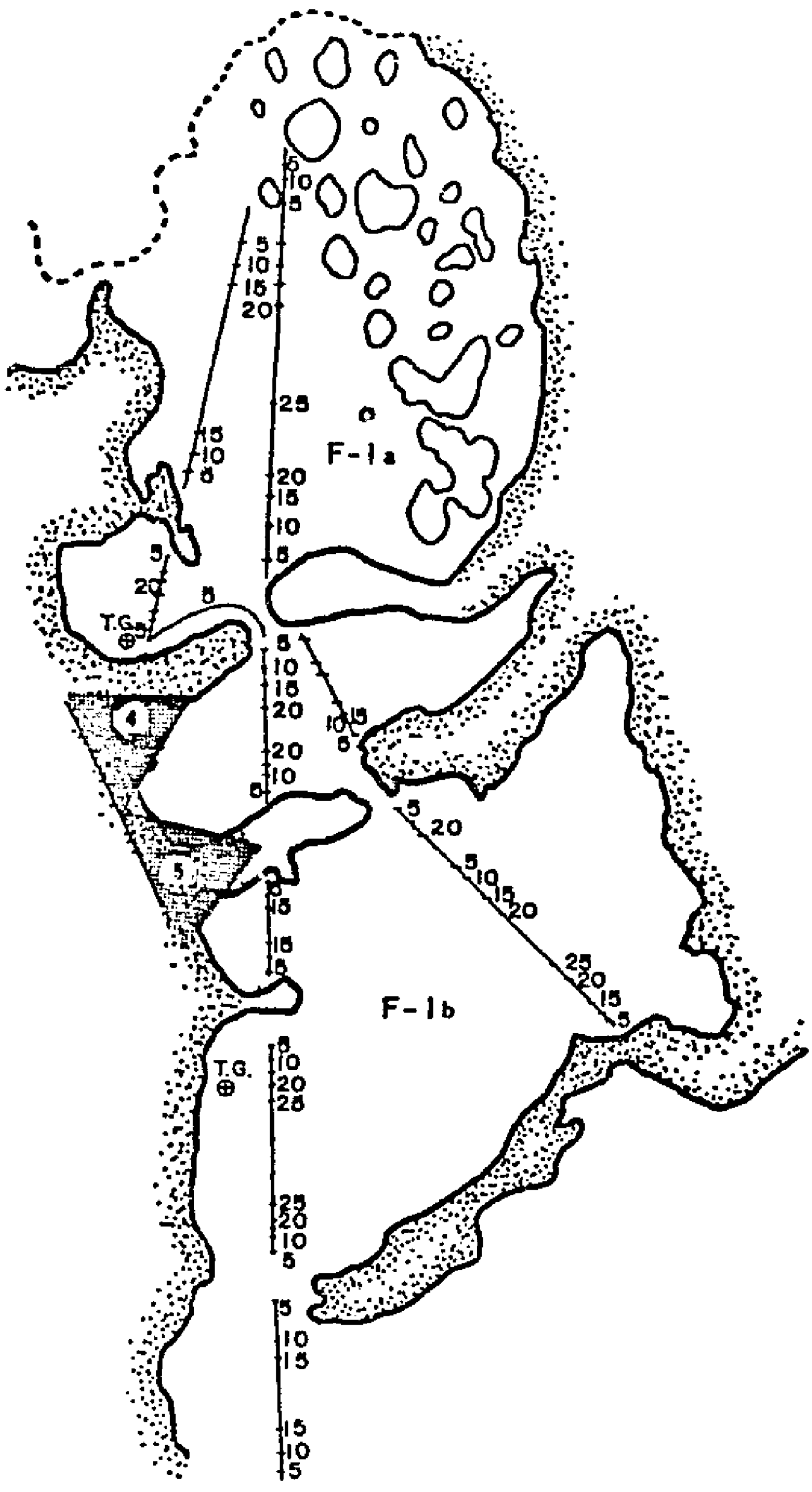

FIGURE 10. Depths in feet of lakes Fla, Flb, and F2. Many shoal areas and peninsulas are ill-defined, emerging from beneath the water's surface with slight tidal changes. Depth soundings along tracks in feet.

Lakes F1a, F1b, and F2 are the largest of the F-series (total 281.2 acres) and because they would not lend themselves readily to water management without extensive construction of walls, etc, it was decided to concentrate our efforts on lakes F3 through F7 and on lake 21 which is connected to an arm of F3.

In the plates that follow, an attempt was made to photograph the major types of downwind shorelines that were potential Artemia egg-harvesting sites. Photos were taken between 1200 and 1600 hours utilizing Kodacolor film from which black-and-white plates were made. Numbered cones on Figures 10 through 17 depict the point from which the photos were taken and the approximate near field covered. "TG" indicates the location of temporary tide gauges established for circulation studies.

The channels between the lakes in the F-series are of particular importance because some of them will have to be modified with gates and screens in support of the Artemia culture scheme.

Shoreline and Channel Description

a. Lakes F1a, F1b, F2 (281.2 acres) (Figures 10 and 11)

These large lagoon lakes lie in a roughly north-south axis so that the western shoreline is downwind to the prevailing easterly winds. Because of the size and large openings to the lagoon, these lakes were not considered as suitable for the initial Artemia culture venture; therefore only a cursory shoreline survey was made. These bodies of water have a series of finger-like spits and shoals extending from both the east and west shorelines. These projections could serve as a base for barriers that might be constructed should these lagoon lakes be needed for future controlled enclosures for aquaculture.

Plates 4 and 5 depict a typical section of the western shoreline in this area with a very shallow slope and a well-compacted fine sediment with coral and mollusk fragment substrate.

The downwind shoreline of lake F2 follows a northwest-southeast axis. The lake has several shoal areas and small islands. The downwind shore consists of alternate sections of overhanging eroded beach rock and moderately steep shell and rubble beaches as shown in Plate 6. This is in contrast to the southern point of the lake (Plates 7 and 8) and small embayments along the southeastern shore (Plates 9 and 10) that all have a flat, hard-packed substrate of sand, shell fragments, and fine sediments.

b. Channel joining F2 and F3 (Plates 11, 12, and 13)

This is the last well-developed, deep channel in the F-series of lakes as one moves toward F7. The F2-F3 channel is approximately 100 meters long and 10 meters wide, with a maximum depth of 4 meters. In longitudinal section, it is concave with a bar and delta development at both ends of the channel (seen as light line in the background of Plate 11). The channel is asymmetrical in cross-section, with the downwind side exhibiting a much gentler slope. The bottom sediment is a semi-consolidated pelecypod-Acropora fragment biorudite.

c. Lake F3 (45.9 acres) (Figure 12)

The downwind shoreline has a slightly curved configuration along a roughly northwest-southeast axis. A beach-rock outcropping interrupts a beach consisting of deep windrows of shells of the bivalve Fragum fragum (Plate 12). Plate 14 shows an inactive channel between F2 and F3. Beach rock extends as a shallow shelf into the lake (Plate 13). Plate 15 shows the relatively steep sloped beach along the downwind side of this lake consisting predominantly of loose F. fragum shells up to a meter in depth. Further along toward the F3-F4 channel, the shell beach has periodic intrusions of eroded beach rock (Plate 16).

d. F3-F4 channel (Figure 12)

In cross-section this channel (Plate 17) is a broad, flat channel only a few centimeters deep at high tide. The shoreline consist of shell fragments, while the channel bottom is firm and flat. A narrow bar extends out from the eastern shore as seen in the background of Plate 17.

e. Lake F4 (19.5 acres) (Figure 13)

This oval-shaped lake contains no major shoals or islets. Its long axis is generally east-west. The northwest portion of the downwind shoreline consists of beach rock and shell (Plate 18) which gradually become deep deposits of loose shells toward the west end of the lake (Plate 19). In the foreground of Plate 19 can be seen the beginning of beach rock that extends around to the F4-F5 channel. Along the southwestern shore an undercut beach-rock shoreline has a parallel offshore strip of consolidated shell and rubble that is about 15 feet wide and is exposed at all phases of the tide (Plate 20).

f. F4-F5 channel (Figure 13)

This is another broad, shallow channel, similar to the F3-F4 channel. It is bordered on the west side by a flat rock shelf approximately 100 meters wide which is covered with scattered mounds of shell (Plates 21 and 22). A delta extends from the channel into lake 5 (Plate 23).

g. Lake 21 (Figure 14)

This lake is connected to the northeast arm of lake F3 by means of a narrow channel. It is of particular interest because its relatively small size and proximity to other F lakes suggests its possible use as

FIGURE 11. Lake F2 with 5-foot depth contours.

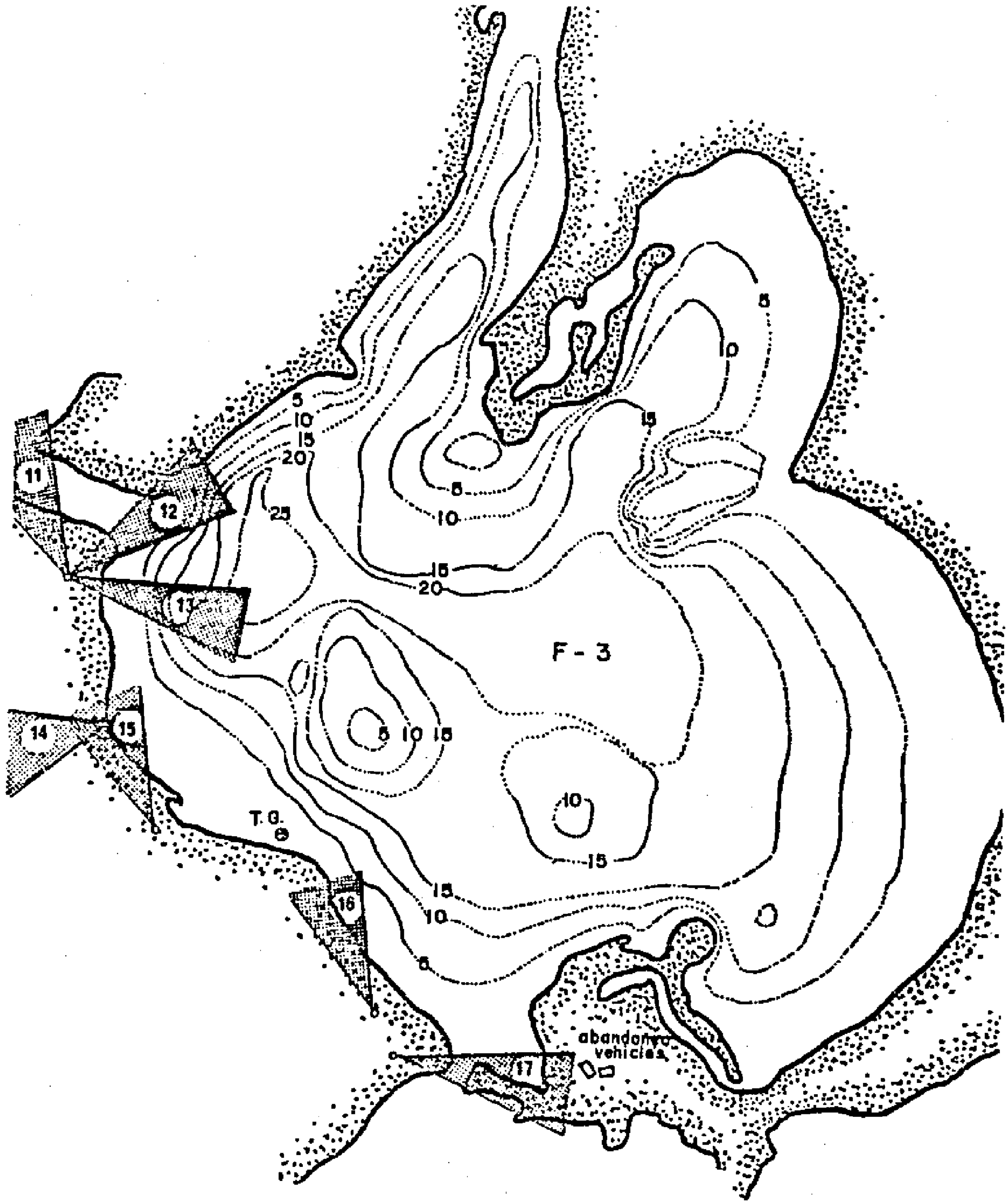

FIGURE 12. Lake F3 with 5-foot depth contours. Shallow channel in the upper portion of figure joins with Lake 21. (See Figure 14.)

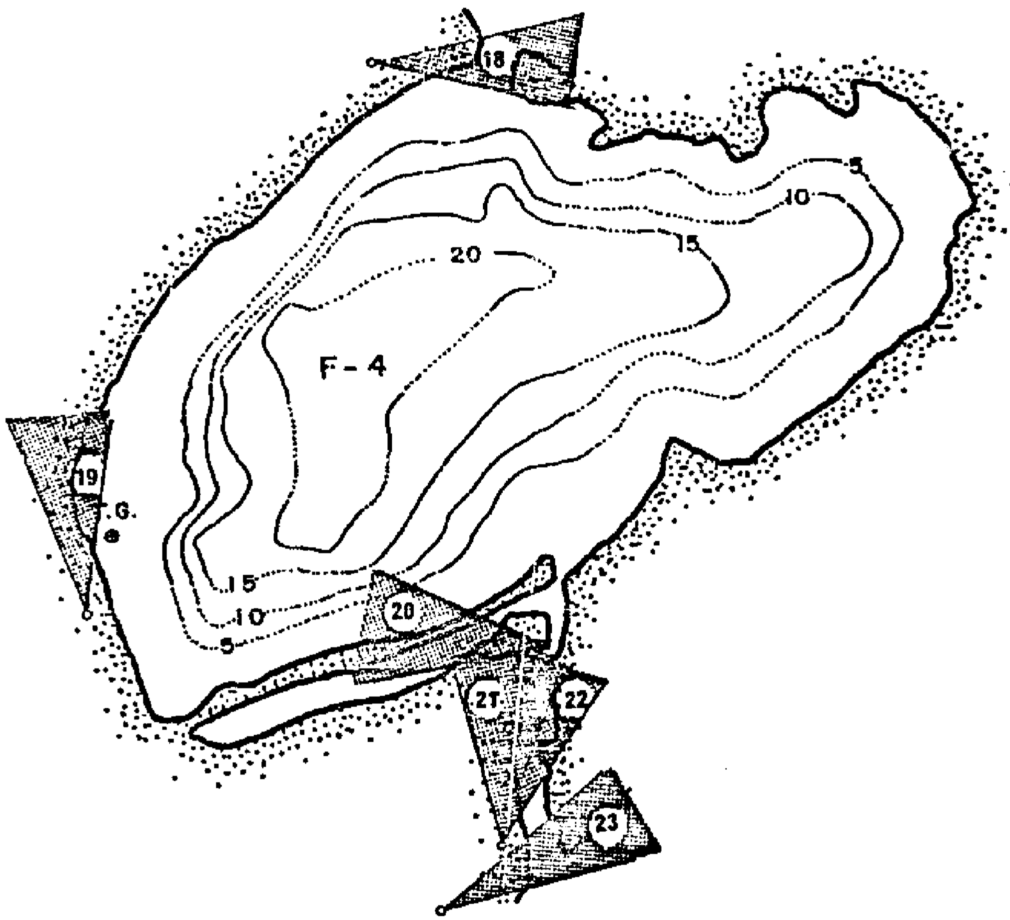

FIGURE 13. Lake F4 with 5-foot depth contours.

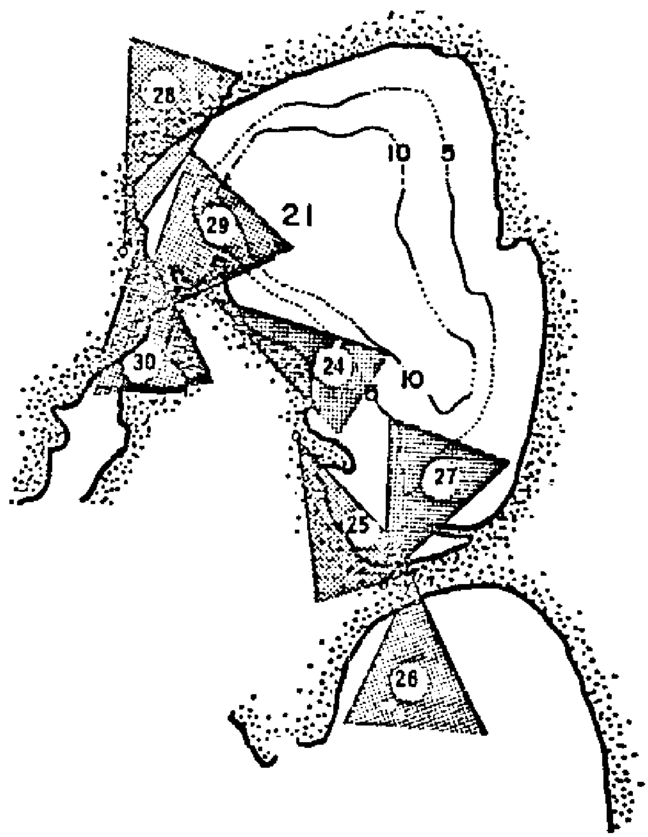

FIGURE 14. Lake 21 with 5-foot depth contour intervals. The shallow channel connecting it to F3 is seen at the left of the figure and a portion of F3 is shown at the bottom of the figure.

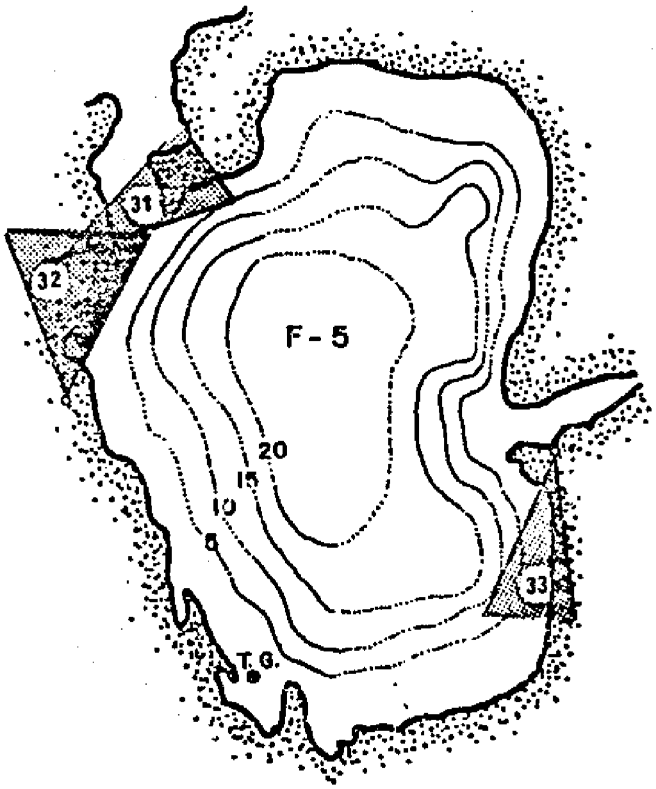

FIGURE 15. Lake F5 with 5-foot depth contours.

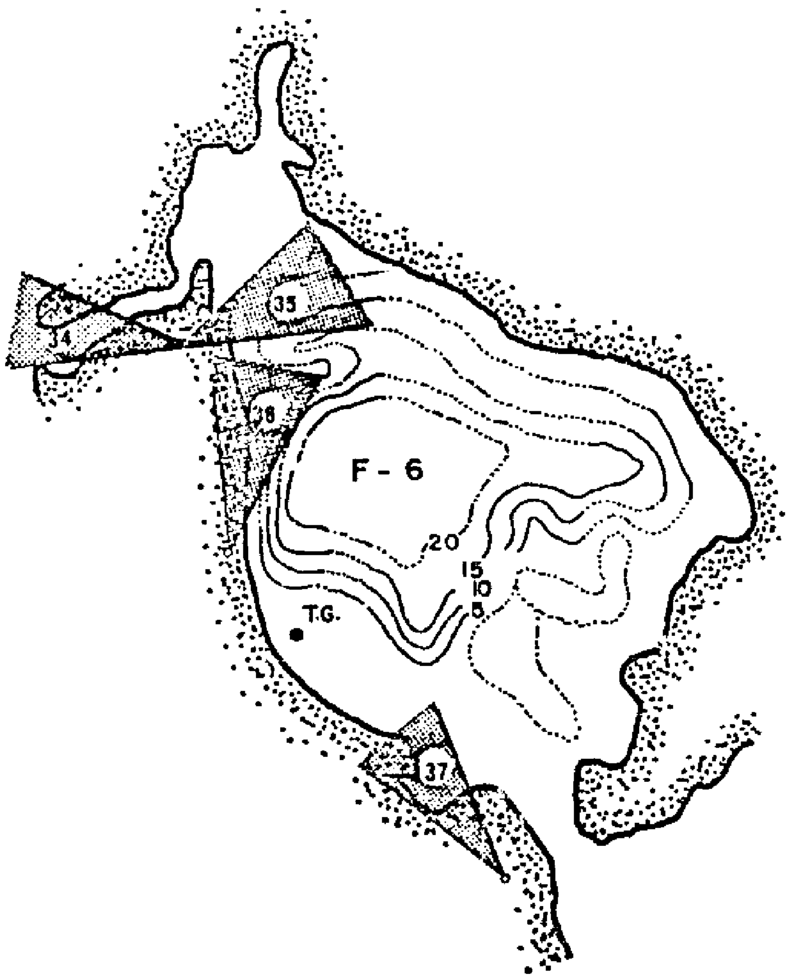

FIGURE 16. Lake F6 with 5-foot depth contours.

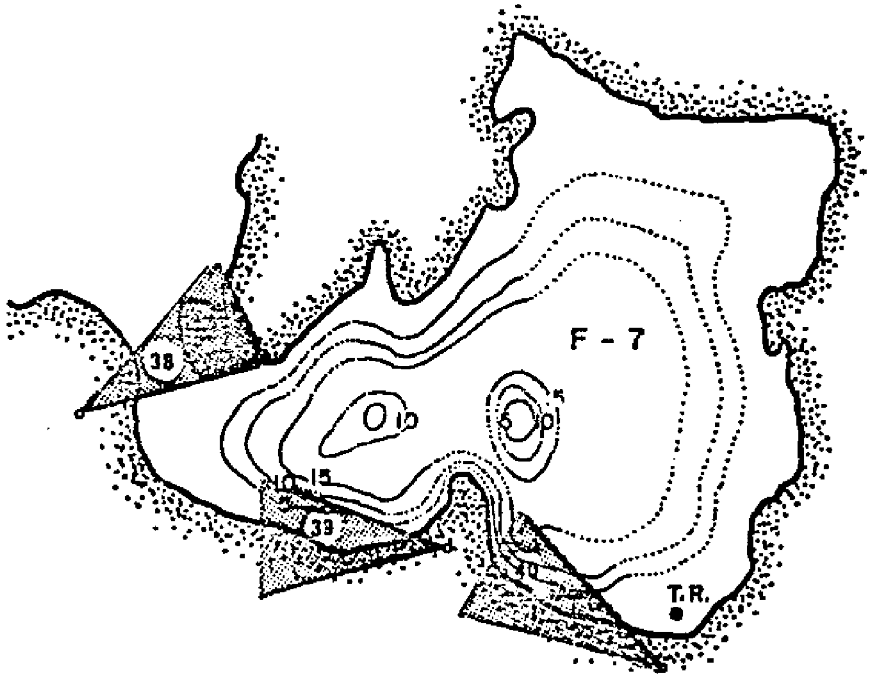

FIGURE 17. Lake F7 with 5-foot depth contours.

Plate 4. Fla

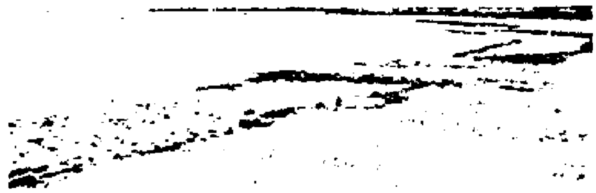

Plate 5. Fla

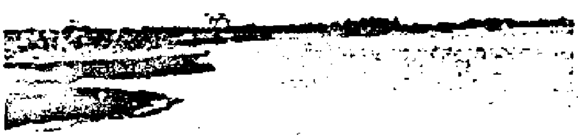

Plate 6. F2

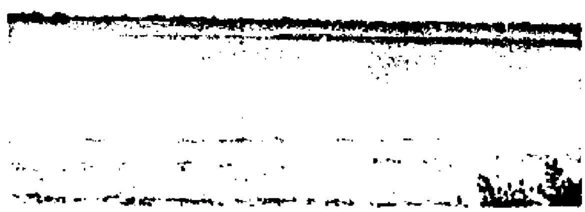

Plate 7. F2

Plate 8. F2

Plate 9. F2

Plate 10. F2

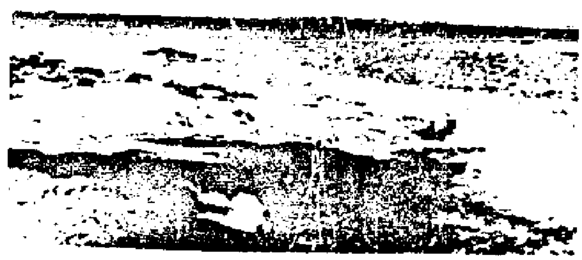

Plate 11. Channel F2-F3

Plate 12. Channel F2-F3

Plate 13. F3

Plate 14. F3

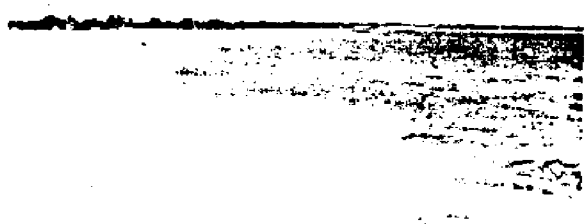

Plate 15. F3

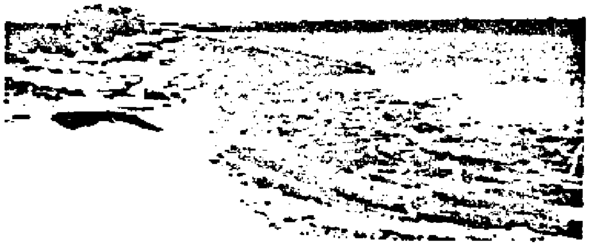

Plate 16. F3

Plate 17. Channel F3-F4

Plate 18. Channel F3-F4

Plate 19. F4

Plate 20. F4

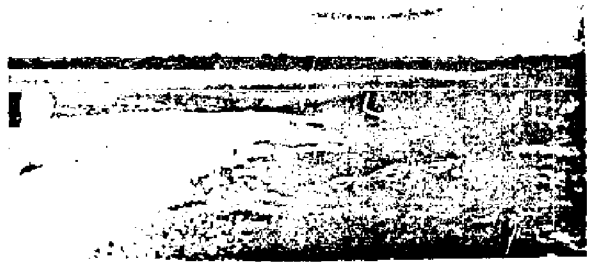

Plate 21. Channel F4-F5

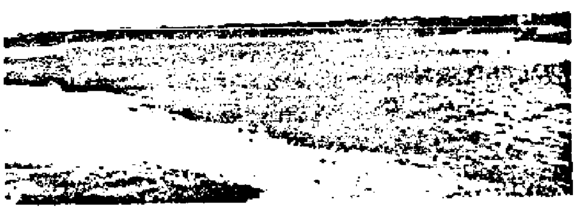

Plate 22. Channel F4-F5

Plate 23. Channel F4-F5

Plate 24. Lake 21

Plate 25. Lake 21

Plate 26. F3

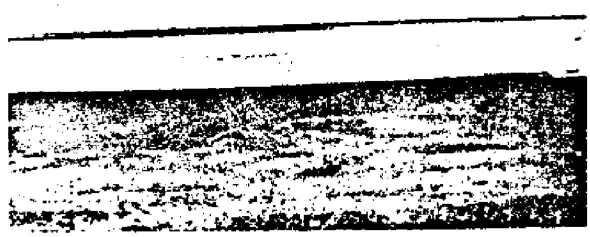

Plate 27. Lake 21

a hatching or sub-culture pond. It is a small, oval-shaped lake which has relatively flat, firm shorelines (Plates 24, 25, and 26) with an offshore bar extending across the southern end (Plate 27). The north-western shoreline has a shallow accumulation of shells (Plate 28), and it is joined to F3 by a curved channel with a maximum depth of 1 meter, with bars at either end (Plates 29, 30, and 31).

h. Lake F5 (11.5 acres) (Figure 15)

This is a kidney-shaped lake with no shoals or islets. Its long axis is north-south. The northwest shoreline consist of mounds of loose shells 0.5 meters deep. The western extremity of the lake has a narrow, exposed strip of shell mound extending offshore (Plate 32) behind which is a relatively flat, hard platform. The southeastern shore is a broad, flat platform with little loose material (Plate 33).

i. F5-F6 channel (Figure 16)

This channel is a straight, shallow connection aligned in a nearly east-west direction. It has beach rock and shell berms along the south shore (Plate 34) and deltas at both ends. The delta in F6 is shown in Plate 35. The greatest depth of this channel averages only a few centimeters at low water, with a shallow sill at the F5 end that is exposed at low tide.

j. Lake F6 (13.6 acres) (Figure 16)

This is an irregular-shaped lake with its longest axis in a northeast-southwest alignment. Extensive shoal areas are found at both ends, with roughly one-third of the area of the lake being less than 5 feet deep. The northwestern portion of the shoreline consists of relatively flat eroded beach rock with numerous fragments of Acropora coral and Tridacna clams embedded in it. A shallow mound of mollusk shells occurs about 10 feet back from the water's edge (Plate 36). Along the southwest shore the beach widens to about 30 feet, with the same eroded beach-rock formation and shallow mounds of shells 15 feet from the water's edge (Plate 37).

k. F6-F7 channel (Figure 17)

This channel is an extremely flat, shallow passage that does not allow significant transport of water except at high tide (Plate 38). It has a beach-rock crust base without significant shell fragments. On the south-west shore approximately 50 feet from the channel are mounds of weathered bivalve shells.

l. Lake F7 (12.6 acres) (Figure 17)

This highly saline lake has an irregular shape with the longest axis in a northeast-southwest direction. It has two shoal areas and a projection from the south shore. It has a broad, almost flat beach-rock beach with very few weathered mollusk shell fragments (Plates 39 and 40). The lee shorelines of lakes F6 and F7 are suitable for vehicular traffic and probably have the best configuration for the collection of Artemia eggs.

Artificial Channels

As production facilities are expanded, the construction of artificial channels might be advisable. Such construction of channels, e.g., between F7 and I4, should not present major problems, since the beach-rock crust is less than 30 centimeters thick and is underlain by five to seven meters of unconsolidated biorudite and biomicrite in this locale. Elsewhere the dividing ridges may be immediately underlain by reef rock infilled with recrystallized calcite, which would be much more resistant to excavation. Construction of control gates in the F-series channels should present little difficulty. However, some head loss by tide-forced groundwater seepage will be inevitable.

Plate 28. Lake 21

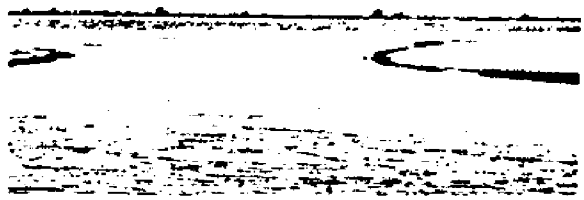

Plate 29. Lake 21

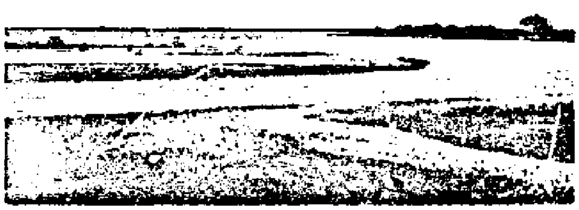

Plate 30. Channel F3-Lake 21

Plate 31. Channel F4-F5

Plate 32. F5

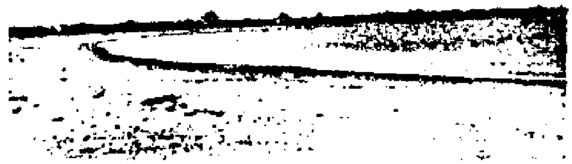

Plate 33. F5

Plate 34. Channel F5-F6

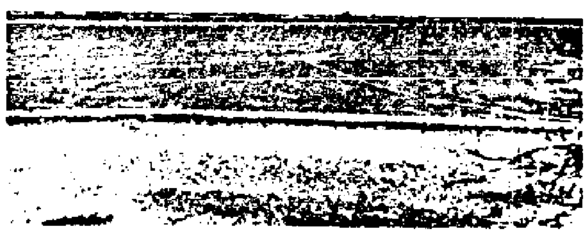

Plate 35. F6

Plate 36. F6

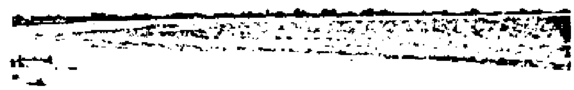

Plate 37. F6

Plate 38. Channel F6-F7

Plate 39. F7

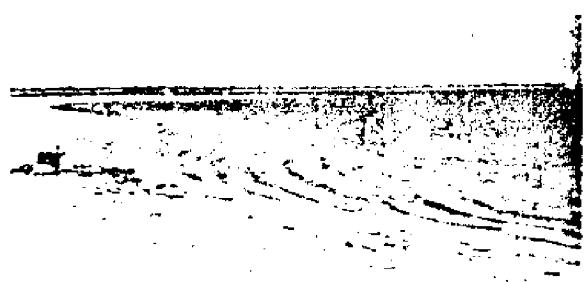

Plate 40. F7

CIRCULATION IN THE F-SERIES LAKES

During the March, 1971, reconnaissance of Christmas Island various possible schemes for the productionof Artemia were considered utilizing the available lake systems. Since Artemia eggs were an attractive possibility as an initial product, inducing stress situations (such as raising the salinity) which would stimulate egg production was examined in relation to available bodies of water. The F-series of interconnected lakes were examined from the standpoint of taking advantage of natural tidal flow, with the aid of gates and sluices, to transport Artemia from low-salinity to higher-salinity bodies of water.

Tides

Water levels in the lakes were studied to determine (1) the existing flushing rates or residence times of water in each lake; (2) the volumes of flow that could be expected if tides were used to produce a net circulation through the lake series; (3) whether there are naturally occurring tidal-phase differences between lakes that could be used to promote net flows; and (4) the mean-water-level differences between lakes that could be used to promote net flows.

Water levels were measured in each lake at the locations shown in Figure 9. Readings were taken every hour from 1100 (local time) November 8 to 2000, November 10. During the same period, hourly readings were taken of wind velocity and surface-water temperature in lake F1b. The relative elevations of all gauges shown in Figure 9 were determined by survey, so that differences in mean water level between lakes could be computed.

The tide records will be discussed starting with the outermost lake, F1a, which is the one most directly connected with the main lagoon, and moving landward through the series, passing toward lakes that are sequentially farther removed from the lagoon.

Tides in the Main Lagoon

The tide in the outermost lake, F1a, may be taken to represent the tide in the neighboring region of the main lagoon. F1a does not open immediately to the main lagoon, but we note that wherever the lakes are interconnected by fairly wide passages there is negligible distortion of the tide wave over short distances. This shows clearly in the similarity of the records from F1a and I4, which are connected via the main lagoon. Thus we regard the record from F1a as the tide in the local, inner portion of the main lagoon. This tide is shown in Figure 18. The range is about one foot (0.3 meter), and the form of the wave is strongly distorted.

Tides measured in the inner end of the lagoon do not necessarily represent conditions throughout the whole lagoon. When a large lagoon has limited communication with the surrounding ocean, the tide in the inner parts of the lagoon will lag behind that which is close to the atoll inlets. The delay can be more than one hour. Such delays are found at Fanning Island (Gallagher et al, 1971) and are very likely to be present here. The tide is routinely recorded in the lagoon at London village, and relatively simple empirical formulas could be derived to give the tide in the inner lagoon from the London measurements.

The distortion of the lagoon tide is interesting to note. The water rises quickly and recedes slowly, with the crest shifted forward in time -- a pattern that characterizes nonlinear distortion of the wave. In general there are two processes that can produce nonlinear distortion of a tide: passage of the wave through extensive regions of shallow water, and bottom friction (Gallagher and Munk, 1971). Although both processes are undoubtedly present in the lagoon, the shape of the wave indicates that the first is predominant here. The lagoon is large enough so that a nondistorted tide entering from the open ocean will undergo a shoaling transformation, becoming steeper in front somewhat like an ordinary swell wave approaching a beach. (A good example of frictional distortion appears inside the lake series; it will be discussed later.) The nonlinear distortion of the lagoon tide at Christmas Island is very pronounced; the island would be an excellent place to conduct field studies of this phenomenon.

It was considered useful in examining the data to compare the Christmas Island lagoon tide with the Honolulu tide. Both curves are given in Figure 18. There is no simple relation which would give accurate lagoon predictions based on Honolulu. However, rough estimates could be made: the lagoon tide has somewhat less than half the Honolulu amplitude, high water lagging by about two hours and low by about five hours.

Tides in the F-Lake Series

A set of hourly water-level readings, through the lake series, is presented in Figure 19. Tides in the outer lakes, through F4, follow the local lagoon tide with little if any discernable differences. This is simply because these lakes are connected by relatively large passes which permit appreciable volume flow.

The first noteworthy tidal difference occurs between F4 and F5. These lakes are connected by a shoal pass about one foot deep and roughly 25 feet wide, which impedes the tidal flow. The impedence displays the character of a nonlinear frictional process. High tides in F5 are reduced in amplitude by as much as a factor of two and may lag those in F4 by as much as two hours. The nonlinearity of the channel resistance enhances these effects (amplitude reduction and phase delay) on the larger tides. The tidal phase difference between F4 and F5 could be used for limited practical purposes, and this will be discussed later.

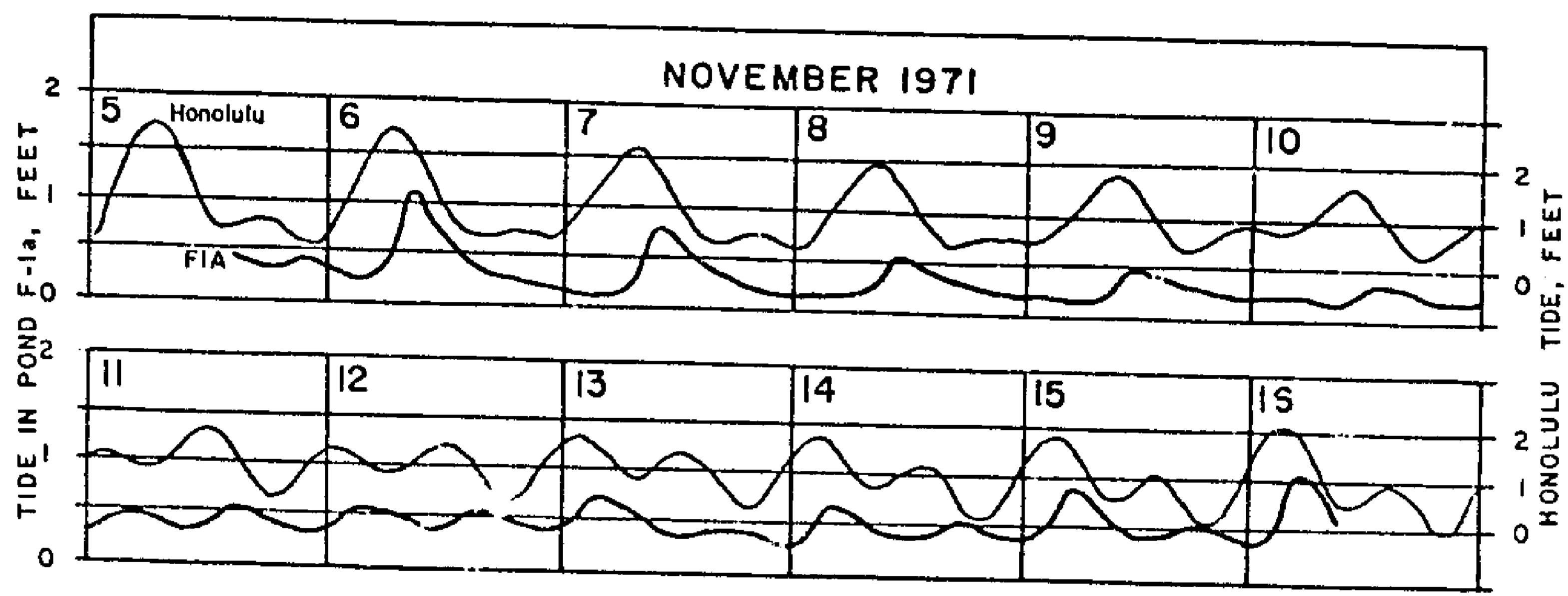

FIGURE 18. Recorded tide in Pond F1a. Honolulu tide shown for comparison.

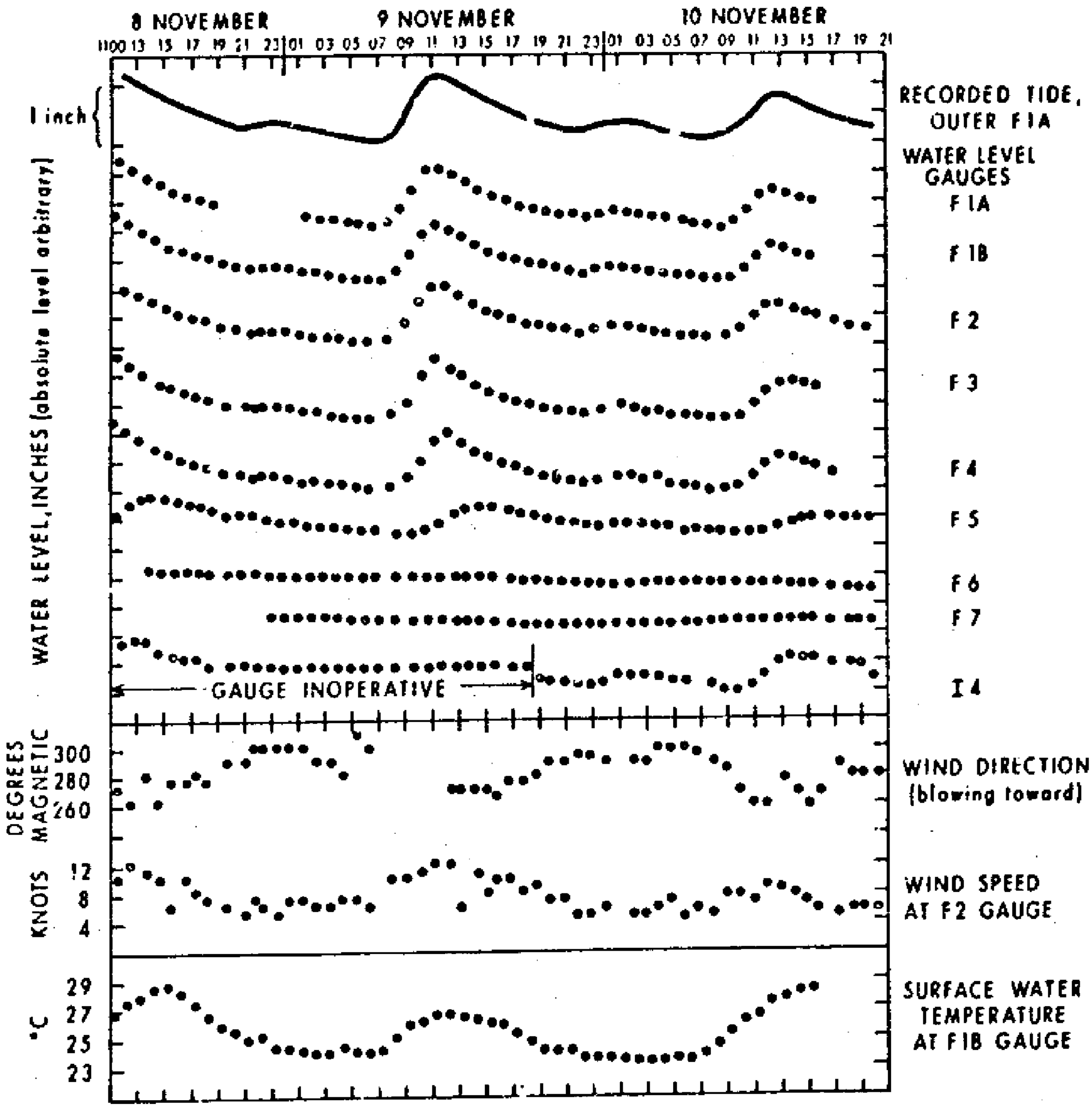

FIGURE 19. Water levels, wind speed and direction, and surface water temperatures measured in and near the F-lake series.

The channels connecting F5 with F6, and F6 with F7, are less than 20 feet wide and less than one foot deep. In fact, the sills of these channels lie above the mean water level of F5, so that only the higher tides penetrate into F6 and F7. These penetrations do not cause normal tides in F6 and F7; they are simply additions of water which tend to replace what has evaporated. Such additions did not occur during our period of hourly monitoring, and the curves in Figure 19 show an evaporation rate of about one-half inch/day. From the evaporation rate, the height of the tide in F5, and the measured difference in mean water levels between F5 and F6, it can be concluded that the occasional penetrations of water from F5 must occur at least as often as once a month. It cannot be proved with this set of measurements, but it seems highly probable that the penetrations occur diurnally during spring tides, happening 3 to 6 days in a row, about every two weeks.

Volume Exchanges and Residence Times

Residence times and daily percentage volume exchanges are tabulated below for the lakes which have normal tidal flushing. For the computations, a mean depth of 15 feet was taken for all lakes, and lake areas were planimetered from a map based on aerial photos. Residence time is computed as the volume of the lake divided by the tidal volume-exchange rate. If a lake were perfectly mixed at all times, then on the average a water parcel would stay in the lake for the residence time. Since the lakes are probably not perfectly mixed in reality, the computed residence times should be treated as minimum values.

Lake	Volume, ft^3 *	% of Lake Volume Exchanged Per Day	Residence Time, days
F1a	189×10^6	8.8	11.4
F1b	154×10^6	8.8	11.4
F2	274×10^6	8.8	11.4
F3	105×10^6	8.8	11.4
F4	42×10^6	8.8	11.4
F5	30×10^6	4.5	22.2

* Based on an average depth of 15 feet.

Lakes F6 and F7 do not have normal tidal exchange and must be treated differently. Volume exchange has been calculated for the observed cycle of evaporation and occasional refilling. The numbers below refer to water, but not to dissolved substances.

Lake	Volume, ft^3	% of Lake Volume Exchanged Per Month	Residence Time, months
F6	27×10^6	6.7	15
F7	32×10^6	6.7	15

Mean Water Level in the Lake Series

Mean water level for each lake is listed below, where the elevation in F1a has been used as an arbitrary zero level. Errors in the levels survey and in the tide readings could amount to about ± 0.05 ft. Thus to within the limits of measurement accuracy, mean water level is constant throughout the outer lakes, as would be anticipated from their free communication with the lagoon tide. Note that I4, which lies adjacent to the most landward F-lakes, is in good communication with the main lagoon and shares the same water level.

Unlike the other table entries, the water levels listed for F6 and F7 do not represent steady, average values. As mentioned before, water is added to these lakes only during spring tides; the rest of the time their levels are falling, due to evaporation at the rate of about 0.50 inch/day. (In the rainy months, January through May, the average net rate of evaporation over precipitation would be reduced to about 0.25 inch/day.) At the time of our hourly monitoring, F6 and F7 stood about 0.65 feet below the mean water level in the outer lakes. Their monthly or semi-monthly range of water level is probably between six and twelve inches. Generally, or perhaps even all the time, F6 and F7 stand below the mean water level in F5 and I4 -- a fact which could be used in a system of flow control.

Lake	Mean Water Level	Lake	Mean Water Level
F1a	0.00 ft	F5	-0.05
F1b	0.01	F6	-0.64 (on 9 Nov.)
F2	-0.04	F7	-0.65 (on 9 Nov.)
F3	-0.05	I4	0.00
F4	-0.04		

Temperature and Wind

Surface water temperature and wind velocity were observed hourly during November 8 through 10; the data are presented in Figure 19. Surface temperature in lake F1b undergoes a diurnal cycle, peaking near mid-day with a range of about 5°C. Since no tidal effects are seen, this curve is probably typical of most of the outer lakes in the series. A similar range could be expected in F6 and F7, but the actual temperatures would probably be higher.

The southeast trades are present almost constantly at Christmas Island. Calms occur less than 2% of the time (Jenkin and Foale, 1968). During the measurement period the wind showed a clear diurnal pattern, strengthening to about 12 knots at mid-day and dying off to 5 knots during the night. Wind direction was also diurnal; the lighter wind blew toward about 260° magnetic and shifted to 300° as it grew stronger. The winds produced no measured water-level changes in the lakes except in F6 and F7 where during the mid-day hours when wind velocity is maximum there is about one-half inch of set-up at the leeward sides of the lakes. This effect can be seen in Figure 19.

Temperature and wind have an effect on evaporation which in turn relates to the salinity of these lakes. Figure 9 gives surface-salinity readings taken in March and November of 1972.

Possibilities for Altering or Controlling Flow Through the Lakes

The phenomena discussed above will allow three general types of flow-control utilizing energy from the natural environment.

It would be relatively simple to produce a one-way flow in either direction through the inner lakes in the F-series. This is due to the fortunate circumstances that lakes of the adjacent I-series lie quite close to these F-series lakes, and have the tidal characteristics of the local main lagoon. For example, a one-way gated barrier across the pass between F3 and F4, in combination with a one-way gated channel from F5 to I3, would produce a unidirectional flushing through F4 and F5. The flow could be set in either direction and would be entirely driven by the tides. Variations on this theme could be used to get many flushing and/or holding possibilities in lakes F3 through F7. Lakes F1 and F2 would be more expensive to control, because blocking their wide interconnecting passages would involve much more extensive construction work.

If F6 or F7 were to be included in the tidal flushing scheme, the channel entering each would have to be deepened. This could be desirable, but it might also be useful to leave F6 and F7 in their present state and take advantage of their unusual pattern of evaporation and occasional renewal. This natural flow pattern produces monthly or semi-monthly salinity cycles in which salinity may vary by five or ten percent of its mean value. Other periodicities could be achieved by minor alterations of the inlet channels.

A third possibility exists for making use of naturally generated flow. Because of the nonlinear impedence of the F4-F5 channel, the water in F5 is lower than in F4 or I3 during most rising tides -- by about three inches. This head difference could be used to produce periodic flows through tanks or small pools constructed adjacent to F5.

Internal Structure and Circulation in F6

Structure

The internal structure and circulation in a single lake were studied to determine how nutrients might be dispersed in the lake: in particular, those nutrients that tend to be trapped in stagnant, lower waters. In addition it was necessary to know how passively floating brine shrimp eggs would be used to collect them for harvesting.

In general, questions such as these are very difficult to answer in complete detail for natural water bodies. For a body the size of an F-lake, a carefully planned, fully instrumented study lasting several man-weeks would be necessary. In the present case, such time and manpower were not available and advance knowledge of the lakes was inadequate for planning a comprehensive study. However, one lake was studied for three days with crude techniques. Tentative answers can be offered, and if a complete study should be necessary, it could now be planned.

F6 was selected for the preliminary survey. It is favorable because of its small size and simple shape. By working during a period when tidal effects were absent, the isolated influence of the wind could be studied, rather than the more complex patterns that would be present if circulation were driven by both wind and tides. This simplification not only increased the chances of discerning sensible patterns during a short survey -- it may also be relevant to actual conditions in an aquaculture operation. Quite possibly certain stages of brine shrimp culture (especially egg production and harvesting) might be conducted in lakes such as F6, which are periodically closed and purely wind-driven.

Figure 20 is a vertical temperature section roughly aligned with the wind direction; the section location is indicated in Figure 21. The data were taken in mid-morning over a period of about one hour. Subsurface readings were made with an instrument of questionable reliability. The device showed serious zero drift, and it was nearly impossible to get good absolute readings. The general nature of the vertical profile at each station was adjusted so that surface temperatures agreed with mercury thermometer measurements. The section is probably roughly correct in its main features, but it does not necessarily present an accurate picture of details or exact absolute temperatures. Independent information about surface circulation was used in locating the intersections of isotherms with the lake surface.

There are four main features of the thermal structure. The bulk of the lake is nearly isothermal. Under the action of the wind, a pool of cooler surface water is accumulated along the leeward shore. Its temperature and position indicate that it must be the least saline water

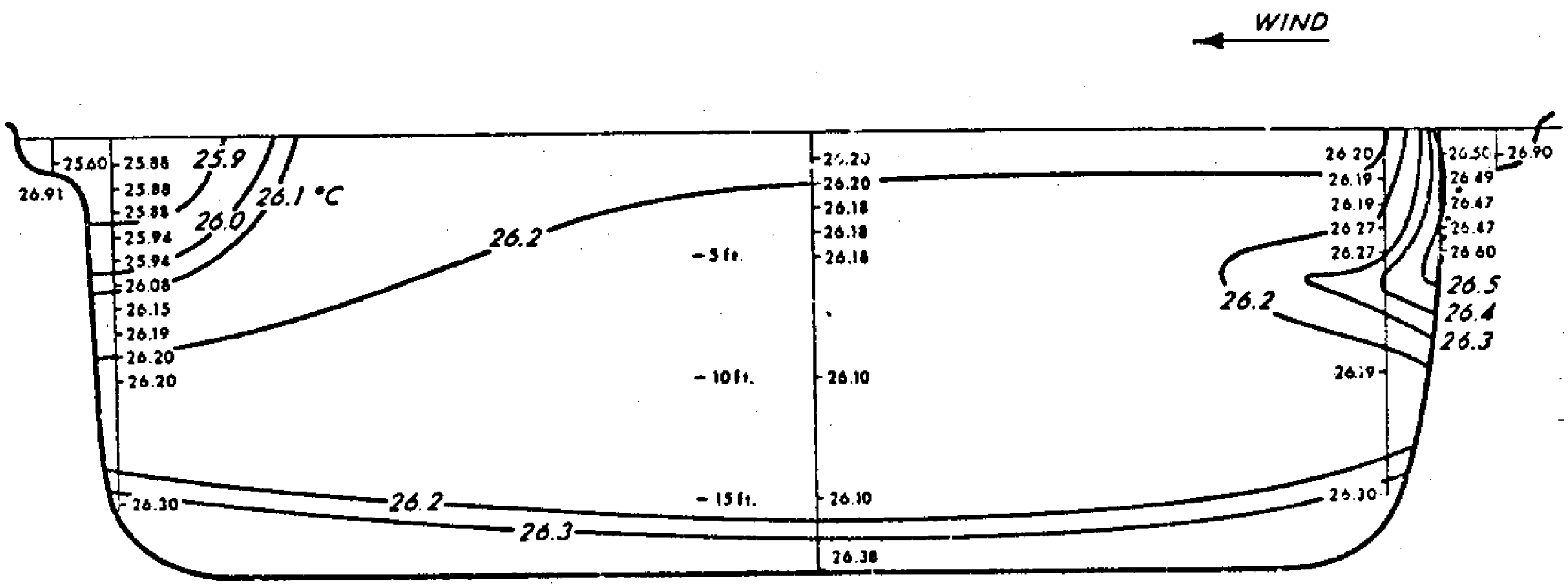

FIGURE 20. Vertical temperature section across lake F6. (Section shown in Figure 25a.)

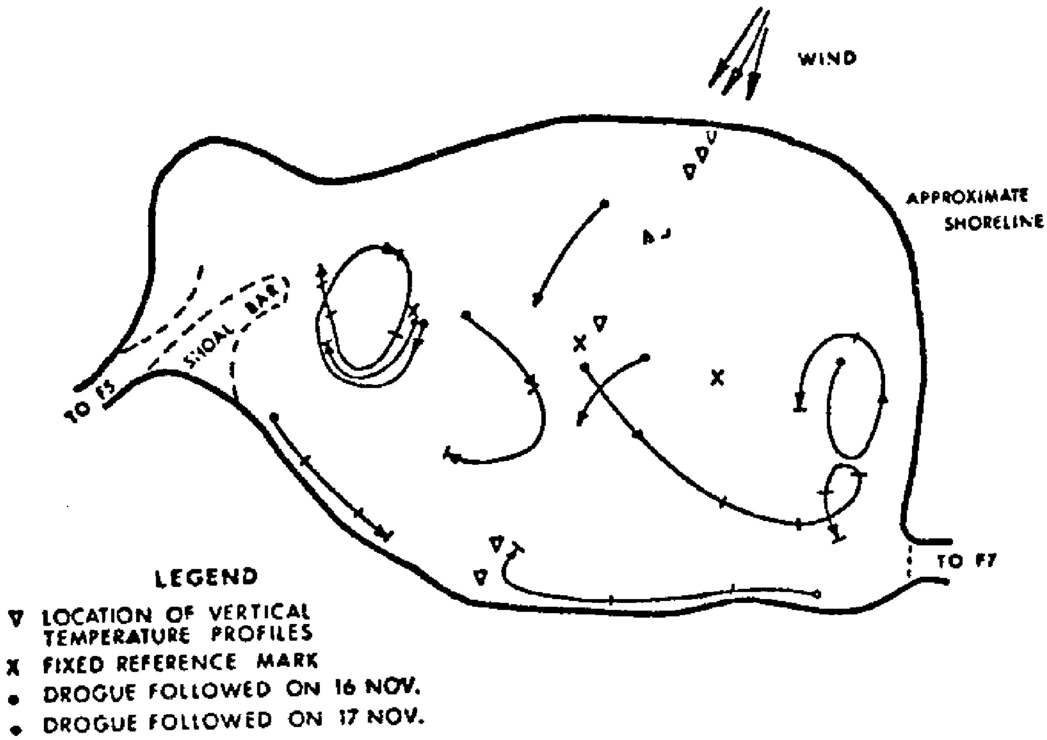

FIGURE 21. Tracks of drogues set at a depth of one foot in lake F6.

in the lake; its origin is probably the monthly or semi-monthly inflow from F5. During the night when the wind slackens, this water probably extends further upwind over the lake's surface and loses some of the heat it gains by daily warming over the shallow, inshore flats. The amount of this water and its physical properties are probably quite variable in time. Along the shoal shelf adjacent to the windward shore there is also appreciable solar warming and evaporation. This appears to form water of intermediate density which sinks along the bottom and spreads out, with mixing at medium depths. The exact extent of the horizontal spreading indicated by the isotherms in Figure 20 is speculative. The bottom of the deep portion of the lake is overlain by a layer of warmer (and therefore saltier) water which appeared to be less than a foot thick. It is probably renewed (or partially renewed) by the occasional formation of unusually saline water -- probably in the windward shoals, as discussed above. In connection with this water, it is noted that most of the lake's bottom, except along the leeward shore, is covered with a thick, pink, gelatinous growth of blue-green algae* which seems to thrive in some of the more saline environments at Christmas Island. The distribution of these algae in F6 tends to indicate the windward shoals as the source of the bottom water. Samples of the algae dredged near the center of the lake smelled strongly of H_2S. It could be that an anoxic condition is produced inside the gelatinous layer (which is several inches thick), or that the thin, bottom layer of water is anoxic. The existence of the warm bottom layer and its possible anoxic condition both indicate that this water is relatively stagnant. Certainly the lowest foot or so of water is not subject to vigorous mixing. However, it is unlikely that a potentially serious "nutrient trap" exists. Even if molecular diffusion is the only mixing process present, a foot-thick bottom layer would have a half-life on the order of one week; the bottom layer would lose over half of its excess concentration of any substance within seven days. So although the stagnant layer could tie up some of the lake's nutrients, it cannot act as a sink or a permanent trap. (Of course, it would be necessary to minimize nutrient use by benthic algae, but this would be true whether the bottom layer were stagnant or not.)

The surface salinity of F6 was 74.5 o/oo when measured with a refractometer. The salinities in F6 were above the upper limit of the field instrument (40 o/oo) used to measure salinities at different depths so distributions of this property were not determined. The temperature data permit some inferences about the salinity profile; these were presented above.

The temperature section and the structure it indicates are probably roughly typical of all downwind sections, except those adjacent to the ends of the lake. The gross features of the structure shown are likely to be present nearly all the time.

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* Blue-green is the common name for the taxonomic division of Cyanophyta.

Circulation

Currents in F6 tended to be slow and complex in pattern. In this situation, relatively little would be learned from a fixed current meter, and so drogues were used. They were set at one-foot and five-foot depths and followed with a skiff. Three fixed markers along the cross-wind axis of the lake and natural features on the shoreline were used in estimating the positions of the drogues. Any single position may be incorrect by 100 feet or so, but the overall forms of the drogue tracks are fairly accurate. Figure 21 gives the tracks of the surface (one-foot) drogues, and Figure 22 is a construction showing an average surface-flow pattern which seems indicated. The wind drives the surface water in two large eddies which have narrow return flows against the wind at the ends of the lake. This layer of surface circulation extends down less than five feet in the central portion of the lake, and to greater depths (probably exceeding five feet) toward either end of the lake. In addition, the less-dense water along the windward shore seems to move in two elongated eddies as shown. A typical surface current speed is three feet per minute.

The drogues set at five feet traced the patterns shown in Figure 23. Generally the currents at this depth are as strong as those at the surface. Unfortunately, nothing more can be done with the subsurface flow than to present the drogue tracks. Whatever is going on is more complicated than the surface flow, and the data are insufficient to allow interpretation.

Two additional points should be mentioned in connection with the lake's circulation. First, freely floating objects having even a small exposure to the air are driven to the leeward shore by the wind. Second, near the end of the observation period, the wind grew stronger than at any time during the study; its speed was estimated at 12 knots. A definite pattern of Langmuir circulation was established over most of the surface of the lake. (In this form of circulation, water particles in the surface layer are driven downwind, in paths which are roughly helical. The helixes have axes in the direction of the wind and lying parallel to the water surface. The sense of rotation in the helixes alternates regularly from one to the next, so that alternating bands of surface convergence and divergence are created between them. Foam and floating organic material are collected along the convergences, producing characteristic, parallel "wind slicks".) From the spacing of the slicks observed in F6, it was estimated that the Langmuir circulation was stirring the surface layer to a depth of about three feet. When this condition is established during strong winds, the horizontal eddies pictured earlier probably cease to exist, and floating objects would be advected toward the leeward shore by the Langmuir cells.

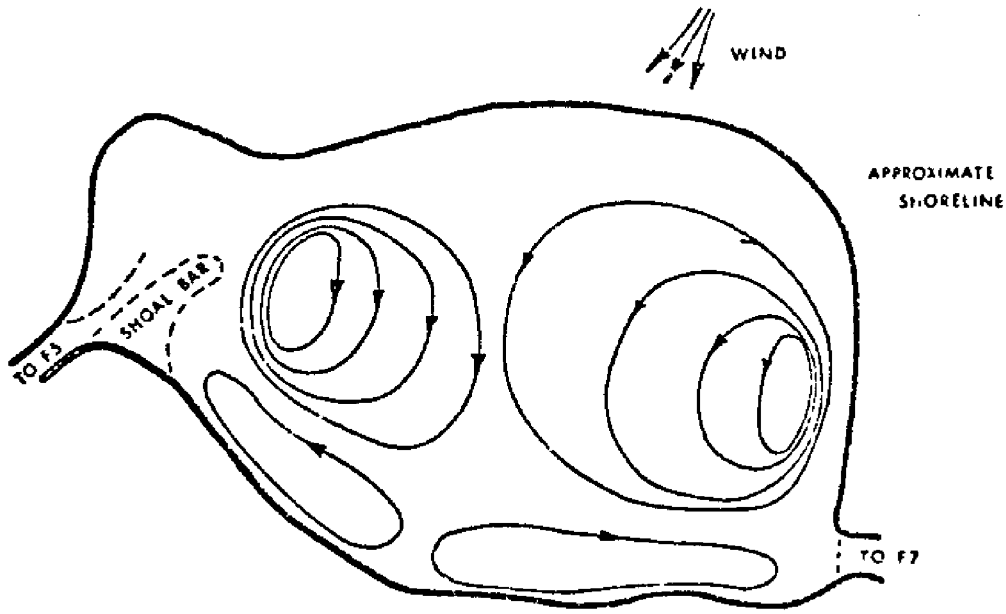

FIGURE 22. Surface circulation in lake F6 as indicated by drogue tracks.

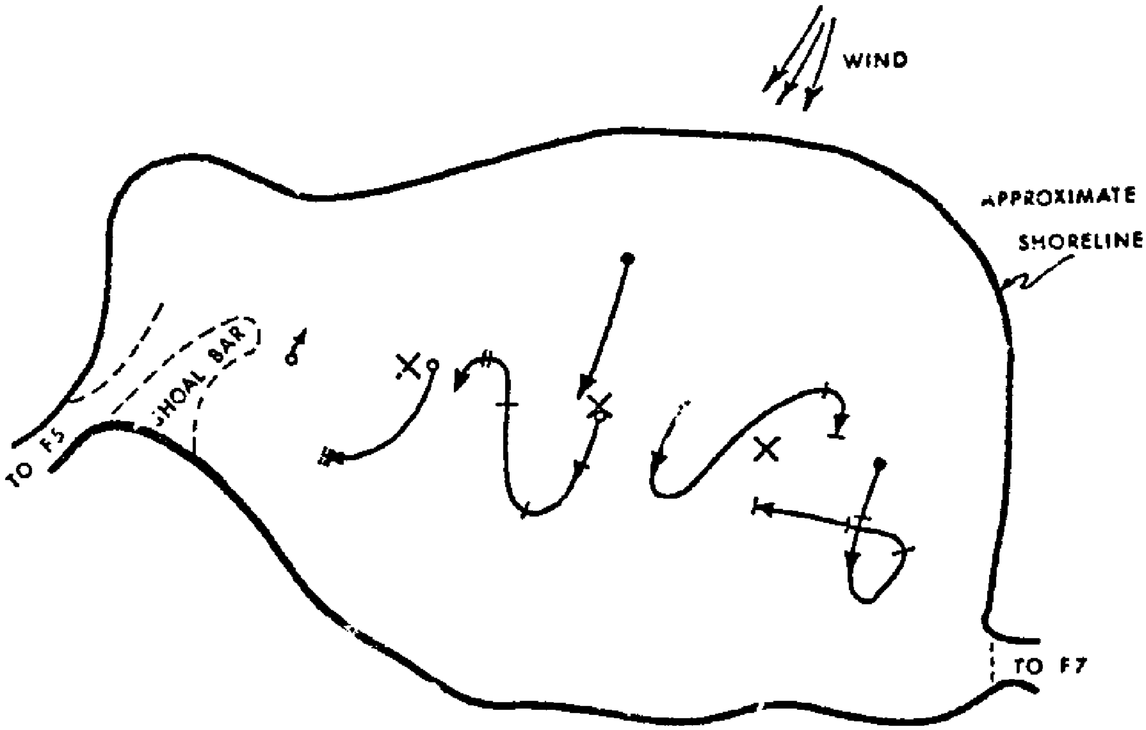

FIGURE 23. Tracks of drogues set
at a depth of 5 feet in lake F6.

The natural circulation in a wind-driven lake such as F6 could certainly be used in collecting and harvesting shrimp eggs. They would be conveyed to the leeward shore by the direct action of the wind and/or by Langmuir circulation (assuming the eggs float at or near the surface). Eggs that did not go aground would tend to collect at the convergence near the midpoint of the leeward shore, under the action of the horizontal eddies that exist during light-to-medium winds.

BIOLOGICAL ASPECTS OF ARTEMIA CULTURE

The brine shrimp, Artemia salina, are unique animals. In nature they occupy an unusual ecological niche shared with very few other animals and a few algal organisms upon which they graze for food. This observation, and the evidence presented in the following sections, argue favorably for the initiation of large-scale aquaculture investigations of Artemia as a protein source for both human and livestock consumption.

Artemia Biology

Artemia are small (1-2 cm long) crustacea of the subclass Branchiopoda, order Anostraca. They are found primarily in the highly saline waters of natural salt lakes and seas of the world, and in the brine of man-made solar salterns. They cannot live for long in fresh water. In the saltern waters the great osmotic pressure resulting from highly concentrated electrolytes vi tually excludes all other animals from the ecosystem, and limits the plant life to only a few algae and bacteria.

In the natural habitat, Artemia graze upon single-cell algae at all stages of their life cycle. They thrive in crowded cultures (3,000 adults and 12,000 nauplii/m^3) (Bowen, 1968), and both larvae and adults are phototropic. The efficiency of food conversion is very high; maximum values of 20%, 53%, and 79% have been obtained by different investigators (Reeve, 1963d; Gilchrist, 1960; Sick, 1968; von Hentig, 1971).

Artemia have a rapid generation time, achieving sexual maturity on the average in two weeks after hatching (Gilchrist, 1960; von Hentig, 1972), and will then reproduce continuously throughout their six-month to one-year life span. Differences in growth rate and time to attain sexual maturity cited in the literature are probably a function of (1) the species of algal food available; (2) the presence or absence of bacteria; and (3) the physiological state of the algal food (Sick, 1968; Gibor, 1955), inter alia. As already indicated, adult Artemia have been observed to give birth to about 40 live nauplii (the first larval stage), per day throughout their adult life. This represents a high level of fecundity which, if mortality can be controlled, can result in extremely high yields of adult Artemia.

Teramoto et al (1961) reared Artemia to maturity in one week, growing them on a mixture of yeasts and vitamins. Bowen (1965) and Bowen et al (1966) have brought Artemia to sexual maturity in two weeks, growing them on a mixture of brewer's and bakers' yeast.

The suitability of Artemia for aquaculture is enhanced by the fact that the physical cultural conditions, e.g., temperature, salinity, pH, O_2 tension, etc, are the same for the larval stages as for the adults. That is, there is no special nursery environment required. Furthermore, all stages of the life-cycle graze on the same microalgae, so that specialized environments and feeds, such as are required for the penaeid shrimps, need not be maintained. Cannibalism does not occur, since Artemia are filter-feeding herbivores and consume only small particulate matter such as single-cell phytoplankton, yeasts, and bacteria.

Artemia in their natural habitats appear in dense clouds of adults where wind and wave action concentrate them in the shallows of salt lakes and salterns (Baker, 1966). Even in normal dispersion, Parker (1900) reported 1.200 Artemia per cubic meter in Lake Urmi, and Mason (1967) reported the population in Mono Lake in the summer months to be 4,000 adults and 12,000 nauplii per cubic meter.

As noted, Artemia are filter-feeding herbivores, pumping sea water by means of coliary-type action and selecting out the appropriate size class of particulate matter. The unicellular algae and bacteria are concentrated in an oral groove or gullet, and ingested. In the high-salinity waters in which Artemia occur, relatively few unicellular algal species normally occur. The work of Gibor (1956a, 1956b, and 1957) and of Provosoli et al (1959) indicate that Dunaliella viridis, Platymonas, and Stephanoptera gracillus are suitable helophytic microalgae as feed for the culture of Artemia. Carpelan (1964) noted that in lakes of low salinity, Stichococcus has been found to dominate, the phytoplankton community being essentially a unialgal culture. In lakes of higher salinity either Dunaliella salina or Stephanoptera gracilis predominate, and since these latter algae are preferred feed (Sick, 1968; Gibor, 1956) we shall indicate the conditions that favor these organisms.

Dunaliella sp. salina was found in large numbers in several of the slaine lakes at Christmas Island. High temperatures, such as those encountered on Christmas Island (24°C - 30°C, Jenkin and Foale, 1968) are well within the tolerance of D. salina which was shown to grow best at 30°C. Well suited to high saline conditions, D. salina was shown to grow 60%, 120%, and 115% faster in waters whose respective salinities were 2, 3, and 4 times that of normal sea water (Gibor, 1956a). An autotroph, D. salina demands no organic supplements and requires only inorganic nutrients such as phosphates and simple nitrogenous substances, e.g., urea (Gibor, 1957), for growth and reproduction. Sea water, concentrated by evaporation, probably contains copious amounts of the required trace minerals (Gibor, 1956a).

Nimura (1963) reports that Chlamydomonas, a common algal species often used as feed for filter-feeding marine invertebrates, interfered with the grazing and growth of Artemia when the algal cell concentrations were high. Reeve (1963a, 1963b, 1963c) and Gilchrist (1960) report that Artemia did not discriminate between Chlorella and Dunaliella in mixed algal cultures. Reeve's studies show that the filtration rate -- the number of phytoplankton cells filtered per unit time -- decreases as the algal cell concentration increases, and a constant maximum ingestion rate is attained. This maximum ingestion rate is also inversely related to algal cell size. The maximum efficiency of growth was at a salinity of 35 o/oo with 25 - 30 algal cells per mm^3. The experiments were performed at 30°C with the shrimp in the log phase of growth. The highest efficiency in the weight of animal produced per weight of plant consumed, reported by Reeve, was 79% at these fairly low algal cell concentrations.

Reeve also reported that females had a higher feed-conversion ratio than males. Sick (1968) points out that broods produced from organisms feeding on a more nutritious food supply, such as D. salina, contain higher percentages of females than broods from organisms grazing on less nutritious algae.

Food-conversion efficiency was studied by Mason (1963) by measuring the dry-weight gain of Artemia divided by the dry weight of consumed algae. Independent measurements were made comparing C_{14} uptake in Artemia with that lost from the medium. His values range between 9 and 20 percent. Sushchenya (1962, 1964) reports similar values, while Gibor (1956a) and Reeve (1963d) recorded higher efficiencies. Gibor found 53% efficiencies by measuring wet weight of shrimp gain, compared to wet weight of algae fed. The shrimp nauplii gazed on Dunaliella viridis. The efficiencies measured by Reeve ranged from 0 to 79%, depending on temperature, salinity, and the age of the shrimp culture. He concluded that under appropriate cultural conditions an efficiency of 50% could be maintained for the conversion of plant to animal tissue. Fujinaga (1969) calculated productivities of 50 grams of Artemia per ton of water per day.

Ideal conditions for the growth of Artemia may be maintained in saline lakes by adjusting the salinity and nutrient content of the water to select for a monospecific microalgal culture of appropriately sized (6-15μ) cells, and a substrate population density of 20,000 - 100,000 cells/ml. At appropriate salt concentrations other herbivores such as rotifers, protozoans, and cladocerans, which would compete for the algae, can also be excluded.

The only known diseases of Artemia are due to certain parasites such as the larvae of the tapeworm of the seagull (this cestode is probably Cysticorcus) reported by Heldt (1926) and Young (1952), and a yeast, Metschnikowia kamiensku, reported by Kamienski (1899) and Spencer et al (1964). Bowen (personal communication) believes a spirochete may also be a parasite on Artemia.

Although extremely euryplastic, certain chemical environments have been demonstrated to retard growth and/or increase mortality. Artemia do occur in high-carbonate (12,125 mg CO^3/l) lakes, e.g., Mono Lake, California (Dunn, 1953), although high concentrations of CO_3^- and HCO_3^- were shown to be lethal to them (Col and Brown, 1967). This is believed to be a result of the narcotic effects of bicarbonate. Croghan (1958a) and Boone and Baas-Becking (1931) discussed the problem of potassium toxicity. These papers stated that concentrations of potassium greater than 100 mM/l are lethal to Artemia unless the Na/K ratio is at least ten. Gilchrist (1954, 1956, 1958) and Dutrieu (1960) showed that a lack of O_2 strongly impedes growth of A. salina. Since O_2 consumption in crustaceans is a function of body surface area, growth of the larger females is more retarded by alck of O_2 than that of the smaller males. Mathias (1934) observed that gravid females survive for only short times in O_2-impoverished water. Dutrieu and Crista-Branchome (1966) stated that adequate O_2 is critical during the emerging phase, and should be greater than 3 ml/l, though adults have less stringent respiratory requirements.

Artemia are not known to be toxic and both the nauplii and adults have been fed to fish and shellfish for many years. Reports of pesticide accumulation in Utah brine shrimps and their adverse effect upon the nutrition of larval organisms have come from several sources (Grosch, 1967; Ehrlich, 1968; Bookhout and Costlow, 1970), but this is an environmental pollution effect, and is not inherent in Artemia. In an analysis for pesticides in Artemia reported by Bookhout and Costlow (loc cit) brine shrimp nauplii from California contained 2,300 ppb DDT while those from Utah had 7,050 ppb DDT. Artemia nauplii also accumulate copper when grown in aquaria treated with copper. Herald and Dempster (1965) reported that toxic symptoms appeared in fish that were fed brine shrimp from these aquaria.

Pesticide accumulation in Artemia continues to be a problem of great concern among aquaculturalists attempting to rear organisms through delicate larval stages. As recently as July 17, 1972, Dr. M. Fujiya, Director, Nansei Regional Fisheries Research Laboratory, reported that eggs of Artemia salina from both San Francisco Bay and Salt Lake contained significant quantities of DDT which he stated was apparently responsible for the poor growth of fish in controlled experiments. On July 21, 1972, the presence of DDT in Artemia eggs was further verified by Dr. K. Shigueno, Director of the Fisheries Research Station at Kagoshima City, Japan, who determined the level of contamination to be 0.2 ppm (Cordover, personal communication). It is reasonable to assume that Christmas Island is remote from the major sources of DDT contamination and the levels in Artemia might be expected to be minimal.

Potential as a Culture Organism

The highly specialized adaptation of the osmo-regulation mechanism of Artemia, which enables them to tolerate, grow, and reproduce in an environment that is hostile to most other animals, suggests that a rare opportunity exists for culturing this organism without the costly need to control predation and competition from other forms that would intrude on the cultural environment in normal sea water. Adaption to an extremely wide range of salinities (euryhaline tolerance) is not the only characteristic of Artemia that makes it attractive as an animal for husbandry. The reproductive cycle of Artemia is very well suited to a cultural system.

Artemia are uniquely suited to aquaculture because they reach maturity within two weeks (Gilchrist, 1960; von Hentig, 1972) and reproduce continuously [up to 200 nauplii every five days or less (Webber, 1969)] during their life span of six months to one year. Artemia gain weight rapidly and, being herbivores, nourish themselves entirely from algae (phytoplankton) which can be cheaply supplied. Furthermore, Artemia larvae demonstrate food habits which demand no unique or special requirements. Their fecundity is unimpaired by confinement or crowding, and their eggs and larvae are hardy and readily respond to manipulations controlling their production. They are resistant to extremes of temperature (9°C - 35°C) and salinity (5 o/oo - 150 o/oo) and their life history is well known. Ideally, Artemia can be cultured at controlled salinities where the ecosystem consists primarily of the brine shrimp and one predominant phytoplankton species. In summary, Artemia successfully satisfies the criteria for an aquaculture organism proposed by Bardach et al (1972).

Present production of brine shrimp and their eggs comes from the harvest of wild populations upon which little or no management has been imposed. There are indications that with proper management a continuous high yield of both brine shrimp and their eggs might be expected. Under relatively uncontrolled conditions, Rakowicz (unpublished) attained a production of 3,000 gallons of brine shrimp eggs from one 284-hectare (700-acre) salt lake in San Francisco Bay in a four-month period in 1964. Production of brine shrimp eggs to this extent in the salt lakes of San Francisco Bay is a rare occurrence. Little effort is made to control or produce Artemia in San Francisco Bay. Instead, water-systems management is directed towards salt production, and brine shrimp are simply a by-product of the operation. Production of salt requires water management that may be unfavorable to Artemia production. High production of brine shrimp and their eggs in the San Francisco Bay lakes comes at unpredictable times when conditions are accidentally suitable.

Management of saline lakes for the production of brine shrimp has been studied by Rakowicz (unpublished) in isolated lakes and miniature systems. The results of these studies indicate a high probability of success for Artemia culture on Christmas Atoll. Land values near populated areas have been a deterrent to developing such a system of salt lakes in the United States, where the cost of constructing an Artemia lake production system would be substantial. Favorable sites anywhere in the world are most limited, for the climate should be tropical or subtropical, with low average rainfall, and the sites should be adjacent to the sea.

The unique physiography of Christmas Atoll -- a large, low-lying island with numerous chains of shallow saline lakes, situated in a tropical area of low rainfall -- makes this site most suitable for the production of Artemia. Disadvantages of Christmas Atoll are its remoteness from markets and the low nutrient level of the lagoon and lagoon lakes.

A key factor in producing suitable brine shrimp eggs is that they be free of pesticides. As previously discussed, various persistent chemicals in the chlorinated-hydro-carbon category -- the most notable being DDT -- are retained in brine shrimp eggs, and the nauplii after hatching can be lethal in quantity to aquatic animals which feed on them. Christmas Atoll could become a major source of Artemia free of harmful pesticides. The atoll has little agriculture aside from the coconut plantations, and therefore should remain relatively uncontaminated.

Market Potential

In 1947 Alvin Seale of the Steinhart Aquarium, San Francisco, discovered that the encysted form of brine shrimp (referred to as "eggs" but actually a blastula stage of development) will remain viable for at least ten years when stored in a dry and cool place, and will hatch in salt water. Since then the eggs have been collected in large quantities from their natural environments, and marketed commercially throughout the world as a convenient source of constant live food for aquarium fishes (Dees, 1961). Live Artemia are seined from the salt evaporation ponds of Leslie Salt Company, adjacent to San Francisco Bay, and frozen for shipment to pet shops all over the world (Jenne, 1960). There is also a sizeable market for live brine shrimp which are air-shipped from the San Francisco Bay source, as well as for whole freeze-dried, and a dry, flaked Artemia product (Fishman, personal communication).

In addition to fulfilling this market of fish hobbyists, Artemia are presently utilized in aquaculture as food for a variety of organisms including crabs, penaeid shrimps, and fish. Brine shrimp eggs now command a high price for fisheries use in the U.S.A., Europe, and

Japan in culturing prawns, estuarine fishes, etc, and in the aquarium trade for tropical fishes. As world aquaculture expands, it is expected that the supply of high-quality Artemia eggs, now periodically inadequate, will more frequently be unavailable in sufficient quantity to meet the demand. In the future Artemia may also be used to harvest single-celled algae which have grown on sewage or agricultural wastes, thus converting these algae to animal protein of greater nutritional value. Dried brine shrimp might be used as an alternative to the fishmeal presently utilized in the diet of people in the developing countries, and for animal feed.

Estimated annual sales of Artemia eggs in the United States, Japan, and Europe amount to an excess of 14,000 gallons. About 90% of the total is used in the production of tropical fish for aquarium hobbyists. The entire annual harvest of good-quality brine shrimp eggs is normally sold out each year. The present retail price of approximately $50 (U.S.) per gallon, largely determined by the supply, is the limiting factor preventing a more widespread use of Artemia eggs. The production of a pesticide-free Artemia egg in quantity would open additional markets. A cost reduction that would allow the sale of brine shrimp eggs at a lower price, coupled with a rapidly expanding market among aquarium hobbyists, could easily expand sales further to 50,000 gallons or more per year.

Shrimp enjoy almost universal popularity as food, and in an economic sense the limited availability of natural stocks greatly increases their aquaculture potential. Despite steadily rising prices, shrimp consumption in the U.S. has reached a million pounds per day. In addition to playing a key role in the culture of penaeid shrimp, Artemia per se, although small in size, possess both the flavor and high protein content necessary for the development of an edible shrimp product. Preliminary analyses conducted by Brick (unpublished data) at the Hawaii Institute of Marine Biology indicate a protein level as high as 62.78%. (See Table 4.)

Unlike other crustaceans used for man's consumption, Artemia may be used as intact animals without the necessity of removing the exoskeleton as is the case for other shrimps, lobsters, and crabs. The exoskeleton or shell of brine shrimp is only about one micron (1/1000 mm) thick and is so delicate as to be undetectable when eaten. The elimination of peeling and offal disposal should reduce processing costs significantly.

Heresay reports that Artemia have been used as human food by the American Indians, and Delga et al (1960) reports that Artemia are eaten by the people of Libya. Several oriental recipes using whole brine shrimp received very favorable evaluations in taste tests conducted in Hawaii. Finally, live Artemia are being investigated as a possible live bait for certain tuna fisheries.

TABLE 4. COMPOSITION OF ARTEMIA SALINA

Stage/Age	Protein, % (Nx6.25)	Fat, % (ether extract)	Calories/g (ash-free)	Reference
Egg ⊛	52.31	26.06	---	Brick (HIMB), unpublished
Nauplius				
2 hrs ⊛	50.21	15.92	---	Brick (HIMB), unpublished
few hrs	42.50 *	23.20	6600	Dutrieu, 1960
few hrs	----	15.04	5800	Khmeleva, 1968
day 1	50.00	27.24	5896	Coehn (Scripps), unpublished
"Juvenile"				
day 6 ⊛	59.72	7.60	---	Brick (HIMB), unpublished
Adult				
day 10 ⊛	62.78	6.51	---	Brick (HIMB), unpublished

* Based on protein N only.

⊛ Based on San Francisco Bay material.

FIELD AND LABORATORY STUDIES

The maintenance of phytoplankton populations to provide food for Artemia is basic to any brine shrimp culture scheme. Therefore several facets of algal productivity were investigated. These phytoplankton studies at Christmas Island consisted of (1) a broad survey to determine the in situ concentrations of the major essential plant nutrients (nitrogen and phosphorus) in the lakes and lagoons; (2) quantification of the range and characteristics of phytoplankton biomass and productivity, with special emphasis on the F lakes; (3) nutrient enrichment experiments on several types of Christmas Island water to identify potentially limiting nutrients as well as to determine the resultant growth response of the phytoplankton to enrichment with these nutrients; and (4) groundwater nutrient measurements to investigate the feasibility of utilizing these waters as the supplementary nutrient source needed to sustain the high phytoplankton productivity required for a large Artemia yield. In addition, hatching experiments were conducted to determine if the waters of the F lakes would support normal hatching of Artemia eggs.

To describe accurately the grazing kinetics, growth dynamics, and egg production of Artemia salina, it was necessary to culture these crustaceans in a closed system, providing them with a constant non-limiting food supply. This was accomplished through the use of a modified chemostat system in the laboratory of the Hawaii Institute of Marine Biology at Coconut Island, Oahu.

Methods and Materials

Field Studies

Chlorophyll determinations were carried out by the fluorometric method (Strickland and Parsons, 1968) using a Turner Fluorometer Model 111 fitted with a high-sensitivity door. Fluorometer readings were converted directly to Chlorophyll a concentrations by a previous calibration of the instrument used. Primary productivity was estimated by the C-14 technique (Strickland and Parsons, 1968). Water from some of the Christmas Island lakes was extremely difficult to filter due to large concentrations of organic matter. To minimize errors due to incomplete filtration, water samples (from the surface) were taken in small-volume glass BOD bottles (150-ml capacity). One light and one dark bottle were filled at each station and transported to the incubation site at the Sailing Club boathouse where each was inoculated with labeled sodium bicarbonate (1 µCi/2 ml) and suspended at a depth of 0.3 - 0.5 meters in lagoon water with string from a horizontal line strung between two posts. The samples were exposed to full sunlight and incubation times were usually six hours, from 1000 hour to 1600 hour. Upon completion of the incubation period, the bottles were removed from the line and the contents immediately filtered through 25-mm Millipore HA filters, which were then rinsed with filtered sea water, glued to copper planchettes, and stored in a dessicator for later analysis. The activity of the filters was determined by using a Nuclear Chicago Gas-Flow Geiger Counter (Model 1042) with a Micromil ® end-window. The counter was calibrated by the liquid scintillation method of Wolfe and Schelske (1967). Determinations of total alkalinity were done according to the method of Strickland and Parsons (1968). Salinity was determined with an American Optical refractometer. Water samples for nutrient analysis were taken in polyethylene bottles and frozen until they could be analysed at the Hawaii Institute of Marine Biology. Ammonia measurements were determined by the method of Solorzano (1969), while nitrate and phosphate concentrations were determined by the procedures outlined in Strickland and Parsons (1968).

In the absence of grazing organisms, phytoplankton growth rate is typically regulated by three environmental parameters in the natural marine environment. These parameters are (1) light intensity, (2) temperature, and (3) plant nutrient concentrations -- any one of which may limit phytoplankton growth. Because of the constant high light intensity and high ambient temperatures in the shallow-water environment at Christmas Island, it is assumed that phytoplankton growth is regulated (or limited) by the availability of essential nutrients. The purpose of the nutrient enrichment experiments was to identify which class of nutrients (i.e., major nutrients, trace metals, or vitamins) was potentially limiting the phytoplankton growth response.

The nutrient enrichment experiments were carried out using two water samples from the group C lakes (F2 and F4) and one sample from the isolated group D lakes (16a) (Figure 24). The lakes were grouped according to their salinity gradient zones at Christmas Island which relate to their proximity to the open ocean (Figure 21). Because only one nutrient at any time can be limiting phytoplankton growth, selective addition of the essential nutrients to water samples and measurements of the resultant growth response yield a reliable qualitative determination of the limiting nutrient.

Water was collected on the first day of the November, 1971, survey and was divided into four sub-samples: (1) a control with no nutrient enrichment; (2) a sample with total enrichment: nitrate, phosphate, silicate, trace metals, and vitamins (referred to as "AM medium"); (3) a sample with phosphate and nitrate additions only; and (4) a sample with trace metal addition only. AM medium (Antia and Kalmakoff, 1965) was used in half strength as the enrichment source, but still contained concentrations of nutrients in excess of phytoplankton requirements. The samples were incubated in lagoon water at ambient temperature and light at the Sailing Club boathouse in 20-liter carboys for 12 days. Daily biomass measurements were made with the fluorometer to determine the growth response. Carboy 1-F2, a control, was accidentally destroyed on the third day and hence no further measurements were made on this sample.

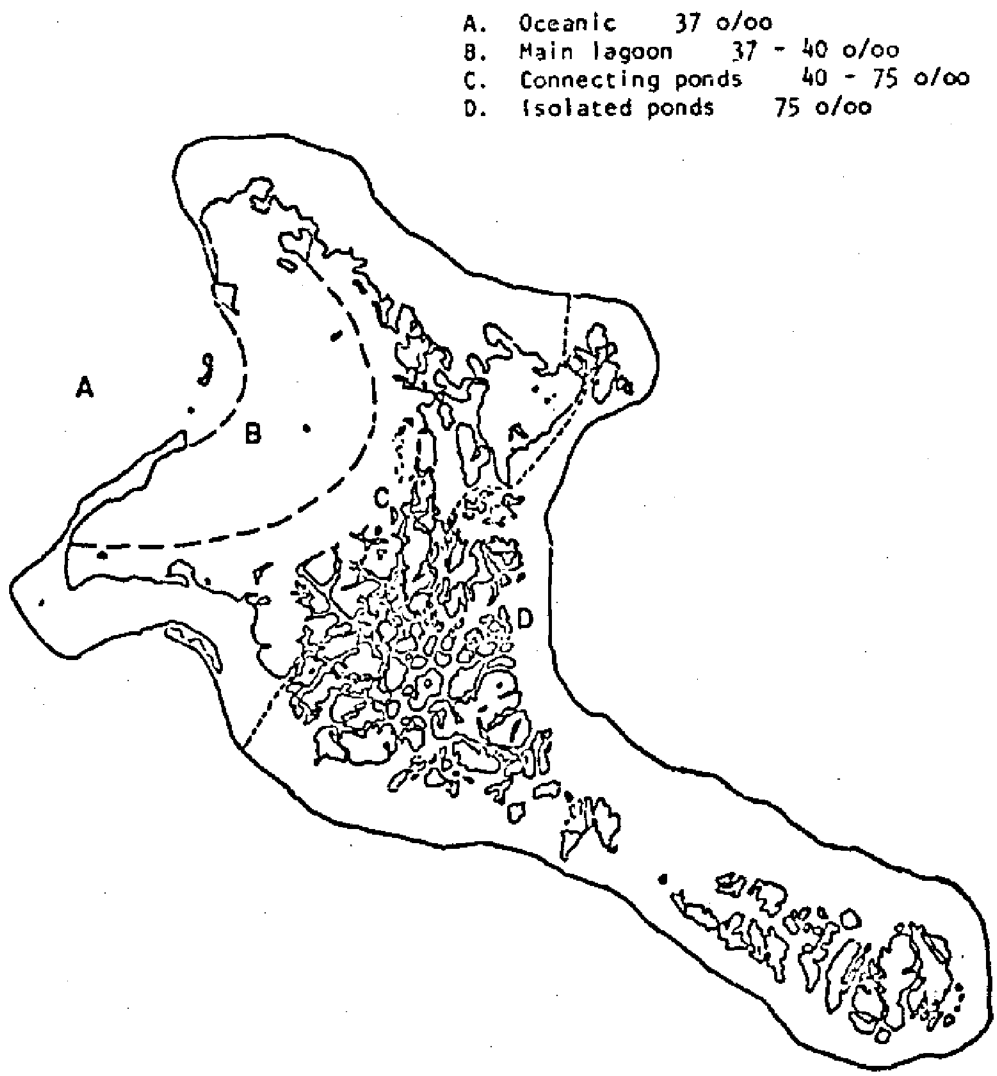

FIGURE 24. Group designations of salinity gradient zones at Christmas Island which relate to their proximity to the open ocean.

Hatching experiments were carried out on water collected from each of the F Lakes The water was placed in pans exposed to full sunlight and the hatch was reported as "good" or "poor", since there was no suitable means available to quantify the results.

Laboratory Studies

The chemostat used in laboratory studies in Hawaii is a double-walled reaction chamber which allows for the continuous culture of phytoplankton under constant light, temperature, and nutrient conditions. The upper portion is equipped with a series of three ports: one for air input and sampling, one second for medium input, and the last one for solution overflow. The medium, containing known concentrations of the essential nutrients, is fed into the chemostat from a pair of sterile, 20-liter nutrient reservoirs, via a peristaltic pump. A sterile-filtered carbonate-saturated air supply is bubbled through the system to insure the availability of bicarbonate for photosynthesis, and to facilitate adequate mixing (Plate 41).

At a given rate of nutrient supply, i.e., a given pumping rate from the medium reservoirs, the phytoplankton population eventually reaches a steady state in which the number of cells being produced is equal to the number expelled via the overflow. This usually took four to seven days under the conditions imposed for these experiments.

The overflow, containing the phytoplankton cells, was collected in a small-volume secondary reservoir connected to a multi-channel peristaltic pump which provided a constant and uniform distribution of food to a series of herbivore flasks. Thus, Artemia in each flask grew under identical food regimes while other parameters (i.e., salinity) were altered.

Filtered water of known salinity was introduced into the herbivore flasks from the corresponding salinity reservoirs via a third peristaltic pump. This system of separate slainity reservoirs made it possible to impose a spectrum of salinity regimes while maintaining constant food conditions.

The Artemia flasks consisted of 2.8-liter containers, each with 1.5 liters of solution. The stoppered flasks were fitted with an air supply and ports for sampling, input, and overflow. The flasks were gently agitated on a shaker table to prevent the phytoplankton from settling, thereby insuring their availability to the filter-feeding Artemia (Plate 42).

The concentration of phytoplankton in the chemostat, the input chamber, and the herbivore flasks was determined daily, using a Celloscope particle counter or a Model A Coulter Counter. Chlorophyll determinations were accomplished by the glass filter technique described in Strickland and Parsons (1968). Phosphate concentrations were determined by the phosphomolybdate technique (Strickland and Parsons, 1968).

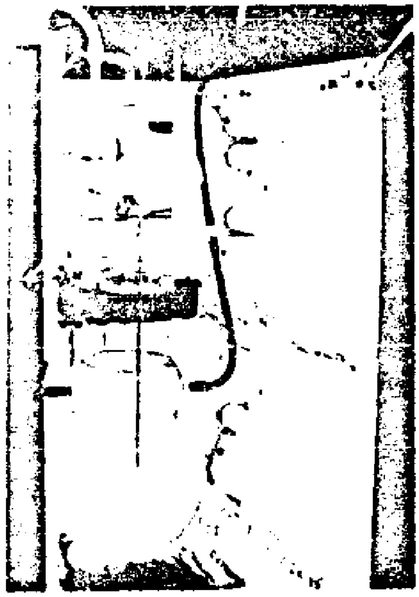

Plate 41. Chemostat apparatus used for the steady-state culture of phytoplankton. Media is added continuously by a peristaltic pump (right), is mixed by a stirrer and the air input (left), and is forced out (center) into the secondary reservoir.

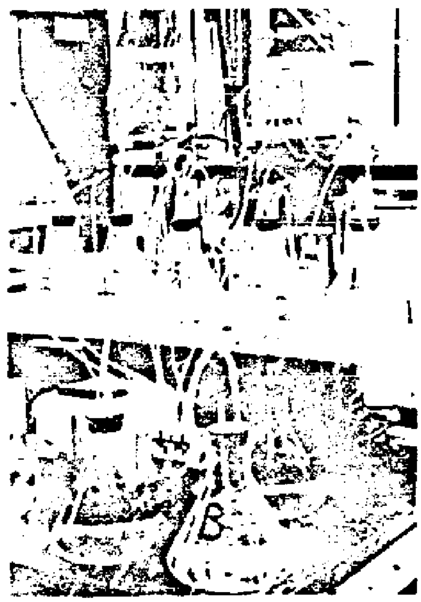

Plate 42. From the reservoir the phytoplankton-rich solution is transferred through small diameter tubing to the herbivore flasks.

Nauplii carbon budgets were compiled using the gas chromatographic analysis with an F & M Scientific 185B Carbon Hydrogen Nitrogen Analyser.

Results

Field Study Results

Since the marine waters associated with Christmas Island show a wide range in salinity, a function of circulation and evaporation, the study area was divided into four groups based upon these salinity characteristics for convenience of analysis. These groups include: (a) ocean stations with the lowest salinity values; (b) main lagoon stations with a salinity range of 37 - 40 o/oo; (c) lagoon-connecting lakes with a salinity range of 40 - 75 o/oo; and (d) completely isolated lakes with a salinity range of 78 o/oo to super-saturation (Table 5 and Figure 24).

Phytoplankton require nitrogen and phosphorus roughly in a ratio of 16:1 (N:P) by atoms. Thus, a consideration of the available environmental nitrogen and phosphorus in terms of ratios can give some insight as to which nutrient might <u>potentially</u> limit phytoplankton growth. Open-ocean samples at Christmas Island showed a phosphate concentration of 0.96 ug-at/l. The resulting N:P ratio of 8:1 is about half that required by phytoplankton. In this case, however, the relatively high *in situ* concentrations of nitrogen indicate that phytoplankton growth in this area is not limited by this element. Excluding the sample from station MLF in which the phosphate concentration was 100 times that at the other stations, the N:P ratio (3:9) again reflects a reduced ratio in the natural environment, but high N values preclude its being the limiting factor. Low N:P ratios prevailed for group C and D lakes. A complete correlation analysis of these data revealed only three significant relationships: (1) nitrate concentration had a significant positive correlation with salinity at the 1% probability level ($r = .62$; d.f. = 23) throughout the system; (2) phosphate concentration had a significant positive correlation with salinity at the 1% probability level ($r = .66$; d.f. = 14) for groups A, B, and C; and (3) chlorophyll *a* concentration had a significant negative correlation with salinity in the isolated lakes (the D series) at the 1% P level ($r = -.51$; d.f. = 23).

The general lack of correlation (e.g., nutrients with chlorophyll, nutrients with productivity) between the measured parameters can probably be ascribed to the complex physical attributes of the atoll. Under normal conditions, one would expect a direct empirical relationship between the rate of nutrient input and the phytoplankton productivity. Water transport through the lagoon-connecting lake system (and even within the main lagoon to a lesser extent) appears to be extremely slow, as evidenced by the general increase in salinity due to evaporation. The prolonged residence times during which this water remains separated from ocean circulation probably magnify the influence of localized phenomena such as nutrient input from groundwater and the input of excreta from large colonies of birds present on the island.

TABLE 5. SALINITY, NUTRIENTS, CONCENTRATIONS OF CHLOROPHYLL a PIGMENT, AND PRODUCTIVITY AT SELECTED STATIONS ON CHRISTMAS ISLAND, MEASURED IN NOVEMBER, 1971

Salinity Groups A, B, C, and D are shown in Figure 24. Productivity index or assimilation ratio reflects the suitability of the environment for phytoplankton growth.

Station Sample	Day	Salinity, Group and o/oo	Nutrient Concentrations, µg-at/liter PO_4-P	NO_2+NO_3-N	NH_4-N	Chlorophyll a, mg/m^3	Productivity, mg C fixed/m^3/hr	Productivity Index, mg C fixed / mg chl. a/hr
		GROUP A						
00	10	34.0	0.96	4.67	3.03	0.33	2.62	7.94
		GROUP B						
MLC	10	37.0	0.033	0.08	0.22	1.15	17.72	15.41
MLB	10	39.0	0.014	0	1.00	0.50	1.94	3.88
MLA	10	39.5	0.019	0.34	0.95	0.46	4.81	10.45
MLF	6	40.0	9.01	0.33	3.65	0.19	1.54	8.11
Mean		38.9	2.27	0.19	1.46	0.58	6.51	9.46
		GROUP C						
AL	5	42.0	--	--	--	0.56	6.07	10.84
1a	3	43.0	0.057	0	0.52	0.49	3.17	6.47
B2	5	43.0	0.019	0	0.87	0.55	4.65	8.45
A1	7	43.5	--	--	--	0.66	4.34	6.58
B5	5	47.5	0.001	0.13	0.30	0.35	5.14	14.69
F1	3	48.0	0.019	1.16	0.[illegible]0	0.18	0.78	4.36
J	6	48.0	3.14	0.24	3.09	0.14	0.39	2.79
F3	3	52.0	0	0	0.75	0.14	1.08	7.68
12	7	52.0	3.13	0	1.13	0.07	0.23	3.29
21	11	55.5	0.13	0.03	1.25	0.14	0.33	2.36
14	7	56.0	1.82	0	1.2[illegible]	0.13	0.61	4.69
F5	2	58.0	15.06	0	4.13	0.25	0.55	2.19
F6	2	74.5	17.92	0	4.24	0.3[illegible]	1.88	6.06
Mean		51.0	3.75	0.14	1.63	0.31	2.25	6.19
		GROUP D						
F7	11	101	--	--	--	0.62	2.98	4.83
37	6	105.5	2.47	0.01	1.05	0.49	*	0
19a	4	245 est.	0	5.53	2.77	0.04	5.48	137.00
16a	2	255 est.	5.07	14.68	6.36	0.02	0.77	38.50
28a	4	265 est.	0	2.30	1.50	0.04	1.89	47.25
27a	4	off scale	0	2.34	1.16	0.03	*	
Mean		175	1.27	4.49	2.56	0.25	2.10	[illegible]9.05

* Dark count exceeds light count, indicating zero productivity.

-- Determination not made.

Thus, it is meaningless to consider these measured parameters on an average phosphate concentration in group B and C (Table 5) because of extreme values such as those at the jetty and at SPAL (MLF), F5, and F6. Likewise, the wide range of nitrogen concentrations in the isolated lakes (group D) precludes any generalizations regarding "typical" nutrient characteristics. Much less variability was found in phytoplankton biomass, as expressed in chlorophyll a concentration, and productivity characteristics in group A, B, and C. The productivity data obtained from the isolated high-salinity lakes are unreliable due to the apparent precipitation of the radioactive sodium bicarbonate solution at these high salinities.

The phytoplankton biomass is typically low throughout the lagoon system (A, B, C) and the associated primary production is less than one would expect in a eutrophic nearshore, low-latitude environment (Caperon et al, 1971; Krasnick and Caperon, in press). These low biomass levels could be the result of the harsh environment caused by high salinity. Not only are few species capable of growth and reproduction at such salinities, but those able to survive are forced to divert copious energy expenditures from growth to osmo-regulation, with a concomitant suppression of the standing stock. Such is not the case with Dunaliella salina, an alga that thrives in high salinities if nutrients are available and serves as a suitable food for Artemia (Gibor, 1956b). Another possible explanation for the observed low biomass levels is grazing pressure. In a nutrient-limited system phytoplankton may be grazed as rapidly as they are produced.

The inference is that no one area at Christmas Island (of those investigated) has any particular advantage for intensive Artemia culture over any other area in terms of existing food substrate concentrations and supply rate. These data also indicate that without enriching the Christmas Island waters there is presently insufficient phytoplankton productivity potential to support the proposed Artemia culture scheme.

The enrichment experiments were carried out to determine which, if any, nutrient species were limiting phytoplankton productivity at Christmas Island. The results of this experiment are presented in Figures 25 and 26 and Tables 6 and 7. No significant growth response was recorded in the non-enriched controls (series 1) (Table 6). A significant growth response, however, was noted in both of the F lakes (group C) enriched with total growth medium, and a less marked increase in those enriched with only nitrate and phosphate. While some variability is evident in the growth rate response (the total enrichment response being higher in both cases than the nitrate-phosphate enrichment), the results indicate that phytoplankton growth in the F lakes is limited by nitrogen or phosphorus and can be significantly increased by the addition of only nitrogen and phosphorus.

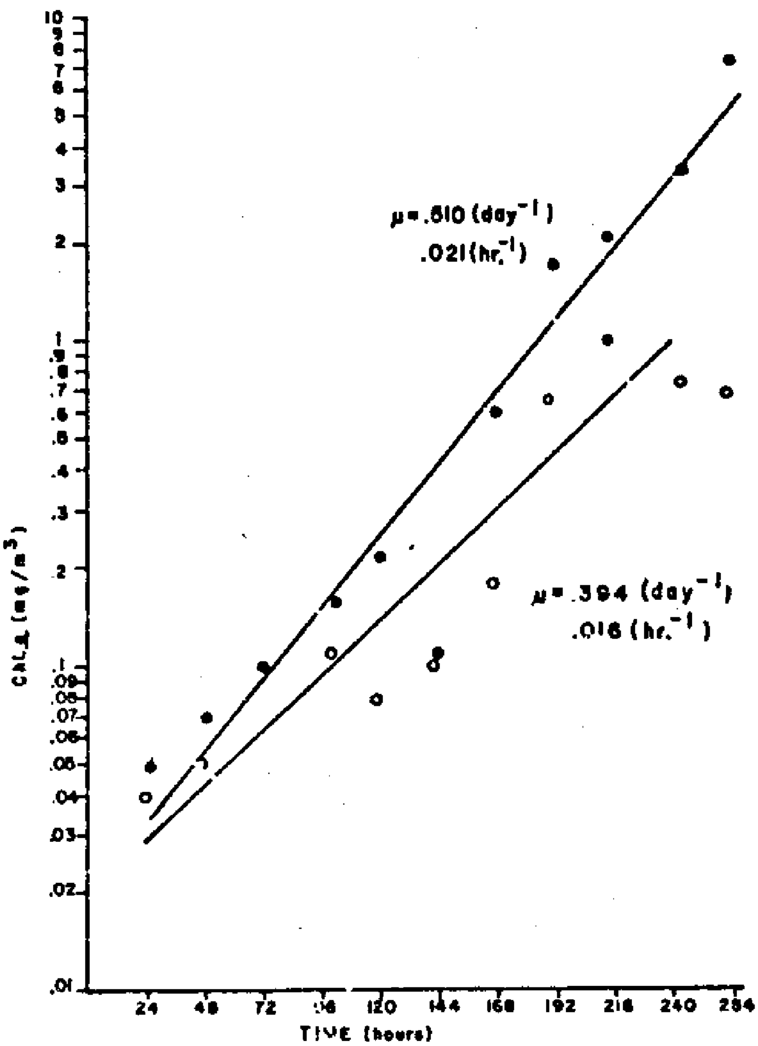

FIGURE 25. Phytoplankton growth response in lake F2 water incubated with phosphate and nitrate additions (o) and total enrichment medium (•) at ambient temperature and light at the Christmas Island Sailing Club Boathouse.

μ = mean growth rate measured in mg of Chlorophyll a m^{-3} t^{-1}.

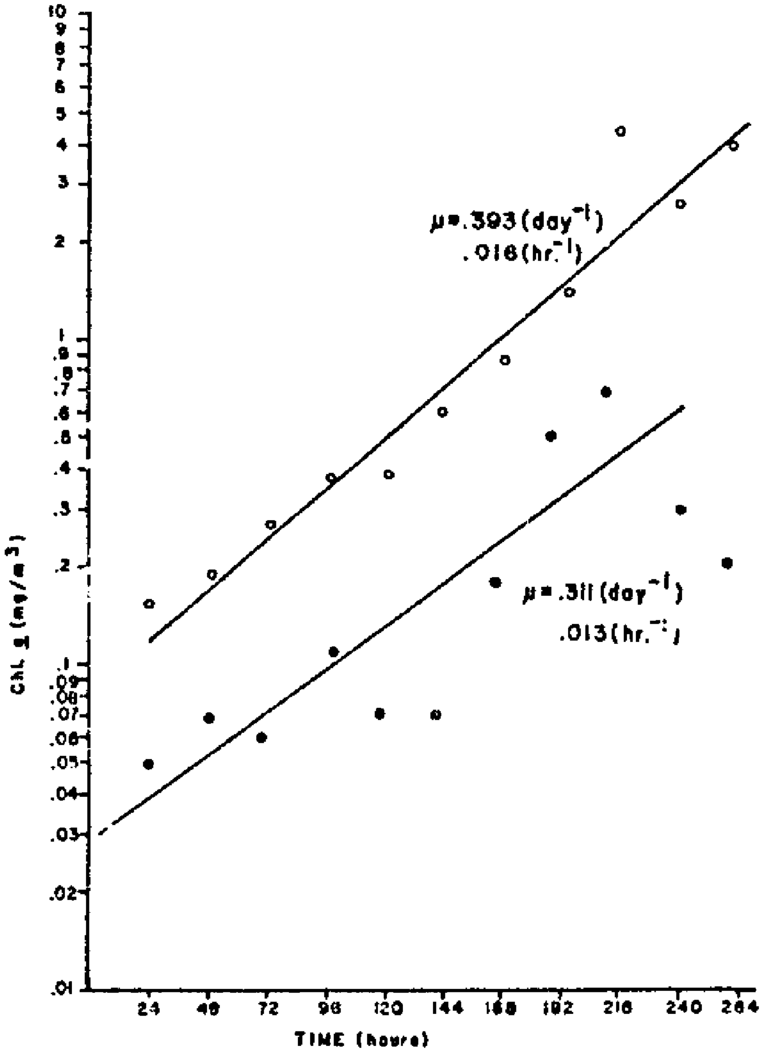

FIGURE 26. Phytoplankton growth response in lake F water incubated with phosphate and nitrate additions (●) and total enrichment medium (o) at ambient temperature and light at the Christmas Island Sailing Club Boathouse.

= mean growth rate measured in mg of Chlorophyll a m^{-3} t^{-1}.

TABLE 6. FIELD ENRICHMENT EXPERIMENTS FOR 12 SAMPLES FROM CHRISTMAS ISLAND LAKES

Incubation at ambient temperatures at the Sailing Club boathouse. Experiment initiated on November 5, 1971, at 1200 hours.

Time, hours	Chlorophyll a Production, mg/m³, under Four Enrichment Conditions											
	Control (No Nutrient Enrichment)			Total Enrichment			Phosphate and Nitrate Only			Trace Metal Only		
	1-F4	1-F2	1-16a*	2-F4	2-F2	2-16a*	3-F4	3-F2	3-16a*	4-F4	4-F2	4-16a*
0	.09	.06	.05	.13	.08	.04	.11	.06	.04	.12	.06	.04
24	.15	.06	.03	.14	.05	.02	.05	.04	.03	.06	.03	.05
47	.07	.08	.04	.18	.07	.02	.07	.05	.03	.03	.02	.04
70	.07	-	.04	.24	.10	.03	.06	.06	.04	.03	.03	.04
100	.10	-	.06	.39	.16	.0[illegible]	.11	.12	.07	.09	.09	.06
118	.06	-	.04	.39	.22	.03	.07	.08	.04	.05	.03	.05
141	.06	-	.04	.61	.11	04	.07	.10	.05	.05	.05	.04
166	.05	-	.05	.96	.61	.04	.18	.18	.05	.05	.05	.05
189	.08	-	.04	1.56	1.72	.04	.51	.71	.06	.06	.06	.05
212	.08	-	.04	4.80	2.32	.04	.70	1.07	.11	.06	.06	.04
243	.03	-	.03	3.17	3.47	.04	.30	.79	.06	.04	.02	.02
261	.06	-	.04	4.75	7.56	.05	.21	.70	.07	.04	.04	.04
285	.10	-	.06	9.96	8.58	.05	.21	.98	.07	-	-	-

* 16 a is an isolated hypersaline lake fed by an active low-salinity spring. It contained phytoplankton, but the low productivity is attributed to the high salinity, which was measured from 180 o/oo to greater than 230 o/oo except in the springs.

TABLE 7. RESULTS OF AN ENRICHMENT EXPERIMENT UTILIZING LAKE WATER FROM TWO LOCATIONS ON CHRISTMAS ISLAND

Samples were incubated at ambient temperatures in the Christmas Island lagoon at the Sailing Club boathouse. (See text for method.)

Date	Source of Water	Flask Number*	Chlorophyll *a*, mg/m^3	Productivity, $\frac{mg\ C\ fixed}{m^3/hr}$	Productivity Index, $\frac{mg\ C\ fixed}{mg\ Chl.\ a/hr}$
11/5	F4	1	.09	0.70	7.78
11/10	F4	2	.39	4.07	10.43
11/14	F4	3	.70	6.37	9.10
11/10	F2	2	.22	1.90	8.64
11/14	F2	3	1.07	14.02	13.09
11/16	F2	4	.02	0.14	7.00

* Flask #1 - Control with no nutrient enrichment

Flask #2 - Total enrichment (nitrate, phosphate, trace metals and vitamins).

Flask #3 - Phosphate and nitrate additions only.

Flask #4 - Trace metal addition only.

Microscopic examination of these samples revealed that diatoms tended to be more prevalent in the total enrichment experiments, while Cryptomonas sp., a small flagellate, and a coccochlorid-like blue-green alga were predominant in the nitrogen-phosphorus enriched samples. It is surmised that the total enrichment medium provided a nutrient required specifically by diatoms, most likely silica, which resulted in the faster growth-rate response and higher final yield of the total enrichment samples. Since diatoms, having a siliceous exoskeleton, are often passed through grazers' intestinal tracts undigested, their culture for aquaculture purposes is not particularly provident.

The use of commercial fertilizers to stimulate phytoplankton growth at Christmas Island presents some obvious cost and logistic problems, and the possibility of using groundwater as the primary enrichment source was therefore investigated. Water lying beneath the ground at Christmas Island has been reported to contain significant quantities of nitrogen and phosphorus (Jenkin and Foale, 1968) at least in the upper freshwater lens. Preliminary drilling was carried out in the vicinity of the F lakes to determine if the underground water would serve as a suitable nitrogen and phosphorus enrichment source.

While the specific nitrogen and phosphorus requirements of Christmas Island phytoplankton are not known precisely, yield coefficients calculated from data from Gibor (1956a) indicate that 20 - 30 x 10^6 cells can be produced per μg-at KH_2PO_4. The combined nitrate-ammonia concentrations from the groundwater samples are well above any known phytoplankton growth-rate-limiting concentrations (Caperon, 1972; Eppley et al, 1969). Existing evidence (Fuhs, 1969) suggests that this is also the case for the phosphorus concentrations, but our laboratory studies investigating this were inconclusive.

Preliminary data suggest that groundwater enrichment of the F lakes might provide the required concentrations of nitrogen and phosphorus if sufficient volumes of both were available. There are insufficient data to support a program using groundwater as the sole source of nutrients for this Artemia production scheme at this time. It is recommended that this be explored as a source of nutrients for future production of Artemia and possibly other organisms.

An important consideration for Artemia culture at Christmas Island revolves around the suitability of the indigenous phytoplankton community as a food substrate for Artemia growth. Artemia have been raised through three generations using Dunaliella sp., isolated from Christmas Island, as the sole food source. Experiments carried out to determine the feeding efficiency of Artemia raised on this particular species are discussed below.

Artemia hatching experiments were carried out in water samples from F1 through F7. A good hatch was found in F1 through F5 water (salinities 48 - 58 o/oo) after 48 hours. A poor hatch occurred in F6 water (74 o/oo) after 72 hours and no hatch occurred in F7 water (101.5 o/oo). These field hatching experiments agree with both laboratory experiments and literature evidence which indicate that hatching is reduced in salinities higher than 55 o/oo and will not occur in salinities above 90 o/oo. While the high salinities in F6 and F7 may have affected the hatching response, these waters also contained a mucus-like substance which may have adversely affected hatching.

Laboratory Study Results

Under conditions described in the "Methods" section of this report, Artemia were grown to sexual maturity in periods ranging from seven to ten days at 32 o/oo salinity and a temperature of 26.0°C. This represents a notable reduction in generation time from values reported in the literature which is believed to be caused by (1) constant dilution of toxic waste products which would otherwise inhibit growth, and (2) the physiological state of the phytoplankton used as a food source, i.e., logarithmic-phase growth. The latter facet is important in terms of the "goodness" of the food source because in this phase of growth the biochemical content of the phytoplankton is such that it results in optimal growth conditions in organisms grazing upon it. Both continuous dilution of waste products and a phytoplankton population in the logarithmic-growth phase strongly suggest that a continuous-culture type of aquaculture on Christmas Island would be most provident.

In Figure 27 the growth response of our system is compared with results obtained by other workers using non-food-limited cultures. It should be noted that while the actual growth rate is similar in most cases (except Khmelva), there is a considerable shortening of the initial log phase in our system which results in faster maturation of the Artemia.

Egg production experiments were conducted in which the Artemia were grown to sexual maturity in water of 32 o/oo salinity and then imposing a salinity change to 55 o/oo. If food concentrations remained non-limiting, gravid females which were exposed to such a change expelled eggs after two to three days, though it was noted that the size of the spawn increased if the salinity was raised directly to 90 o/oo rather than by incremental steps of 32 o/oo to 55 o/oo and 55 o/oo to 90 o/oo.

After expelling eggs at 55 o/oo salinity, females became gravid again immediately. If another salinity stress was not imposed, this second brood was produced viviparously, demonstrating the acclimation of the adult female to the 55 o/oo water.

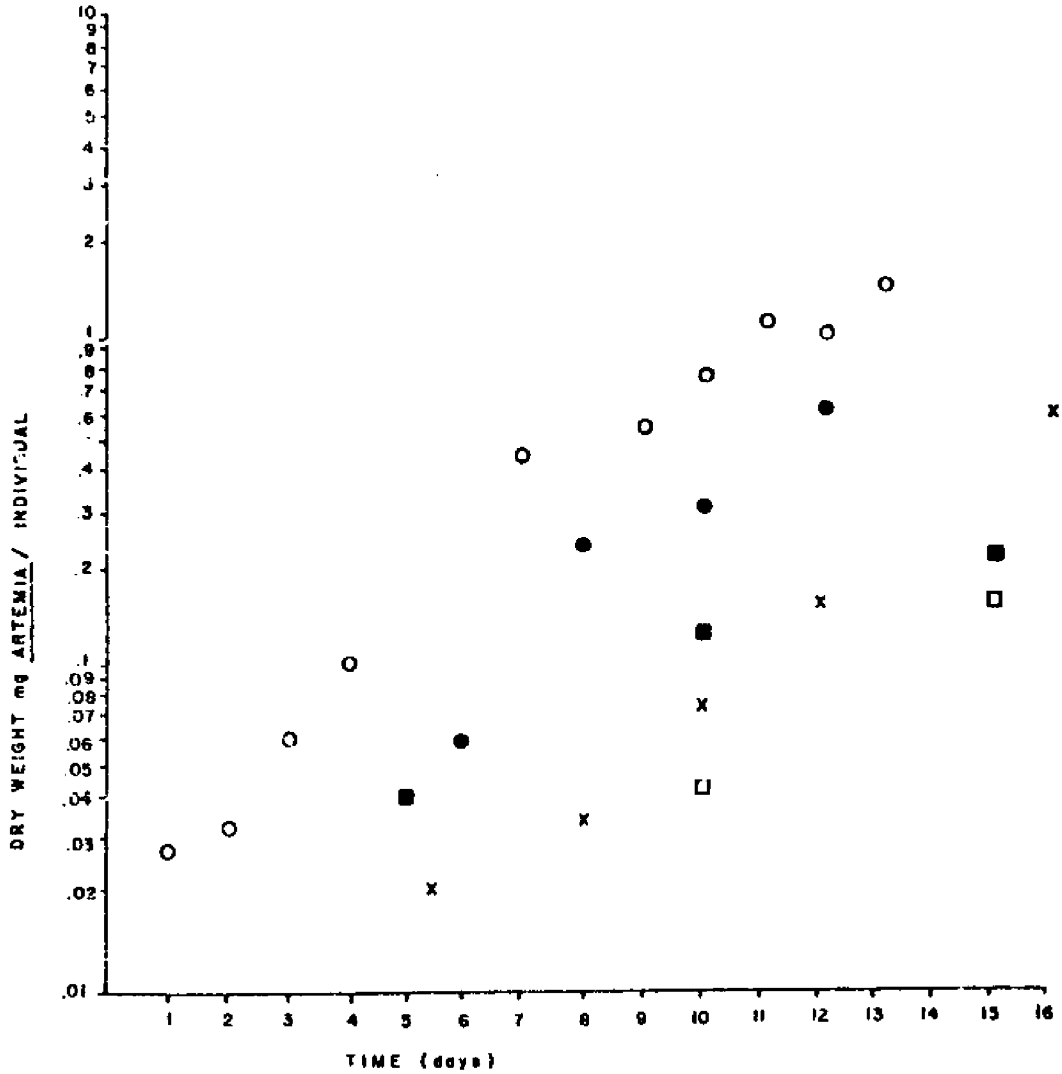

FIGURE 27. Artemia growth curves (mg dry weight per individual vs time) from various investigators, representing a variety of culture conditions.

- O Hawaii Institute of Marine Biology. Continuous culture experiments, 27°C, 6 x 10^4 cells/ml.
- ● Mason, D. (1963). 20°C, 6 x 10^6 cells/day, medium changed daily
- □ Reeve, M. (1963d). 100 cells/mm^3, starved for 3 days after hatching, 20°C, medium changed daily.
- ■ Khmeleva, N. (1968). 25°C, food concentration not given, non-medium data.
- X von Hentig, R. (1971). 20°C, 100 x 10^6 cells/ml, medium completely renewed every 3 days.

Furthermore, it was shown that when the salinity changes occurred over periods as short as 24 hours, the timing of the imposed salinity change became critical in terms of determining ovoviviparous or oviparous production of young. If the salinity change occurred prior to the time that the females had formed cysts, they became acclimated to the raised salinity by the time the eggs developed and they hence exuded live nauplii.

Our experiments suggest that caution should be exercised to insure that the salinity changes are not completed prior to the onset of gestation, and that food concentrations are kept non-limiting (25,000 cells/ml).

The importance of a non-limiting food supply in attaining a maximum growth rate of Artemia cannot be over-emphasized. The growth of nauplii to adults was measured on both a weight and carbon-nitrogen basis (Figure 28). Concurring data show that freshly hatched nauplii (average weight, 0.026 mg) demonstrate a rapid, logarithmic increase in body weight up to the attainment of sexual maturity (1 - 3 mg). Though grazing continues to increase past sexual maturity, the rate of increase in the mean body weight declines as a result of copious energy expenditures toward reproduction. Separate experiments, measuring various parameters of growth, have demonstrated that this initial logarithmic increase will level off prematurely if food concentrations fall below 10^4 cells/ml. In addition to prolonging generation times, limiting food concentrations have been shown to decrease survival of the adults and reduce the size of broods.

Productivity Projections

Initial laboratory results indicate an Artemia productivity of 5 to 7 mg per unit phosphorus per day (5 - 7 mg C/mg P/day). The phytoplankton turnover rate in the laboratory experiments was as high as 1.3 divisions per day, as opposed to .35 divisions per day determined for the F lakes on Christmas Island in field experiments. Since the phytoplankton organism, Dunaliella, used in the laboratory experiments was isolated from Christmas Island, it is reasonable to assume the phytoplankton turnover rate under non-nutrient-limited conditions at Christmas Island could approach 1.3 divisions per day.

Based on the previously discussed egg to nutrient calculation of 2,125 eggs per mg P and per 7 mg N, 9.07×10^{11} eggs can be produced per ton of phosphorus fertilizer and per 7.15 tons of urea per seven days. Using 1.5×10^6 eggs per cubic inch, this represents 6×10^5 cubic inches of Artemia eggs being produced per ton of phosphorus fertilizer and per 7.15 tons urea per seven days. One quart equals 67.2 cubic inches; therefore, a production of 8,930 quarts of eggs, or 2,232.5 gallons of eggs, can be expected per ton of triple superphosphate coupled with 7.15 tons of urea in a seven-day period.

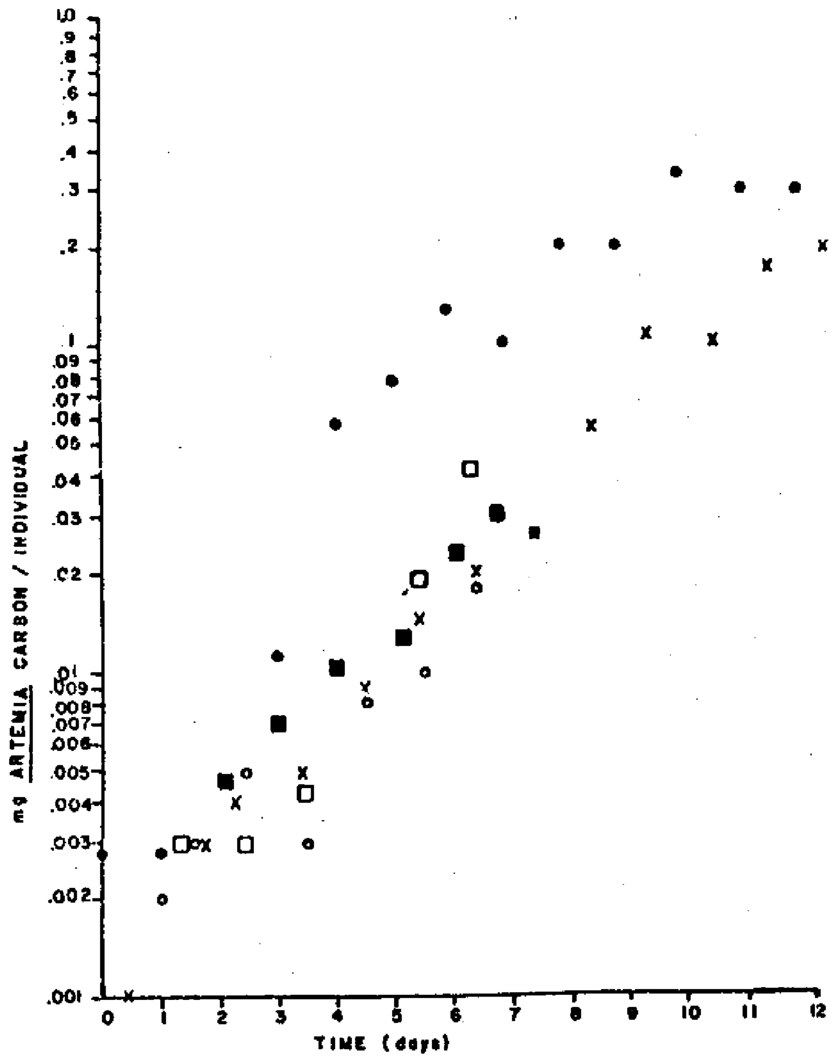

FIGURE 28. Growth rate of Artemia in mg C/individual under constant light and temperature in chemostat apparatus. (See text description.)

Different levels of phytoplankton input rate as follows:

● = 3.6×10^6 cells/hr ○ = 1.3×10^6 cells/hr
□ = 2×10^6 cells/hr X = 2×10^6 cells/hr
■ = 3×10^6 cells/hr

The Nutrient Problem

Considerable effort was made to locate a source of nutrients on Christmas Island before it was decided to import commercial supplies of the plant fertilizers required for phytoplankton production. The number of birds that live part of their lives and nest on Christmas Island have been estimated by various investigators. Schreiber and Ashmole (1970) estimated a total of about 8,700 adult boobies on the island, along with 8,000 red-tailed tropic birds, 10,000 great frigate birds, 16,000 shearwaters and petrels, 25,000 terns of six species, and 14 million sooty terns! Dr. Andrew Berger estimates that the 18 species of sea birds that nest on Christmas Island deposit at least 200 tons of guano per year (Helfrich *et al*, 1972). Despite this substantial deposition of guano annually, no significant deposits of phosphatic guano have been discovered on Christmas Island (Hutchinson, 1950; Jenkin and Foale, 1968). It is speculated that due to the periodic heavy rainfall and the porosity of the coastal plains (where most of the birds nest) much of this fertilizer is washed into the groundwater lens. Its distribution in the salt and freshwater components of the groundwater beneath the island, and the feasibility of recovering this resource for aquaculture, were not within the scope of this study; they should be investigated if brine shrimp production is initiated on Christmas Island.

POTENTIAL FOR COMMERCIAL CULTURE OF BRINE SHRIMP AT CHRISTMAS ISLAND

The suitability of Christmas Island as a site for brine shrimp egg production has been established. Outlined here is a general proposal for a production, harvesting, and processing system for brine shrimp eggs. While additional brine shrimp products are not the principal focus of this study, the production of frozen and freeze-dried adult brine shrimp is also discussed, along with an economic analysis of two production levels of brine shrimp products based upon the existing resources on Christmas Island.

The Potential Market

The world market for brine shrimp eggs is expanding. Several factors apparent in this market indicate growth will continue from a 1971 level estimated at about 15,000 gallons. One factor is a rapidly expanding business supplying tropical fish hobbyists who are already significant consumers of brine shrimp eggs. A second factor is a growing demand on the part of research and commercial aquaculturalists: a market that is judged to be in its infancy and one that is expected to develop rapidly. One issue requiring close attention with respect to the current world supply of brine shrimp eggs for aquacultural purposes is the problem of pollutants such as DDT which have a detrimental effect on the development of larval organisms. High-quality, pesticide-free Artemia products from Christmas Island should occupy an advantageous position on the world market. The market potential for Artemia products should be assessed more precisely.

Based upon present conditions and our general understanding of the demand for brine shrimp eggs, it has been estimated that with a wholesale value of approximately $25 per gallon, world demand is expected to approach 40,000 to 50,000 gallons within the next few years. A preliminary report (Helfrich et al, 1972) projected a production scheme to produce at an annual rate of 30,000 gallons of eggs at the end of the third year of production. Lack of precise information relative to the market demand suggested the inclusion of a second production scheme, designed for an ultimate production level of 15,000 gallons. The 15,000-gallon production scheme is designated as "Plan A" and the 30,000-gallon scheme as "Plan B."

Egg Production

The production of brine shrimp eggs in each production scheme is based upon the fertilization and manipulation of water in the F-series lakes with possible involvement of other closely allied lakes or lake systems. The principal considerations in this project involve the production of phytoplankton as food for Artemia and the ability to control and manipulate salinity of the lake water to obtain the production of brine shrimp eggs.

Although the entire scheme is based upon a development of a production facility in the F-series of lakes, this does not preclude the possibility that it could be located in natural or artificial empoundments at other locations on Christmas Island. It was necessary to make a decision on a potential production site after a rather cursory reconnaissance, so that the limited time available on Christmas Island could be used for a detailed study of the site chosen. It appears that the F-series has natural attributes that can be utilized advantageously to promote the production scheme proposed. In view of the more refined management techniques that were developed on return to the laboratory, it might be advisable to re-evaluate alternate locations on Christmas Island that may be closer to ancillary facilities, and to weigh the advantages and disadvantages of each.

The F-series lakes contain water with a salinity ranging from 40 or 50 o/oo to 100 or 110 o/oo. The scheme presented is based upon a consideration of these salinities as well as the dynamics of water movement required for salinity control, population management, and egg harvesting, in conjunction with an understanding of the biology of the brine shrimp. The basic components of the system are:

1. Hatchery enclosures or tanks in which Artemia eggs will be initially hatched.

2. Rearing lakes into which the juvenile Artemia will be placed and from which adults will be transferred to egg-laying lakes.

3. Phytoplankton lakes to produce a continual supply of Artemia food.

4. Egg-laying lakes of higher salinity into which sexually mature brine shrimp will be transferred for egg production.

A small hatchery facility, possibly consisting of plastic-lined swimming pools, will be used initially to hatch brine shrimp for controlled stocking of the rearing lakes. These shrimp will be hatched from San Francisco Bay eggs and transferred to the closely managed rearing lakes. Thereafter, the scheme will rely upon the production of live young to expand the number of animals to the carrying capacity of the rearing lakes and to produce a harvestable surplus. It may be possible to abandon hatchery tanks after the management of shrimp populations in the rearing and egg-laying lakes is fully accomplished.

Our recent experiments indicate that a system of lakes, pipes, and pumps should be constructed for intensive production of phytoplankton of the proper type and quantity as food for Artemia. The objective would be to gain control over the preferred food species such that optimum selectivity and efficiency may occur in food production and conversion. Exactly how this will be accomplished will be developed in pilot studies at Christmas Island. Portions of adjacent lakes or artificially constructed lakes might be considered. There also remains the possibility of direct management of natural bodies of water in production.

If ample food is available, adult Artemia will continue to produce live young in the rearing lakes as long as they are maintained at a relatively constant salinity. A marked change of salinity will trigger the production of eggs by sexually mature Artemia. This will be accomplished by transferring adult shrimp to a lake of significantly higher salinity.

In the 15,000-gallon production scheme (Plan A), it is proposed that the rearing lake be F5 (salinity of 58 o/oo). A system of gates in modified channels will be built connecting F4 with F5, and F5 with F6. Once these modifications are made, the lakes must be poisoned to remove predators and then carefully managed to control changes in the water level and salinity, and to guard against the introduction of predator eggs and larvae. By controlling the water flow into F6, it can be developed and maintained as a natural high-salinity egg-laying lake.

The transfer of adult Artemia from the rearing lake to the egg-laying lake is required, to secure a constant yield of eggs. This is accomplished by concentrating gravid adults in anchored harvesting devices and/or with a net mounted to a boat. Both of these methods have been used in the San Francisco Bay Artemia operation and are described in greater detail below. The salinity of F6, presently about 75 o/oo, will be maintained at a level sufficient to induce egg production in all of the shrimp introduced into it. It will also be fertilized in order to maintain an adequate food supply for the egg-laying shrimp.

In the 30,000-gallon production scheme (Plan B) F4 becomes the rearing lake, F5 becomes the first egg-laying lake, and F6-F7 becomes a second egg-laying lake at a sufficiently higher salinity. This scheme therefore will require an additional gate at the passage between F3 and F4 and sufficient dredging of the passage between F6 and F7 to make it effectively a single body of water.

Both these schemes will become temporarily static with respect to salinity control, which will require careful monitoring of the dynamics of salinity, fertility, and phytoplankton population control. As static systems, the salinities of all lakes will be increasing, hopefully together, with obvious effects upon the limits of food production and conversion efficiency. Preliminary studies indicate the efficiency is highest at the initial salinity of F5. In Plan B where higher populations are sought, the decrease in productivity and efficiency in the second egg-laying lake makes it appropriate to consider the joining of F6 and F7. Periodically the entire system will need to be flushed and recycled. The passages between lakes should be developed with a consideration of this need.

Egg Harvesting and Processing Storage

Eggs released by gravid females in the high-salinity lakes are positively bouyant and float to the surface. They are then blown by the wind to the lee shore where they amass and can be collected by one of several methods. Steps in two proposed egg-harvesting procedures are outlined here. (See also Figure 29.)

1a. One method would employ an egg-harvesting device consisting of a barrier about five feet from the lee shore which facilitates the concentration of eggs for more efficient harvesting.

1b. Another, less preferred method, is to develop an approximate one-in-twenty slope on the lee shore to be covered by a plastic sheet. With this method the eggs collect along or above the shoreline through the action of waves and wind.

2a. The eggs are scooped from the egg-harvesting device along the edge of the lake with nets made of 60-mesh nylon material. This operation is performed periodically when the egg concentrations reach a magnitude to warrant it.

2b. Similarly, eggs that are collected on the plastic sheets are brushed, shoveled, and netted into containers.

3. The wet eggs are allowed to drain; the drained eggs are transferred to large burlap sacks.

4. The sacks of eggs are transported to a well ventilated processing area where they may be stored on hooks on poles under cover.

Egg Processing

It is envisioned that the eggs will undergo most of their processing on Christmas Island. The processing objectives are to separate the good eggs from the impurities that were simultaneously collected during harvesting and to preserve the viability of these good eggs. The processing of eggs requires fresh water; therefore the location of this activity should be near such a resource. The important steps in brine shrimp egg processing are outlined below, and Figure 30 provides a diagram of this process.

1. Eggs should be washed with fresh water in a specially designed box that separates viable eggs from "empty" eggs, debris, and sand.

2. Viable eggs collect at one end of the washing box and may be emptied into flour sacks through a hole in the bottom of the box. They are quickly rinsed again while in the flour sacks.

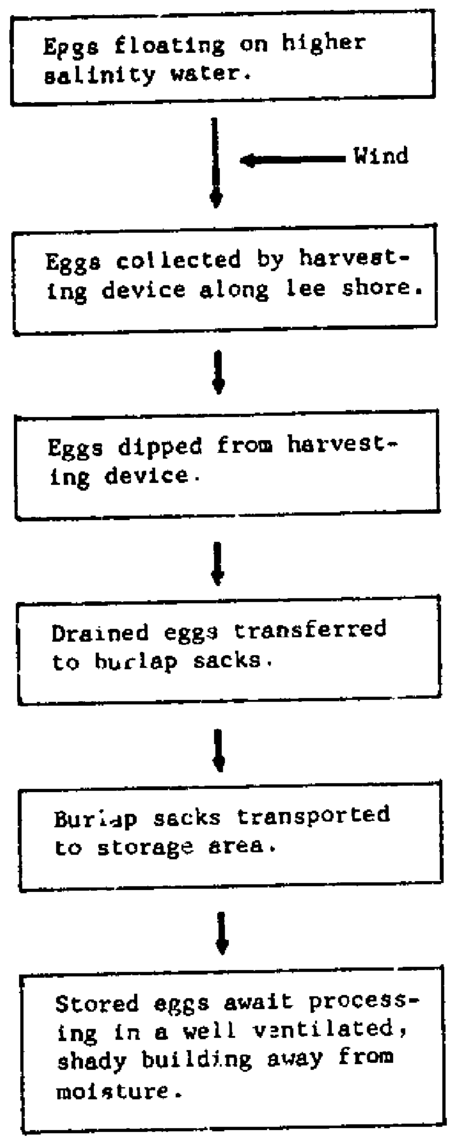

FIGURE 29. The egg-harvesting process.

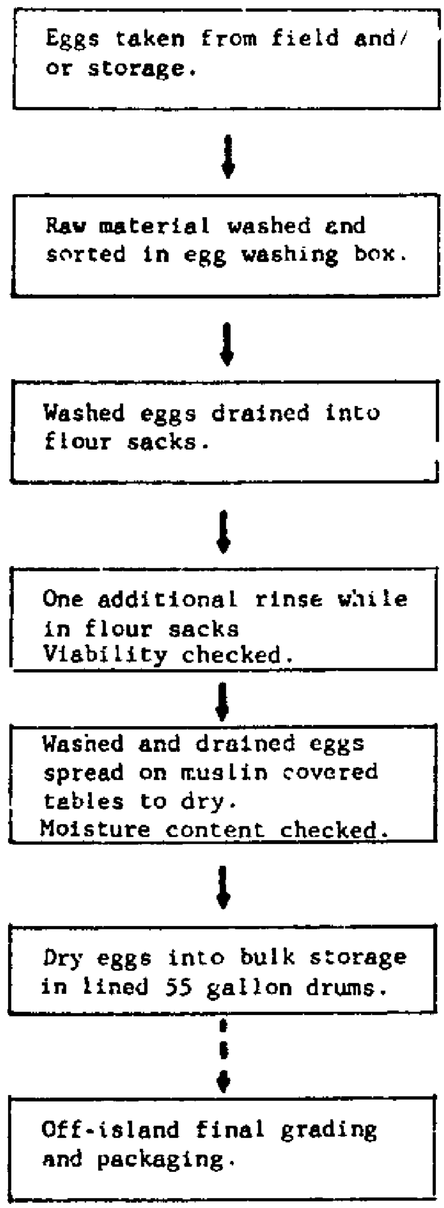

FIGURE 30. Initial egg processing.

Maximum time for washing and rinsing should not exceed 20 minutes. Expeditious washing and drying are essential for a high-quality product. The principal measure of quality is the percent of eggs that are viable. Viability can be measured by holding 2 cc of eggs in a graduated cylinder of water at 80°F for 24 hours. Upon absorption of water, good-quality eggs will be increased in volume by 200%; i.e., the volume of eggs will now be 6 cc as measured in the graduated cylinder.

3. The washed and rinsed eggs should be spread out to dry on muslin-coated tables under conditions that allow 50% moisture removal within 12 hours. These drying tables should be protected from the wind.

4. After the eggs have dried for approximately 24 hours on the muslin-covered tables, they should be brushed into sacks.

5. Moisture checks of the dried eggs should be made before bulk packaging. The level should be below 12%; the optimum is about 7%.

6. The eggs should be put into 55-gallon drums with air-tight plastic liners and clamp tops. They may be either vacuum-packed or flushed with nitrogen gas. The system proposed here only vacuum packs the bulk eggs. Repackaging into smaller containers will probably be performed as required, at a distribution center close to the major markets.

Final Grading and Packaging of Brine Shrimp Eggs

It is envisioned that the final grading and packaging of brine shrimp eggs will be done at distribution centers, possibly in the United States and Japan. In this last step sand, debris, and empty eggs not previously removed are separated from "good" eggs. A recommended device for this operation consists of a small V-shaped trough with a slit on the bottom wide enough to allow a thin curtain of raw material to fall through. This trough is mounted at the end of a rectangular box with solid sides and several open drawers along the bottom at right angles to the length of the box. At one end of the box a variable-speed suction fan pulling air through stacked straws creates a controlled laminar flow of air. Across the bottom of the box is a coarse netting covering the drawers placed side-by-side at right angle to the air flow.

As the thin curtain of eggs falls into the flow of air, sand, debris, good eggs, and empty eggs not previously removed are sorted. If the device is properly adjusted, the sand will fall into the first drawer; good eggs will fall into the second; a mixture of good and empty eggs may be found in the third drawer (these may be reprocessed to sort out some of the good eggs); and the fourth drawer will contain mostly empty eggs.

A quart of good eggs should weigh between 14.2 and 14.6 ounces. In order to insure a high-quality product, it is recommended that hatchability tests be run on each batch of eggs; batches may then be blended to yield a more consistent product. If the eggs are then vacuum-packed or thoroughly flushed with nitrogen gas, they will retain their viability for up to ten years. This compares with life up to about three years and nine months if held at ambient, temperate-zone conditions.

Harvesting Adult Brine Shrimp

In order to initiate egg production and to prevent over-population in the rearing lakes with resultant mass mortality, adults must be removed on a continuous basis. One method utilizes a stationary harvesting device, while a second method uses a moving harvester. Each of these methods has advantages; for best management both should be available for employment as the situation dictates.

a. Stationary Harvester: This harvesting device consists of a pipe or box intake which can be raised or lowered to harvest at different depths of water, and a connected trough with a paddle wheel which draws water from the pipe or box intake and then deposits shrimp and water into a rectangular net enclosure 10' x 4' x 4' deep. This enclosure is lined with 12 to 20-mesh material. The harvesting device should be anchored in the rearing lake at a point where natural conditions cause a concentration of shrimp.

Population control may require the operation of several of these units. The operation of the harvester is facilitated by lowering the intake pipe or trough to the depth at which shrimp are concentrated. Wind power to operate the paddle wheel is an attractive prospect at Christmas Island. The screened enclosure has a mesh size that retains the adult shrimp but allows the juveniles to pass through the mesh and return to the main body of the lake. The concentrated adults are removed with a dip net from the enclosure and placed in containers in an adjacent boat.

b. Moving Harvester: This method of harvesting brine shrimp allows considerable flexibility in removing shrimp from natural aggregations that may not always occur in the same location. The craft is a catamaran-type design with a large-mouthed net, directed forward and funneling down to a removable cod end which is located between the hulls at a point accessible to the operator. As the craft is propelled through the water, the net concentrates the *Artemia* into the removable cod end. When the cod end of the net is full, the shrimp are emptied into containers in the deck and the harvesting continues.

Such a craft can be easily constructed with locally available materials such as 55-gallon drums and angle iron, and powered by a 20-hp outboard motor.

Processing Adult Shrimp

An expanding market exists for frozen and freeze-dried brine shrimp. It was not within the scope of this study to explore the nature of this market. However, both of these items are potentially valuable by-products of brine shrimp egg production and should be considered in the overall scheme of activities. The production of frozen brine shrimp is outlined below and a diagrammatic flow chart is presented in Figure 31. It is envisioned that conventional freezing is possible with existing freezers on Christmas Island. Freeze drying is performed by expensive, large-volume machinery; therefore this operation is not proposed for Christmas Island in the near future. It may be economically feasible to bulk-freeze brine shrimp and have them shipped to a freeze-drying facility elsewhere for further processing.

Although little information is available on the efficacy of sun-drying brine shrimp, the possibility of developing a sun-dried product should be pursued as an alternative means of processing shrimp for human and/or animal consumption.

The freezing procedure for brine shrimp is as follows:

1. The harvested shrimp require transportation to the processing plant (presumably at London village) in enough water to keep them alive.

2. The shrimp brought to the processing facility are placed in specially constructed V-shaped troughs about ten feet long and two feet high, filled with fresh water. At the bottom of each trough is a perforated pipe through which air is forced to cause rapid circulation of the trough contents.

3. Washing in fresh water with violent agitation causes the shrimp to "clean" themselves. An initial wash takes 10 - 15 minutes, while the second takes 5 - 10 minutes. Each trough should be large enough to wash 200 - 250 gallons of live shrimp.

4. The shrimp are then thoroughly drained in mesh baskets.

5. The washed shrimp are then transferred to a filling hopper. With the proper amount of water added to facilitate filling, each quart of shrimp contains from 1-3/4 to 2 ounces of water. The water content of frozen <u>Artemia</u> is an important quality criterion.

6. About 1.25 to 2.00 pounds of shrimp are bagged in each "polybag". These bags are heat-sealed and frozen either in a contact freezer or a tunnel freezer at -20°F. The bags are most easily frozen and handled when they are 5" x 10" x 5/8" thick. When frozen, they can be boxed in 50- to 75-pound quantities and placed in freezer storage. As such, these frozen shrimp are a valuable commercial product. A further freeze-drying process changes both their form and value.

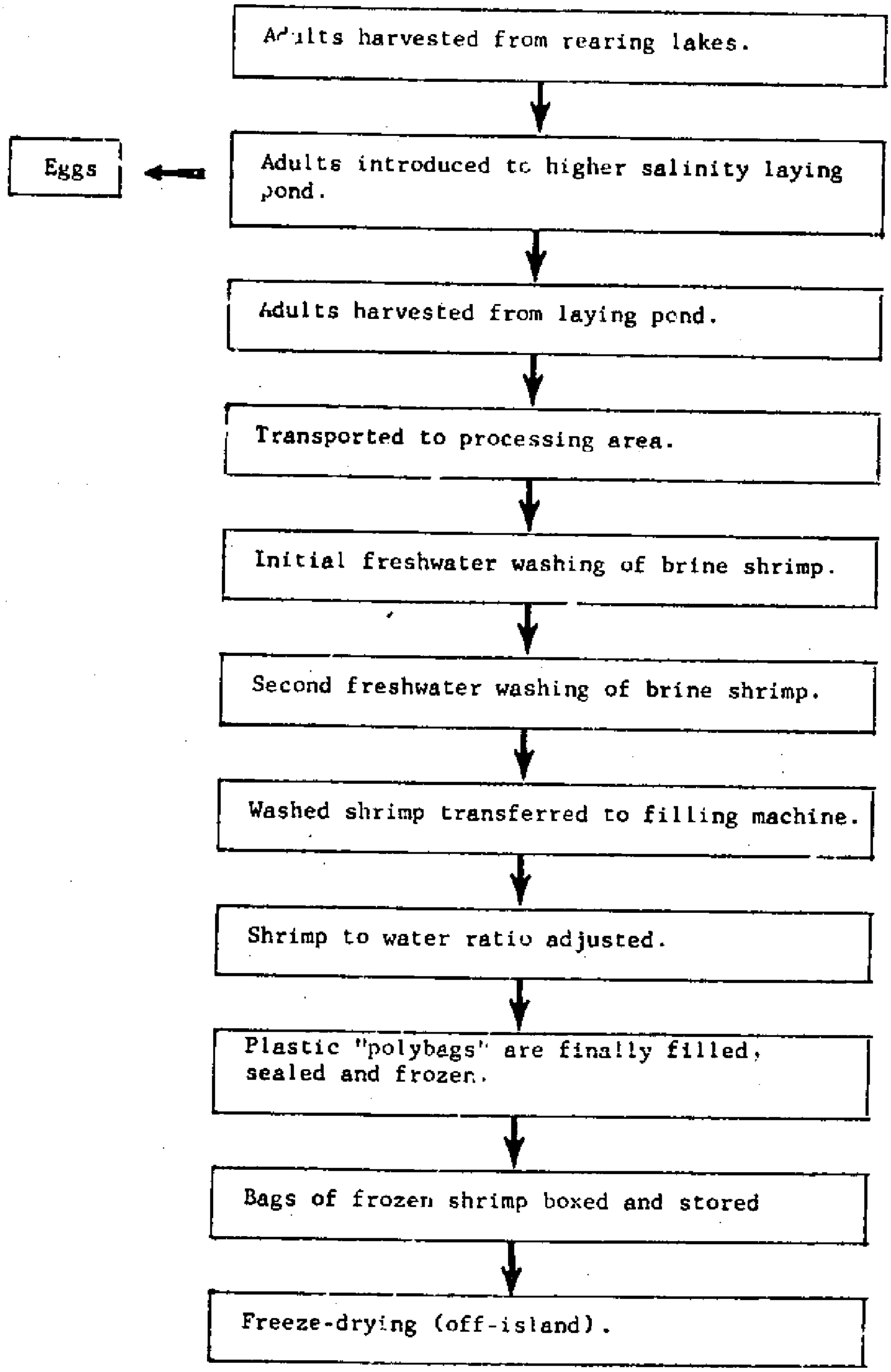

FIGURE 31. Adult shrimp harvesting and processing.

Resource Development

A sequence of resource development and capital investment is proposed here, based on alternate schemes to produce brine shrimp products at Christmas Island and on the ability to offer a superior-quality product at a competitive price and thus capture a substantial portion of an expanding world market for brine shrimp eggs. The plan also foresees the production of supplementary products such as frozen and possibly freeze-dried brine shrimp, as well as the development of other related aquacultural ventures. Figure 32 outlines a proposed sequence of developmental activities leading to the production and processing of Artemia products.

Following a period of negotiation and planning, the staging of material, its transportation to Christmas Island, and the construction of facilities could be completed over a six-month period. It is envisioned that preliminary production tests could be accomplished before Phase I construction is completed. At the end of this period an operations center, a field office, the hatchery and hatchery lakes, a motor pool, a limited number of homes for local contract workers, and the first rearing and egg-laying lakes will be readied. Renovations will also be completed on staff housing, egg processing and storage areas.

The time distribution of production for Plan A is 7,500 gallons of eggs in the first full year of production and 15,000 gallons in the second year and thereafter. In the first year of Plan B the yield is projected at 7,500 gallons, followed by 20,000 gallons in the second year and a plateau of 30,000 gallons to be reached in the third year.

The costs and earnings projections made for these systems attempt to reflect the special conditions on Christmas Island and should not be applied to other situations without careful modification. An attempt was also made to break down the total cost into that part which could be borne by the Gilbert and Ellice Islands Colony (GEIC) on a cost-sharing basis. Further allocations of costs are possible to bring the GEIC participation up to 50 percent.

The weight of the additional equipment and material which brine shrimp egg production on Christmas Island would entail is estimated to range between 50 and 100 tons for the initial staging and construction phase and between 100 and 150 tons annually for egg production. These estimates of annual tonnage will decline as Christmas Island becomes better equipped. However, since there are only two interchangeable methods for moving this quantity of material (air freight or semi-annual shipping), estimates were based on charter air-freight rates. Therefore freight charges may be somewhat over-estimated, but these represent a ceiling on the cost of "immediate and direct" delivery.

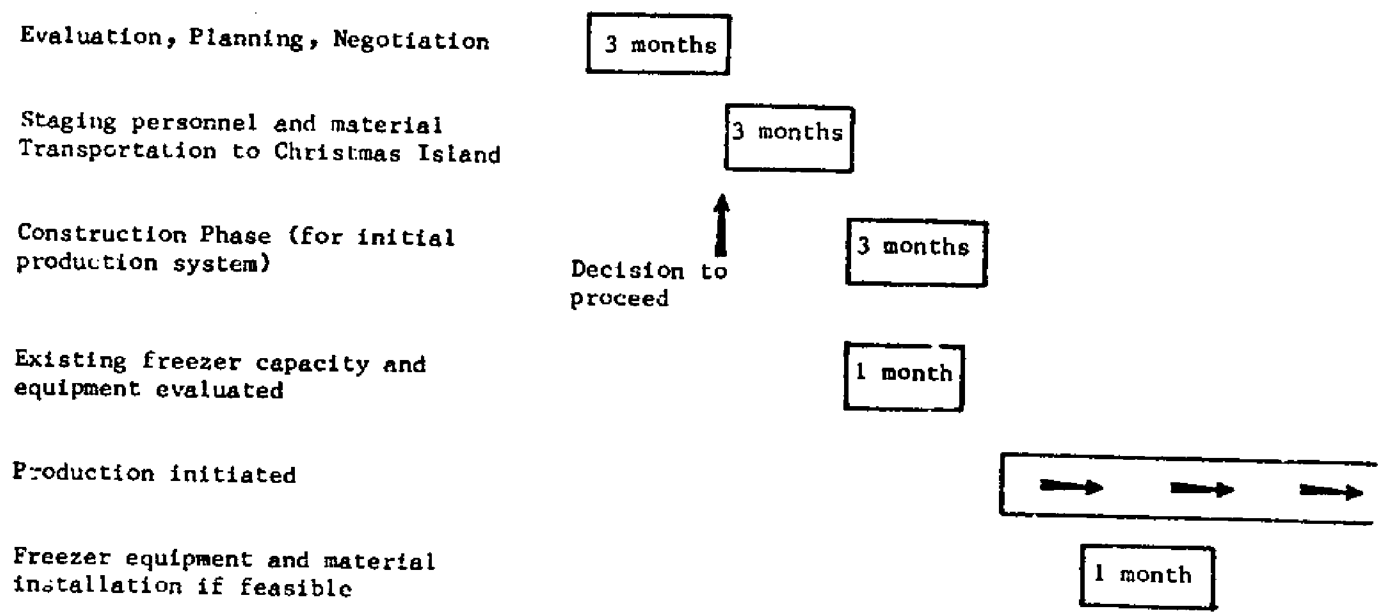

FIGURE 32. The sequence of developmental activities related to _Artemia_ production at Christmas Island (Plan A).

Plan B projects a more intensive construction period of about the same duration (three months) to accomplish the bulk of the necessary work to bring the required lakes up to producing condition. This is a departure from the scheme in the preliminary report, which split the construction into two phases.

To make fullest use of the brine shrimp production system, the condition of the available freezer equipment and facilities should be determined within a short period after the arrival of the construction crew on Christmas Island. If the markets are of sufficient size, the next increment of capital investment should provide the capacity to freeze and store frozen brine shrimp on Christmas Island.

Table 8 shows the annual egg production in each of the first three years of Christmas Island operations for the different production levels. This annual production is converted to a daily basis, giving expected daily production and the value of the products.

Brine Shrimp Egg Production Potential and Field Approximations

If our predictions are valid, any of the F-series lakes under very intensive management possess the potential to equal or surpass the potential annual world supply of brine shrimp eggs (40,000 - 50,000 gallons) in the space of a few generations. (See Table 9.) These predictions are based upon a duplication of optimal laboratory conditions in the field at extremely high levels of fertilization, salinity control, harvesting efficiency, and overall management of the scheme.

Maximum productivity in the rearing-lake system should not be attempted because of the risk of catastrophic losses if maximum density levels are surpassed. Rather, a somewhat more conservative alternative of lower stocking densities is recommended, at least until monitoring and management techniques are refined.

Table 9 projects the potential daily productivity at Christmas Island under optimal conditions (based upon laboratory experiments). Table 10 predicts the potential production of *Artemia* eggs at efficiencies expressed as a percent of production under optimal laboratory conditions. After the projected initial staging and construction period of about six months, egg production will be based on attaining different levels as previously discussed. These final production levels are approximately 10% of the maximum levels obtained in the laboratory.

Frozen and Freeze-Dried Brine Shrimp

Although the magnitude of the market for frozen and freeze-dried brine shrimp is largely unknown at this time, there are indications from personal correspondence and fragmentary information that the market potential may be attractive for both these products. As with brine shrimp

TABLE 8. LEVEL OF *ARTEMIA* EGG PRODUCTION AND VALUE DURING INITIAL STAGES OF DEVELOPMENT

Year of Operation	Annual Production,* gallons x 1000	Daily Production, gallons	Value of Daily Production, U.S.$**
PLAN A: Maximum production at 15,000 gallons annually			
1st	7.5	20.5	$ 410
2nd	15	41.1	822
3rd	15	41.1	822
4th	15	41.1	822
PLAN B: Maximum production at 30,000 gallons annually			
1st	7.5	20.5	$ 410
2nd	20	54.8	1,096
3rd	30	82.2	1,644
4th	30	82.2	1,644

* At production efficiency between 1% and 10% of maximum production under laboratory conditions.

** Based upon $20/gallon FOB Christmas Island.

TABLE 9. F-SERIES LAKES: THEIR VOLUMES, POPULATION DENSITIES, AND POTENTIAL DAILY PRODUCTIVITY

F-Series Lake	Volume, cubic feet	Volume, kiloliters	Potential Population Density, adults/kl*	Eggs Produced in Enriched Water, gal/day**
F1, F2	617×10^6	17.28×10^6	4×10^4	85.71×10^2
F3	105×10^6	2.94×10^6	4×10^4	14.58×10^2
F4	42×10^6	1.18×10^6	4×10^4	5.85×10^2
F5	30×10^6	$.84 \times 10^6$	4×10^4	4.17×10^2
F6	27×10^6	$.76 \times 10^6$	4×10^4	3.77×10^2
F7	32×10^6	$.90 \times 10^6$	4×10^4	4.46×10^2

* Based upon a density of 40 adult _Artemia_ per liter (Bienfang, personal communication). 40 adult _Artemia_ have been sustained per liter under continuous flow conditions where food was non-limiting.

** Assuming a 50:50 sex ration and 10 eggs/female/day.

TABLE 10. POTENTIAL DAILY PRODUCTION OF BRINE SHRIMP EGGS IN SEVEN F-SERIES LAKES AT CHRISTMAS ISLAND

F-Series Lake	Egg Production, in gallons, at Various Efficiencies*								
	100%	90%	75%	50%	25%	10%	1%	0.1%	0.01%
F1, F2	85.71×10^2	77.14×10^2	64.28×10^2	42.86×10^2	21.43×10^2	8.57×10^2	8.57×10	8.57	8.57×10^{-1}
F3	14.58×10^2	13.12×10^2	10.94×10^2	7.29×10^2	3.65×10^2	1.46×10^2	1.46×10	1.46	1.46×10^{-1}
F4	5.85×10^2	5.27×10^2	4.39×10^2	2.93×10^2	1.46×10^2	5.85×10	5.85	5.85×10^{-1}	5.85×10^{-2}
F5	4.17×10^2	3.75×10^2	3.13×10^2	2.09×10^2	1.04×10^2	4.17×10	4.17	4.17×10^{-1}	4.17×10^{-2}
F6	3.77×10^2	3.39×10^2	2.83×10^2	1.89×10^2	9.43×10	3.77×10	3.77	3.77×10^{-1}	3.77×10^{-2}
F7	4.46×10^2	4.01×10^2	3.35×10^2	2.23×10^2	1.12×10^2	4.46×10	4.46	4.46×10^{-1}	4.46×10^{-2}

* Efficiencies expressed as percent of production under optimum laboratory conditions.

TABLE 11. PROJECTED PROCESSING COSTS AND RETURNS FOR FROZEN BRINE SHRIMP

Operation or input	Cost per pound or per item
Transfer of adults from egg-laying ponds to plant	2¢
Washing and rinsing	1¢
Cost of "polybag"	2¢
Filling bag	½¢
Storage	2¢
Shipping	10¢
Total Cost (Honolulu)	17½¢

Projected wholesale price: 30 to 35¢/lb

Projected margin: 12½ to 17½¢/lb*

* On the basis of 1,000 lb per day, the margin above operating costs would be $125 to $175.

TABLE 12. PROJECTED COSTS AND RETURNS OF PRODUCING FREEZE-DRIED BRINE SHRIMP

Operation or input	Cost per pound or per item
9 pounds of frozen brine shrimp	$ 2.70
Charge for producing 1 pound of freeze-dried product	2.50
Shipping @ 10¢/lb (9 lb frozen to Taiwan; 1 lb dried product to Honolulu)	1.00
Packaging	.10
Total Cost (Honolulu)	$ 6.30

Projected wholesale price: $8.00/lb

Projected margin: $1.70/lb

eggs, frozen and freeze-dried *Artemia* will enter an expanding world-wide market. However, this is not a market that will absorb unlimited quantities of *Artemia* products; therefore, a better understanding of the market potential should be acquired. A rough estimate of the cost of production of both frozen and freeze-dried brine shrimp is given in Tables 11 and 12

Cost Estimates for Brine Shrimp Egg Production

The cost of developing the available resources on Christmas Island was estimated for two levels of brine shrimp egg production. This included new construction, renovation, staffing, and other operational costs. An operations center, a motor pool, a field station, a hatchery and related ponds, and a processing and storage area are among the high-priority items in the construction phase. The cash-flow summaries for brine shrimp egg production by our proposed schemes are presented in Table 13. These summaries are based upon a value of $20/gallon which will presumably give the operation a good competitive advantage in the world market.

The following tables outline the cost of the resources required to renovate, equip, and prepare facilities for brine shrimp production (Tables 14 through 30). These are the current best estimates. An attempt was made to indicate a rough breakdown between the costs that might be best carried by the outside investor and those costs that are typical of those already being incurred in the normal activities within the GEIC operations extant at Christmas Island.

TABLE 13. PRELIMINARY CASH-FLOW SUMMARY FOR BRINE SHRIMP EGG PRODUCTION AT CHRISTMAS ISLAND

	Expenditures	Receipts	Balance	Cumulative Balance
PLAN A: Maximum production at 15,000 gallons annually				
Construction Phase	$140,489	0	$-140,489	$-140,489
First Year	158,295	$ 150,000	- 8,295	-148,784
Second Year	143,695	300,000	+156,305	+ 7,521
Third Year	148,195	300,000	+151,805	+159,326
Fourth Year	143,445	300,000	+156,555	+315,881
Total	$734,119	$1,050,000	+315,881	
PLAN B: Maximum production at 30,000 gallons annually				
Construction Phase	$ 191,968	0	$-191,968	$-191,968
First Year	275,900	150,000	-125,900	-317,868
Second Year	252,600	400,000	+147,400	-170,468
Third Year	254,600	600,000	+345,400	+174,932
Fourth Year	252,850	600,000	+347,150	+522,082
Total	$1,227,918	$1,750,000	+522,082	

TABLE 14. PLAN A: TOTAL COSTS

Item	Construction Phase	1st Year Production	2nd Year Production	3rd Year Production	4th Year Production
Building (and material)	$ 11,000	$ 6,400	$ 2,900	$ 2,400	$ 2,400
Equipment	103,500	13,100	7,050	12,050	7,300
Supplies	27,050	9,900	8,850	8,850	8,850
Labor	9,700	68,000	63,000	63,000	63,000
General Support	39,239	60,895	61,895	61,895	61,895
Total	$190,489	$158,295	$143,695	$148,195	$143,445

TABLE 15. PLAN A: ANNUAL CASH FLOW PROJECTION

Time Period	3 months	1 year	1 year	1 year	1 year
Projected Production	0	7,500 gal	15,000 gal	15,000 gal	15,000 gal
Value of eggs @ $20/gal	0	$150,000	$300,000	$300,000	$300,000
Less Costs	-$190,489	158,295	143,695	148,195	143,445
Annual Balance	-$190,489	-$ 8,295	+$156,350	+$151,805	$156,555
Cumulative Balance	-$190,489	-$198,784	-$ 42,479	+$109,326	+$265,881

TABLE 16. PLAN A: ITEMIZED PROJECTED SHARES, GEIC AND OUTSIDE

Item	Construction Phase	1st Year Production	2nd Year Production	3rd Year Production	4th Year Production
G E I C SHARE					
Building (& material)	$ 9,050	$ 2,400	$ 1,400	$ 1,400	$ 1,400
Equipment	35,950	8,600	5,80C	7,800	5,800
Supplies	8,550	5,500	5,500	5,500	5,500
Labor	3,700	10,000	10,000	10,000	10,000
General Support	5,340	8,395	8,395	8,395	8,395
	$62,590	$34,895	$31,095	$33,095	$31,095
OUTSIDE SHARE					
Building (& material)	$ 1,950	$ 4,000	$ 1,500	$ 1,000	$ 1,000
Equipment	67,550	4,500	1,250	4,250	1,500
Supplies	18,500	4,400	3,350	3,350	3,350
Labor	6,000	58,000	53,000	53,000	53,000
General Support	33,899	52,500	53,500	53,500	53,500
	$127,899	$123,400	$112,600	$115,100	$112,350
TOTAL COST	$190,489	$158,295	$143,695	$148,195	$143,445

TABLE 17. PLAN A: SUMMARY OF PROJECTED SHARES, GEIC AND OUTSIDE

Time Period	Total Cost	GEIC Share		Outside Share	
		US $	% of TC	US $	% of TC
Construction	$190,489	$ 62,590		$127,899	
1st Year	158,295	34,895	22.04	123,400	77.95
2nd Year	143,695	31,095	21.63	112,600	78.36
3rd Year	148,195	33,095	22.33	115,100	77.66
4th Year	143,445	31,095	21.23	112,350	78.32
Total	$784,119	$192,770	24.58	$591,349	75.41

TABLE 18. PLAN A: CONSTRUCTION PHASE, FIELD WORK (Channels, Gates, Water Control and Lake Preparation, Hatchery)

Item	Condition	Life, years	Cost, each	Number	Total Cost	Source	
						[illegible]	Outside
Buildings (materials)							
Office Area (200 sq ft	S	10			$ 2,400	$ 2,400	
@ $12/sq ft)					2,400	2,400	
Equipment							
Office furniture	U	5			500	500	
Office equipment	U	5			250	250	
Adult BS harvesting equipment	N	5	$ 500	1	500		$ 500
Water control gates	N	10			3,000		3,000
Pumps & pipelines for hatchery	N	5			3,500	3,500	
Channel improvement		5			1,000	1,000	
Tide gauges & water quality							
monitoring	N	10			2,000		2,000
Boat, trailer & engine	N	5			5,000		5,000
Field lakes (hatchery lakes							
& field tr[illegible]l lakes)	N	5	1,200	6	7,200		7,200
Egg harvesting devices at							
$3/running ft	N	1			1,500		1,500
Phyto-production system					50,000	25,000	25,000
Total					$74,450	$30,250	$44,200
Supplies							
Miscellaneous materials							
& supplies					$ 1,000	$ 1,000	
Scientific supplies					500		$ 500
Screens					200		200
Plumbing fittings & supplies					1,000	750	250
Spares - pumps					300	300	
Cement					200		200
Posts, lumber					1,000	1,000	
Reinforcing steel					150	150	
Fish poison					1,500		1,500
Spares - outboard engine					200		200
Spares - trailer					100		100
Paint					50		50
Nets, trawls, mesh material							
for adult harvesting (lakes)					3,000		3,000
Rope					500		500
Cable, wire					500		500
Poly-sheeting					500		500
Dip nets					200		200
Total					$10,900	$ 3,200	$ 7,700

S = salvaged

U = used

N = new

TABLE 19. PLAN A: CONSTRUCTION PHASE, OPERATIONS CENTER

Item	Condition*	Life, years	Cost, each	Number	Total Cost	Source: GEIC	Source: Outside
Buildings (materials)							
Office area (200 sq ft @ $1/sq ft)	R	5			$ 200	$ 200	
Mess area (500 sq ft @ $2/sq ft)	R	5			1,000	1,000	
Bath area (300 sq ft @ $3/sq ft)	R	5			900	300	$ 600
Motor Pool (1,000 sq ft @ 50¢/sq ft)	R	5			500	500	
Total					$ 2,600	$ 2,000	$ 600
Equipment							
Generator	N	5	$2,500	2	$ 5,000		$ 5,000
Radio (main station	N	5	250	2	500		500
Antenna (main station)	N	5	200	1	200		200
Scientific equipment	N	5			2,500		2,500
Refrigerator	N	5	400	2	800		800
Calculator	N	10	100	2	200		200
Office furniture	U	5			500	$ 500	
Freshwater well (JOC) (& pump & pipes)	N	20			5,000	1,000	4,000
Automotive repair equipment	N	5			2,000		2,000
General shop equipment	N	5			2,000		2,000
Ranges	N	10	250	2	500		500
Personnel carriers	N	5	2,000	2	4,000	4,000	
Motorcycles	N	5	300	2	600		600
Medical equipment	N	5			500		500
Mobile radios	N	5	150	5	750		750
Surveying equipment					500		500
Total					$25,550	$ 5,500	$20,050

* R = Reconditioned N = New U = Used

TABLE 19. PLAN A: CONSTRUCTION PHASE (CONTINUED)

Item	Condition	Life, years	Cost, each	Number	Total Cost	Source: GEIC	Source: Outside
Supplies							
Office supplies					$ 500		$ 500
Scientific supplies					500		500
Metal shapes & stock					500	$ 250	250
Lumber					2,000	2,000	
Paint					200		200
Wiring					1,500		1,500
Electrical supplies					500		500
Carpentry supplies					250		250
Automotive spares					2,000	1,000	1,000
Screening					100		100
Fiberglass					500		500
Kitchen supplies					200		200
Lubricants					200	100	100
Medical supplies					500		500
Cement & reinforcing steel					300	200	100
Fertilizer @ $100/ton				40	4,000	4,000	
Total					$13,750	$ 7,550	$ 6,200

TABLE 19. PLAN A: CONSTRUCTION PHASE (CONTINUED)

Egg Storage, Processing, Product Storage

Item	Condition	Life, years	Cost, each	Number	Total Cost	Source: GEIC	Source: Outside
Buildings (materials)							
Temporary storage (eggs) (1,000 sq ft @ $1/sq ft)	R	5			$ 1,000	$ 750	$ 250
Processing area (eggs) (2,000 sq ft @ $1/sq ft)	R	5			2,000	1,500	500
General storage (1,000 sq ft @ $1/sq ft)	R	5			1,000	800	200
Bulk storage (processed eggs) (1,000 sq ft @ $1/sq ft)	R	5			1,000	800	200
Water storage & water piping	N	10			1,000	800	200
Total					$ 6,000	$ 4,650	$ 1,350
Equipment							
Furniture	U	5			$ 200	$ 200	
Water pumps	N	10	$ 300	1	300		$ 300
Fans (egg processing)	N	5	200	2	400		400
Processing equipment	N	3			2,000		2,000
Drying tables (marine plywood sheets)	N	5	20	20	400		400
Scientific equipment	N	5			200		200
Total					$ 3,500	$ 200	$ 3,300
Supplies							
Pipes					$ 500	$ 500	
Burlap bags			$ 2	500	1,000	1,000	
Flour sacks			1	100	100		$ 100
Lumber					300	300	
Processing supplies					500		500
Total					$ 2,400	$ 1,800	$ 600

TABLE 19. PLAN A: CONSTRUCTION PHASE (CONTINUED)

Manning Schedule and General Support (3-month construction period)

Item	Source of Personnel**	Quarterly Wages	No. Individuals i.e. quarters	Total Cost	Source: GEIC	Source: Outside
Labor						
Construction Supervisor	O.C.	$ 3,000	1	$ 3,000		$ 3,000
Field Biologist	O.C.	3,000	1	3,000		3,000
Laborer -- mechanic	L.C.	250	2	500	$ 500	
Laborer - carpenter	L.C.	250	6	1,500	1,500	
Laborer - heavy equipment	L.C.	250	2	500	500	
General Support	L.C.	200	6	1,200	1,200	
Total				$ 9,700	$ 3,700	$ 6,000
General Support						
Equipment services truck (@ $3/hr [$2,000] front-end loader @ $5/hr [$2,000])				$ 4,000	$ 4,000	
Fuel (10 gal/day @ 70¢/gal for 120 days)				840	840	
Food				500	500	
Freight (Air - $10,000 per round trip of 100,000 lb cargo - 2 trips)				20,000		$20,000
Transportation of personnel (piggy-back on freight or surface transport)				2,000		2,000
Logistics coordinator (half-time position for 3 months in Hawaii)				1,899		1,899
Contingency				10,000		10,000
Total				$39,239	$ 5,340	$[illegible],899

** O.C. = Outside Contract L.C. = Local Contract

TABLE 20. PLAN A: (15,000) PRODUCTION-RELATED EXPENSES

Item	Total Cost	Source: GEIC	Source: Outside	Total Cost	Source: GEIC	Source: Outside
	1st Year of Production			2nd Year of Production		
Building Materials						
Lumber	$ 1,000	$1,000		$ 500	$ 500	
Cement	100	100		100	500	
Steel	300	300		300	300	
Pipes	2,000	1,000	$1,000	500	500	
Fiberglass	2,000		2,000	1,000		$1,000
Miscellaneous	1,000		1,000	500		500
	$ 6,400	$2,400	$4,000	$2,900	$1,400	$1,500
Equipment						
Harvesting (replacement)	1,500	1,500		1,500	1,500	
Processing (replacement)	500	500		500	500	
Scientific (replacement)	500		500	500		500
Personnel carriers	2,000	2,000				
Truck & trailer (@ $3/hr)	3,000	3,000		3,000	3,000	
Front-end loader (@ $5/hr)	1,600	1,600		800	800	
Boat	2,000		2,000			
Outboard engine	500		500	500		500
Radion	250		250	250		250
Generators	1,000		1,000			
Vacuum pump	250		250			
	$13,100	$6,600	$4,500	$7,050	$5,800	$1,250

Item	Total Cost	Source: GEIC	Source: Outside	Total Cost	Source: GEIC	Source: Outside
	3rd Year of Production			4th Year of Production		
Building Materials						
Lumber	$ 500	$ 500		$ 500	$ 500	
Cement	100	100		100	100	
Steel	300	300		300	300	
Pipes	500	500		500	500	$ 500
Fiberglass	500		$ 500	500		500
Miscellaneous	500		500	500		
	$ 2,400	$1,400	$1,000	$2,400	$1,400	$1,000
Equipment						
Harvesting (replacement)	1,500	1,500		1,500	1,500	
Processing (replacement)	500	500		500	500	
Scientific (replacement)	500		500	500		500
Personnel carriers	2,000	2,000				
Truck & trailer (@$3/hr)	3,000	3,000		3,000	3,000	
Front-end locder (@ $5/hr)	800	800		800	800	
Boat	2,000		2,000			
Outboard engine	500		500	500		500
Radios	250		250	250		250
Generators	1,000		1,000			
Vacuum pump				250		250
	$12,050	$7,800	$4,250	$7,300	$5,800	$1,500

TABLE 20. PLAN A: (15,000) PRODUCTION-RELATED EXPENSES (continued)

Item	Total Cost	Source: GEIC	Source: Outside	Total Cost	Source: GEIC	Source: Outside
	1st Year of Production			2nd Year of Production		
Supplies						
Harvesting	$ 500		$ 500	$ 500		$ 500
Liners (1/50 gal) (@ $2)	600		600	600		600
Shipping containers (baggage & processed eggs)	1,000		1,000	250		250
Fertilizer (@ $100/ton)	4,000	$4,000		4,000	$4,000	
Burlap bags	500	500		500	500	
Flour sacks	200		200	200		200
Muslin (@ 50¢/yd)	500		500	200		200
Nets, trawls, mesh	500		500	500		500
Automotive spares	1,000	1,000		1,000	1,000	
Scientific spares	100		100	100		100
Radio spares	200		200	200		200
Generator spares	200		200	200		200
Boating supplies & spares	500		500	500		500
Outboard spares	100		100	100		100
	$9,900	$5,500	$4,400	$8,850	$5,500	$3,350

Item	Total Cost	Source: GEIC	Source: Outside	Total Cost	Source: GEIC	Source: Outside
	3rd Year of Production			4th Year of Production		
Supplies						
Harvesting	$ 500		$ 500	$ 500		$ 500
Liners (1/50 gal) (@ $2)	600		600	600		600
Shipping containers (baggage & processed eggs)	250		250	250		250
Fertilizer (@ $100/ton)	4,000	$4,000		4,000	$4,000	
Burlap bags	500	500		500	500	
Flour sacks	200		200	200		200
Muslin (@ 50¢ yd)	200		200	200		200
Nets, trawls, mesh	500		500	500		500
Automotive spares	1,000	1,000		1,000	1,000	
Scientific spares	100		100	100		100
Radio spares	200		200	200		200
Generator spares	200		200	200		200
Boating supplies & spares	500		500	500		500
Outboard spares	100		100	100		100
	$8,850	$5,500	$3,350	$8,850	$5,500	$3,350

TABLE 21. PLAN A: PERSONNEL COSTS

Item	Source of Personnel	Number of Individuals	Total Cost	Source: GEIC	Source: Outside	Total Cost	Source: GEIC	Source: Outside
Labor			1st Year of Production			2nd Year of Production		
General Manager	O.C.	1	$18,000		$18,000	$18,000		$18,000
Production Manager (Biologist)	O.C.	1	15,000		15,000	15,000		15,000
Consulting & Operational Svcs	O.C.		25,000		25,000	20,000		20,000
Biological Tech	L.C.	1	1,000	$ 1,000		1,000	$ 1,000	
Mechanic's Helper	L.C.	1	1,000	1,000		1,000	1,000	
Harvesting & Processing	L.C.	5	5,000	5,000		5,000	5,000	
Construction & Maintenance	L.C.	1	1,000	1,000		1,000	1,000	
General Support	L.C.	2	2,000	2,000		2,000	2,000	
			$68,000	$10,000	$58,000	$63,000	$10,000	$53,000
			3rd Year of Production			4th Year of Production		
General Manager			18,000		18,000	18,000		18,000
Production Manager (Biologis')			15,000		15,000	15,000		15,000
Consulting & Operational Svcs			20,000		20,000	20,000		20,000
Biological Tech			1,000	1,000		1,000	1,000	
Mechanic's Helper			1,000	1,000		1,000	1,000	
Harvesting & Processing			5,000	5,000		5,000	5,000	
Construction & Maintenance			1,000	1,000		1,000	1,000	
General Support			2,000	2,000		2,000	2,000	
			$63,500	$10,000	$53,000	$63,000	$10,000	$53,000
General Support			1st Year of Production			2nd Year of Production		
Transportation of personnel (incl. consultant) 16 RT (@ $300 RT)			$ 4,800		$ 4,800	$ 4,800		$ 4,800
Freight-import (@ $4,800 1-way)			9,600		9,600	9,600		9,600
Freight-export (@ $4,800 1-way)			9,600		9,600	9,600		9,600
Fuel & lubricants (20 gal/day at $70)			5,110	$5,110		5,110	$5,110	
Food (@ $3/day for O.C. personnel)			3,285	3,285		3,285	3,285	
Equipment repair & maintenance			1,000		1,000	2,000		2,000
Logistics coordinator (half-time)			7,500		7,500	7,500		7,500
Contingency			20,000		20,000	20,000		20,000
			$60,895	$8,395	$52,500	$61,895	$8,395	$53,500
			3rd Year of Production			4th Year of Production		
Transportation of personnel			4,800		4,800	4,800		4,800
Freight-import			9,600		9,600	9,600		9,600
Freight-export			9,600		9,600	9,600		9,600
Fuel & lubricants			5,110	5,110		5,110	5,110	
Food			3,285	3,285		3,285	3,285	
Equipment repair & maintenance			2,000		2,000	2,000		2,000
Logistics coordinator			7,500		7,500	7,500		7,500
Contingency			20,000		20,000	20,000		20,000
			$61,895	$8,395	$53,500	$61,895	$8,395	$53,500

TABLE 22. PLAN B: TOTAL COSTS

Item	Construction Phase	1st Year Production	2nd Year Production	3rd Year Production	4th Year Production
Building	$ 14,900	$ 10,800	$ 5,500	$ 5,500	$ 5,500
Equipment	120,150	28,750	22,250	24,250	22,500
Supplies	36,600	21,400	19,900	19,900	19,900
Labor	13,500	103,200	93,200	93,200	93,200
General Support	56,818	111,750	111,750	111,750	111,750
Total	$241,968	$275,900	$252,600	$254,600	$252,850

TABLE 23. PLAN B: ANNUAL CASH FLOW PROJECTION

Time Period	3 months	1st year	2nd year	3rd year	4th year
Projected Production	0	7,500 gal	20,000 gal	30,000 gal	30,000 gal
Value of eggs @ $20/gal	0	$150,000	$400,000	$600,000	$600,000
Less Costs	-$241,968	- 275,900	- 252,600	- 254,600	- 252,850
Annual Balance	-$241,968	-$125,900	+$147,400	+$345,400	+$347,150
Cumulative Balance	-$241,968	-$367,868	-$220,468	+$124 932	+$472,082

TABLE 24. PLAN B: ITEMIZED PROJECTED SHARES, GEIC AND OUTSIDE

Item	Construction Phase	1st Year Production	2nd Year Production	3rd Year Production	4th Year Production
G E I C SHARE					
Building	$12,950	$ 4,800	$ 2,500	$ 2,500	$ 2,500
Equipment	41,450	20,800	18,800	18,800	18,800
Supplies	16,350	11,000	11,000	11,000	11,000
Labor	6,000	20,200	20,200	20,200	20,200
General Support	11,020	18,250	18,250	18,250	18,250
	$87,770	$75,050	$70,750	$70,750	$70,750
OUTSIDE SHARE					
Building	$ 1,950	$ 6,000	$ 3,000	$ 3,000	$ 3,000
Equipment	78,700	7,950	3,450	5,450	3,700
Supplies	20,250	10,400	8,900	8,900	8,900
Labor	7,500	83,000	73,000	73,000	73,000
General Support	45,798	93,500	93,500	93,500	93,500
	$154,198	$200,850	$181,850	$183,850	$182,100
TOTAL COST	$241,968	$275,900	$252,600	$254,600	$252,850

TABLE 25. PLAN B: SUMMARY OF PROJECTED SHARES, GEIC AND OUTSIDE

Time Period	Total Cost	GEIC Share		Outside Share	
		US $	% of TC	US $	% of TC
Construction	$ 241,968	$ 87,770	36.27	$154,198	63.72
1st Year	275,900	75,050	27.20	200,850	72.79
2nd Year	252,600	70,750	28.00	181,850	71.99
3rd Year	254,600	70,750	27.78	183,850	72.21
4th Year	252,850	70,750	27.98	182,100	72.01
Total	$1,277,918	$375,070	29.35	$902,848	70.64

TABLE 26. PLAN B: CONSTRUCTION PHASE, FIELD WORK (Channels, Gates, Water Control and Lake Preparation, Hatchery)

Item	Condition	Life, years	Cost, each	Number	Total Cost	Source: CELC	Source: Outside
Buildings (materials)							
Office Area (200 sq ft @ $12/sq ft)	S	10			$ 2,400	$ 2,400	
Field assembly area (200 sq ft @ $12/sq ft)	S	10			2,400	2,400	
Equipment							
Office furniture	U	5			500	500	
Office equipment	U	5			250	250	
Adult BS harvesting equipment	N	5	$ 500	3	1,500		$ 1,500
Water control gates	N	10			6,000		6,000
Pumps & pipelines for hatchery	N	5			4,000	4,000	
Channel improvement		5			2,000	2,000	
Tide gauges & water quality monitoring	N	10			2,000		2,000
Boat, trailer & engine					5,000		5,000
Field lakes (hatchery lakes & field [illegible] 3 lakes)	N	5	$1,200	9	10,800		10,800
Egg harvesting devices at 31 running ft	N	1			3,000		3,000
Phyto-production system					50,000	25,000	25,000
Total					$85,050	$31,750	$53,300
Supplies							
Miscellaneous materials & supplies					$ 2,000	$ 2,000	
Scientific supplies					1,000		$ 1,000
Screens					500		500
Plumbing fittings & supplies					1,500	1,000	500
Spares - pumps					600	600	
Cement					600		600
Posts, lumber					2,000	2,000	
Reinforcing steel					200	200	
Fish poison					3,000		3,000
Spares - outboard engine					200		200
Spares - trailer					100		100
Paint					50		50
Nets, trawls, mesh material for adult harvesting (lakes)					4,000		4,000
Rope					500		500
Cable, wire					500		500
Poly-sheeting					1,000		1,000
Dip nets					400		400
Total					$18,150	$ 5,800	$12,350

S = salvaged

U = Used

N = new

TABLE 27. PLAN B: CONSTRUCTION PHASE, OPERATIONS CENTER

Item	Condition*	Life, years	Cost, each	Number	Total Cost	Source: GEIC	Source: Outside
Buildings (materials)							
Office area (200 sq ft @ $1/sq ft)	R	5			$ 200	$ 200	
Mess area (500 sq ft @ $2/sq ft)	R	5			1,000	1,000	
Bath area (300 sq ft @ $3/sq ft)	R	5			900	300	$ 600
Motor pool (1,000 sq ft @ 50¢/sq ft)	R	5			500	500	
Total					$ 2,600	$ 2,000	$ 600
Equipment							
Generator	N	5	$2,500	2	$ 5,000		$ 5,000
Radio (main station)	N	5	250	2	500		500
Antenna (main station)	N	5	200	1	200		200
Scientific equipment	N	5			3,000		3,000
Refrigerator	N	5	400	2	800		800
Calculator	N	10	100	2	200		200
Office furniture	U	5			500	$ 500	
Freshwater well (JOC) (& pump & pipes)	N	20			5,000	1,000	4,000
Automotive repair equipment	N	5			2,000		2,000
General shop equipment	N	5			2,000		2,000
Ranges	N	10	250	2	500		500
Personnel carriers	N	5	2,000	4	8,000	8,000	
Motorcycles	N	5	300	4	1,200		1,200
Medical equipment	N	5			500		500
Mobile radios	N	5	150	10	1,500		1,500
Surveying equipment					500		500
					$31,400	$ 9,500	$21,900

* R = Reconditioned N = New U = Used

TABLE 27. PLAN B: CONSTRUCTION PHASE (CONTINUED)

Item	Condition	Life, years	Cost, each	Number	Total Cost	Source	
						GEIC	Outside
Supplies							
Office supplies					$ 500		$ 500
Scientific supplies					500		500
Metal shapes & stock					500	$ 250	250
Lumber					2,000	2,000	
Paint					200		200
Wiring					1,500		1,500
Electrical supplies					500		500
Carpentry supplies					250		250
Automotive spares					2,000	1,000	1,000
Screening					100		100
Fiberglass					500		500
Kitchen supplies					200		200
Lubricants					200	100	100
Medical supplies					500		500
Cement & reinforcing steel					300	200	100
Fertilizer @ $100/ton				40	4,000	4,000	
Total					$13,750	$ 7,550	$ 6,200

TABLE 27. PLAN B: CONSTRUCTION PHASE (CONTINUED)

Egg Storage, Processing, Product Storage

Item	Condition	Life, years	Cost, each	Number	Total Cost	Source: GEIC	Source: Outside
Buildings (materials)							
Temporary storage (eggs) (1,000 sq ft @ $1/sq ft)	R	5			$ 1,000	$ 750	$ 250
Processing area (eggs) (2,000 sq ft @ $1/sq ft)	R	5			2,000	1,500	500
General storage (1,000 sq ft @ $1/sq ft)	R	5			1,000	800	200
Bulk storage (processed eggs) (2,000 sq ft @ $1/ sq ft)	R	5			2,000	1,800	200
Water storage & water piping	N	10			1,500	1,300	200
Total					$ 7,500	$ 6,150	$ 1,350
Equipment							
Furniture	U	5			$ 200	$ 200	
Water pumps	N	10	$ 300	1	300		$ 300
Fans (egg processing)	N	5	200	2	400		400
Processing equipment	N	3			2,000		2,000
Drying tables (marine plywood sheets)	N	5	20		600		600
Scientific equipment	N	5			200		200
Total					$ 3,700	$ 200	$ 3,500
Supplies							
Pipes					$ 500	$ 500	
Burlap bags			2	1,000	2,000	2,000	
Flour sacks			1	200	200		$ 200
Lumber					500	500	
Processing supplies					1,000		1,000
Total					$ 4,200	$ 3,000	$ 1,200

TABLE 27. PLAN B: CONSTRUCTION PHASE (CONTINUED)

Manning Schedule and General Support (3-month construction period)

Item	Source of Personnel**	Quarterly Wages	No. Individuals i.e. quarters	Total Cost	Source: GEIC	Source: Outside
Labor						
Construction Supervisor	O.C.	$ 4,500	1	$ 4,500		$ 4,500
Field Biologist	O.C.	3,000	1	3,000		3,000
Laborer - mechanic	L.C.	250	2	500	$ 500	
Laborer - carpenter	L.C.	250	8	2,000	2,000	
Laborer - heavy equipment	L.C.	250	6	1,500	1,500	
General Support	L.C.	200	10	2,000	2,000	
Total				$13,500	$ 6,000	$ 7,500
General Support						
Equipment services truck (@ $3/hr [$4,000] front-end loader @ $5/hr [$4,000])				$ 8,000	$ 8,000	
Fuel (30 gal/day @ 70¢/gal for 120 days)				2,520	2,520	
Food				500	500	
Freight (Air - $10,000 per round trip of 100,000 lb cargo - 2 trips)				20,000		$20,000
Transportation of personnel (piggy-back on freight or surface transport)				2,000		2,000
Logistics coordinator (full-time position for 3 months in Hawaii)				3,798		3,798
Contingency				20,000		20,000
Total				$56,818	$11,020	$45,798

** O.C. = Outside Contract L.C. = Local Contract

TABLE 28. PLAN B: (30,000) PRODUCTION-RELATED EXPENSES

Item	Total Cost	Source: GEIC	Source: Outside	Total Cost	Source: GEIC	Source: Outside
	1st Year of Production			2nd Year of Production		
Building Materials						
Lumber	$ 2,000	$ 2,000		$ 1,000	$ 1,000	
Cement	300	300		200	200	
Steel	500	500		100	300	
Pipes	3,000	2,000	$1,000	1,000	1,000	
Fiberglass	3,000		3,000	1,000		$1,000
Miscellaneous	2,000		2,000	2,000		2,000
	$10,800	$ 4,800	$6,000	$ 5,500	$ 2,500	$3,000
Equipment						
Harvesting (replacement)	4,500	4,500		4,500	4,500	
Processing	1,500	1,500		1,500	1,500	
Scientific	1,200		1,200	1,200	1,200	
Personnel carriers (purchase $2,000 ea)	4,000	4,000		2,000	2,000	
Truck & trailer (@ $3/hr)	6,000	6,000		6,000	6,000	
Front-end loader (@ $5/hr)	4,800	4,800		4,800	4,800	
Boat	4,000		4,000			
Outboard engine	1,000		1,000	1,000		1,000
Radios	250		250	250		250
Generators	1,000		1,000	1,000		1,000
Vacuum pump (@ $250 each)	500		500			
	$28,750	$20,800	$7,950	$22,250	$18,800	$3,450
	3rd Year of Production			4th Year of Production		
Building Materials						
Lumber	$ 1,000	$ 1,000		$ 1,000	$ 1,000	
Cement	200	200		200	200	
Steel	300	300		100	300	
Pipes	1,000	1,000		1,000	1,000	
Fiberglass	1,000		$1,000	1,000		$1,000
Miscellaneous	2,000		2,000	2,000		2,000
	$ 5,500	$ 2,500	$3,000	$ 5,500	$ 2,500	$3,000
Equipment						
Harvesting (replacement)	4,500	4,500		4,500	4,500	
Processing	1,500	1,500		1,500	1,500	
Scientific	1,200		1,200	1,200		1,200
Personnel carriers (purchase $2,000 ea)	2,000	2,000		2,000	2,000	
Truck & trailer (@ $3/hr)	6,000	6,000		6,000	6,000	
Front-end loader (@ $5/hr)	4,800	4,800		4,800	4,800	
Boat	2,000		2,000			
Outboard engine	1,000		1,000	1,000		1,000
Radios	250		250	250		250
Generators	1,000		1,000	1,000		1,000
Vacuum pump (@ $250 each)				250		250
	$24,250	$18,800	$5,450	$22,500	$18,300	$3,700

TABLE 28. PLAN B: (30,000) PRODUCTION-RELATED EXPENSES (continued)

Item	Total Cost	Source: GFIC	Source: Outside	Total Cost	Source: GFIC	Source: Outside
	1st Year of Production			2nd Year of Production		
Supplies						
Harvesting	$ 1,500		$ 1,500	$ 1,500		$1,500
Liners (1/50 gal) (@ $2 ea)	1,200		1,200	1,200		1,200
Shipping containers	2,000		2,000	500		500
Fertilizer (@ $100/ton)	8,000	$ 8,000		8,000	$ 8,000	
Burlap bags	1,000	1,000		1,000	1,000	
Flour sacks	400		400	400		400
Muslin (@ 50¢/yd)	1,000		1,000			1,000
Nets, trawls, mesh	1,500		1,500	1,500		1,500
Automotive spares	2,000	2,000		2,000	2,000	
Scientific spares	300		300	300		300
Radio spares	400		400	400		400
Generator spares	400		400	400		400
Boating supplies and spares	1,500		1,500	1,500		1,500
Outboard spares	200		200	200		200
	$21,400	$11,000	$10,400	$19,900	$11,000	$8,900
	3rd Year of Production			4th Year of Production		
Supplies						
Harvesting	$ 1,500		$1,500	$ 1,500		$1,500
Liners (1/50 gal) (@ $2 ea)	1,200		1,200	1,200		1,200
Shipping containers	500		500	500		500
Fertilizer (@ $100/ton)	8,000	$ 8,000		8,000	$ 8,000	
Burlap bags	1,000	1,000		1,000	1,000	
Flour sacks	400		400	400		400
Muslin (@ 50¢/yd)	1,000		1,000	1,000		1,000
Nets, trawls, mesh	1,500		1,500	1,500		1,500
Automotive spares	2,000	2,000		2,000	2,000	
Scientific spares	300		300	300		300
Radio spares	400		400	400		400
Generator spares	400		400	400		400
Boating supplies and spares	1,500		1,500	1,500		1,500
Outboard spares	200		200	200		200
	$19,900	$11,000	$8,900	$19,900	$11,000	$8,900

TABLE 29. PLAN B: PERSONNEL COSTS

Item	Source of Personnel	Number of Individuals	Total Cost	Source: CEIC	Source: Outside	Total Cost	Source: CEIC	Source: Outside
			1st Year of Production			2nd Year of Production		
General Manager	O.C.	1	$ 18,000		$18,000	$18,000		$18,000
Production Manager (Biologist)	O.C.	1	15,000		15,000	15,000		15,000
Facilities Engineer	O.C.	1	15,000		15,000	15,000		15,000
Operational Services	O.C.		15,000		15,000	15,000		15,000
Consulting Services	O.C.		20,000		20,000	10,000		10,000
Biological Technician	L.C.	2	2,000	$ 2,000		2,000	$ 2,000	
Mechanics Helper	L.C.	2	2,000	2,000		2,000	2,000	
Harvesting & Processing	L.C.	10	10,000	10,000		10,000	10,000	
Construction & Maintenance	L.C.	3	3,000	3,000		3,000	3,000	
General Support	L.C.	4	3,200	3,200		3,200	3,200	
			$103,200	$20,200	$83,000	$93,200	$20,200	$73,000
			3rd Year of Production			4th Year of Production		
General Manager			18,000		18,000	18,000		18,000
Production Manager (Biologist)			15,000		15,000	15,000		15,000
Facilities Engineer			15,000		15,000	15,000		15,000
Operational Services			15,000		15,000	15,000		15,000
Consulting Services			10,000		10,000	10,000		10,000
Biological Technician			2,000	2,000		2,000	2,000	
Mechanic's Helper			2,000	2,000		2,000	2,000	
Harvesting & Processing			10,000	10,000		10,000	10,000	
Construction & Maintenance			3,000	3,000		3,000	3,000	
General Support			3,200	3,200		3,200	3,200	
			$111,750	$18,250	$93,500	$111,750	$18,250	$93,500
General Support			1st Year of Production			2nd Year of Production		
Transportation of personnel 24 RT (@ $300 RT)			$ 7,200		$ 7,200	$ 7,200		$ 7,200
Freight-import (@ $4,800 1-way)			14,400		14,400	14,400		14,400
Freight-export (@ $4,800 1-way)			14,400		14,400	14,400		14,400
Fuel & lubricants (50 gal/day at $70)			12,775	$12,775		12,775	$12,775	
Food (@ $3/day for O.C. personnel)			5,475	5,475		5,475	5,475	
Equipment repair & maintenance			2,500		2,500	2,500		2,500
Logistics coordinator			15,000		15,000	15,000		15,000
Contingency			40,000		40,000	40,000		40,000
			$111,750	$18,250	$93,500	$111,750	$18,250	$93,500
			3rd Year of Production			4th Year of Production		
Transportation of personnel			7,200		7,200	7,200		7,200
Freight-import			14,400		14,400	14,400		14,400
Freight-export			14,400		14,400	14,400		14,400
Fuel & lubricants			12,775	12,775		12,775	12,775	
Food			5,475	5,475	5,475	5,475	5,475	
Equipment repair & maintenance			2,500		2,500	2,500		2,500
Logistics coordinator			15,000		15,000	15,000		15,000
Contingency			40,000		40,000	40,000		40,000
			$111,750	$18,250	$93,500	$111,750	$18,250	$93,500

TABLE 30. CONSTRUCTION AND PRODUCTION EXPENSES
(Artemia Egg Production Only)

Item	1st Year of Production			2nd Year of Production			3rd Year of Production		
	Construction	Production	Total	Construction	Production	Total	Construction	Production	Total
Building (materials)	$38,000	$ 3,000	$41,000	$ 2,000	$ 6,000	$ 8,000	$ 2,000	$ 9,000	$11,000
Equipment	84,800	5,000	89,800	10,000	7,500	17,500	10,000	10,000	20,000
Supplies	51,550	7,000	58,550	10,000	34,000	44,000	10,000	46,000	56,000
Outside contract labor	7,200	113,000	120,200	3,200	113,000	116,200	3,200	133,000	136,200
Local contract labor	1,700	10,000	11,700	634	12,000	12,634	467	15,000	15,467
General support and maintenance	13,538	20,000	33,538	5,000	30,000	35,000	5,000	40,000	45,000
Transportation	51,000	18,500	69,500	3,000	30,000	33,000	3,000	40,000	43,000
Total			$424,288			$266,334			$326,667

CHRISTMAS ISLAND FACILITIES

The only commercial activity on Christmas Island today is the Gilbert and Ellice Islands Colony (GEIC) copra plantation which is known as the Christmas Island Plantation (CIP). Apart from the airfield and several now-abandoned military installations, the most important land use on the island is for coconut culture, which occupies only about 16% of the atoll's land area (Jenkin and Foale, 1968). Operation of the Christmas Island Plantation is managed from the settlement of London, located at the tip of the narrow peninsula north of the entrance channel to the main lagoon (Plate 43). Most of the island's present population of about 500 resides in London village, although permanent settlements have been established at Poland in the southwest corner of the island and at Banana Wells near Christmas Island airfield.

Laborers on the plantation, with their families, are brought to Christmas from the Gilbert and Ellice Islands on a three-year contract under which a copra cutter earns about $30 (Aust.) per month. His transportation to and from Christmas Atoll is paid for, along with his housing and medical needs. Basic food needs such as flour, canned corned beef, saloon pilot crackers, etc, are available at the plantation store, but there is no operating cold storage and fresh vegetables are almost nonexistent. Food available locally consists primarily of fish, which is ver abundant, some local pigs and chickens, and the products of a few small garden plots. Successful experiments with the culture of vegetable crops in plastic greenhouses suggest that this activity could be expanded to provide fresh produce for a larger population than is presently served.

In addition to the plantation labor force, there is a plantation manager (presently Mr. John Bryden), the resident District Commissioner (presently Mr. Kitiseni Lopati) of the Line Islands, and a support staff including a radio operator and a small Colony Police Force. The District Commissioner serves as Chief Magistrate for the Line Islands. At the present time there is no medical doctor stationed on Christmas, although a medical technician is available.

A labor force of up to ten men on a permanent basis and many more for short-term periods (as might be required for unloading a ship) can be supplied from the resident population. If a larger work force is required, it would be possible to import men from the Gilbert and Ellice Islands. The Gilbertese on Christmas and those imported are carefully screened, and many can drive motor vehicles and operate equipment.

Plate 43. Settlement of London at tip of peninsula north of entrance to the main lagoon.

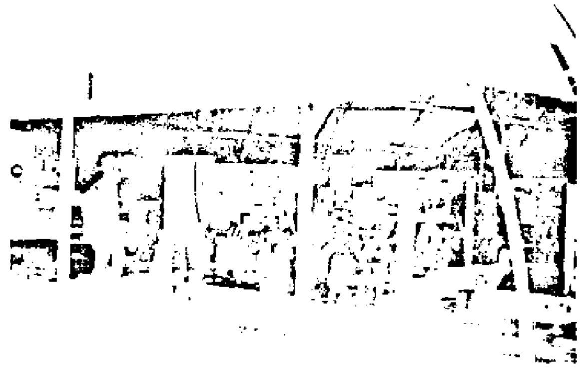

Plate 44. Diesel generators supplying electrical power to London village area.

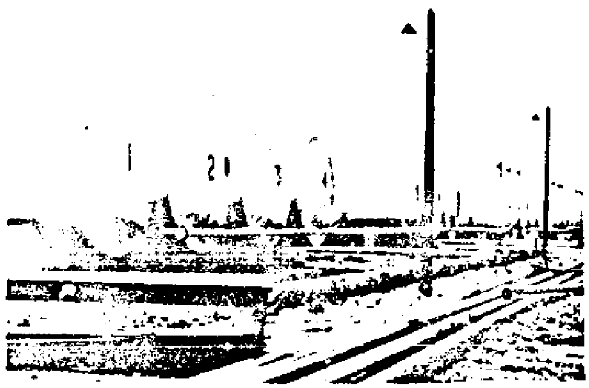

Plate 45. Fuel storage tank farm located one mile north of London village. (Pipeline to London village waterfront.)

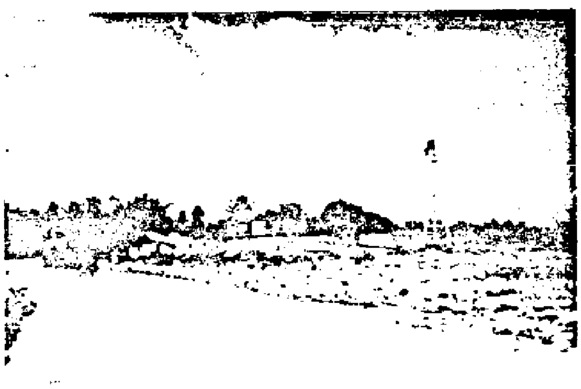

Plate 46. Windmill at Banana Wells. The JOC camp trucks water from this source.

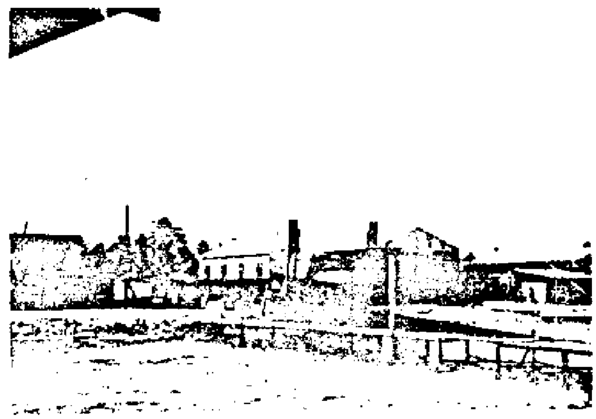

Plate 47. Marine railway [illegible] port facility.

The following facilities and equipment are located at London village and/or are used in the plantation operations:

Power: Electrical power is available from diesel generators (Plate 44) located near London village. Only one of three generators is presently operational, a 62.5 KW generator of 220/440 volts. (NOTE: generators are British 50-cycle as opposed to U.S. standard 60-cycle.) Concerning the other two generators, one has been stripped for parts and the other is awaiting parts. Electrical power is supplied only three hours a day from 7:00 to 10:00 p.m. At Poland there is a 12 KW generator.

Fuel and Fuel Storage: Diesel fuel and gasoline are available for normal plantation use; they are brought in now in 55-gallon drums. A new tank farm of 13 tanks (with a capacity of 11,500 Imperial gallons each) with pipelines to the waterfront at London is located about one mile north of the village (Plate 45). Although apparently not now in use, the complex appears to be in excellent condition.

Fresh Water Supply: Fresh water for drinking is supplied to London village from Decca waterhole through a five-mile pipeline to a 6,000-gallon storage tank in the village. Brackish water for washing is obtained in the village from groundwater pumped by a windmill.

Banana Wells village obtains water from a trench well in the village which is pumped into a storage tank by means of a windmill (Plate 46). This source also serves the JOC camp via tanker truck.

Poland village is supplied via a pipeline from New Zealand Airfield; the water is pumped by a windmill through the pipeline.

Details on the distribution of freshwater lenses at Christmas Island are presented by Jenkin and Foale. They estimate a total of more than 7×10^9 gallons of fresh water available on Christmas Island, and a maximum output of 4,532,672 gallons per day.

The water resources were adequate to supply American forces between 1942 and 1948 when the island population reached 10,000, and during operations "Grapple" and "Dominic" between 1956 and 1964 when the population was as high as 5,000 persons.

Port Facilities: The entrance channel to the lagoon and the port facilities at London have been dredged several times in the last two decades, most recently in about 1963. The channel has now silted up once more to a depth of about 2 meters (6 feet). Therefore, most ships anchor off London, and power launches (of which there are two), lighters (of which there are four), and a 40-ton-capacity barge are used between ship and shore. Water alongside the pier is 5 to 6 meters (15 to 18 feet) deep. A dockside crane capable of lifting three tons and a marine railway in apparently good condition are included in the port facility (Plate 47).

Warehouses and Cold Storage: Numerous metal buildings are available for dry storage. An ammonia freezer plant, last operated in 1965, appears to be in good condition, although associated machinery may not now be operable and, being of British manufacture, requires 50-cycle electrical power. The plant consists of nine freezer boxes, each of approximately 1,300 cubic foot capacity (Plate 48). Obtaining replacement parts for the existing machinery might also present a problem.

Equipment: The plantation now has in operation two ten-ton flatbed trucks (for hauling copra), a tractor and lowboy trailer, a tank trailer for hauling fresh water, and several smaller vehicles including landrovers and small trucks. Heavy equipment consists of two D7 and on D4 tractors (bulldozers), one Ford rubber-tire tractor, a small mobile crane, a road grader, a bus, and a large RB38 crane with dragline. Most of the equipment is in poor running condition and presently occupies the time of a 12-man maintenance staff to keep it operational. Four new farm tractors are expected in the near future.

Supplies: The plantation store stocks only basic food items, miscellaneous canned goods, soap, kerosene, cloth, beer, soft drinks, and spirits.

The primary road system on the island is excellent and the secondary roads are adequate; other than requiring road markers, they provide easy access to most of the remote areas. A tar-sealed primary road (A1) connects London and Christmas Airfield and extends single-width to South-East Point. The other main secondary roads (A2, A3, A4 and Carver Way) are compact, coral roads in fair condition (Plate 49). Numerous "tracks" allow easy access to the shores of most of the lagoon lakes.

Christmas Island (formerly Cassidy) Airfield is in good condition (Plate 50). The main runway is 6,000 feet long, concreted, and can therefore handle large aircraft. The U.S. Air Force has a warehouse adjacent to the airport which presently contains abandoned vehicles, including a water-tank trailer and tractor, a forklift, and diesel generators. All of this equipment is in need of repair. No regular air service is presently available to or from Christmas Atoll. The only regular visits to the Atoll by ships are by the Colony vessel and a Bank Line copra vessel which, between them, stop three or four times a year at Christmas.

The former Joint Operations Center (JOC) (Plate 51) (later this was a U.S. Air Force base called "Austere") located near Main Camp, is now abandoned. JOC is in better condition than any of the other abandoned military installations on the island. The JOC compound contains a mess hall, kitchen, sufficient quarters to accommodate

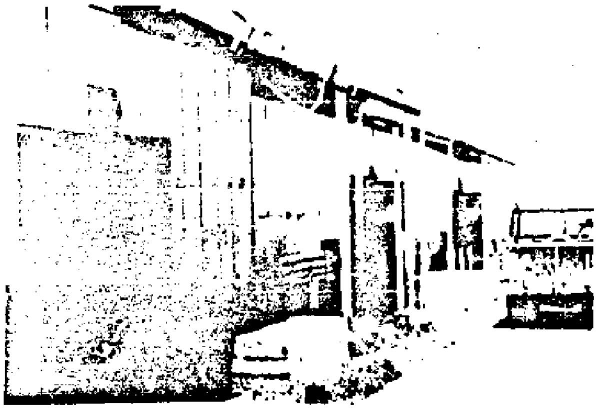

Plate 48. Ammonia freezer plant at London village.

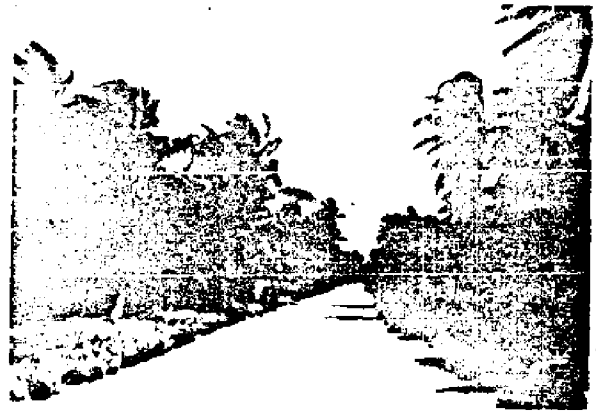

Plate 49. Section of macadam road near London village.

Plate 50. Aerial view of Christmas Island (Cassidy) airfield.

Plate 51. Joint Operations Center (JOC).

about 100 people, a large warehouse, repair sheds, generator shed, shower, toilet and washroom buildings, and a small walk-in freezer of approximately 350-cubic foot capacity. Water supply tanks are sound. All electrical equipment and lights are American power, i.e., 100/220 volt, 60 amp. The entire base is enclosed by a chainlink fence. The buildings are in fair condition, but the electrical distribution system will require overhauling. The air conditioning units for the mess hall are in poor condition.

If available, JOC should be used as a management and supervisory base for any operations contemplated at Christmas Atoll. The facilities there are easily adaptable to comfortable living with a minimum of work and the electrical system is designed for U.S. power. Adequate storage is also available on the site. The mess hall is a fully insulated building and could be air conditioned. Any operation should plan to supply its own generator, of a capacity to fit anticipated requirements, with a smaller standby generator for refrigeration. It should also provide its own vehicles and these should be of a common make, so that parts could be interchanged. The nature of the terrain is well suited for motorcycles as a means of rapid transportation for individuals. Food would also have to be brought along. A large operation should provide its own additional fuel, since large vessels cannot reach the docks at London and, unless offshore discharge facilities are constructed, use of the bulk fuel tanks may not be feasible. Thus, drum fuel may have to be provided.

DISCUSSION

This research program was initially based upon (1) a knowledge of the general biology of Artemia and its highly efficient energy conversion characteristics, (2) a recognition of the advantages accrued by an organism that could thrive at high salinities and temperatures, (3) a general awareness of natural attributes of Christmas Island, and (4) a desire to bring these factors together in a manner in which private enterprise might become involved to mass-produce animal protein to supply the rapidly expanding needs of aquaculture and the fish hobby market, and perhaps ultimately for direct human consumption. An additional attraction in the proposed endeavor would be to bring a new revenue-producing enterprise to a developing country striving to evolve in the twentieth century largely on a one-crop agricultural economy.

As the many facets of this project were explored, it became necessary to involve other disciplines, with the final research team representing a broad spectrum of interests and skills. The initial reconnaissance of Christmas Island in March, 1971, allowed the team to explore various portions of the island and to formulate a plan of research based upon a tentative Artemia-production scheme. Other than obtaining some general information on hydrography, geology, and general physiography, this first expedition spent an inordinate amount of time dealing with transportation and logistics problems which proved valuable in planning a second expedition and in our later considerations of the construction and operation aspects of the proposed culture scheme.

As the result of recommendations made during the March, 1971, visit to Christmas Island, a concept of utilizing the F-series of interconnected lakes evolved. It was envisioned that the natural flow of water, possibly utilizing controlled tidal flow, a siphon system, and even wind-powered pumps, might be used to manipulate water in which the shrimp are raised and aid in transferring them into high-salinity water to initiate egg production. Because Artemia eggs are presently the highest value brine shrimp product that can be produced, it was concluded that a culture scheme should be devised specifically for their production, with adult shrimp and possibly other aquacultural organisms being a secondary consideration. It was envisioned that once a profitable brine shrimp egg production scheme was operational, other related activities would readily follow.

The objectives of the second expedition were more clearly defined as a result of the first visit. Specific physiographic, biological, hydrographic, and geological studies were planned and executed. It seemed a certainty that large deposits of plant nutrients were to be found on Christmas Island as the result of the huge bird colonies on the island.

As a search for such deposits proved fruitless, we realized that periodic heavy rainfall and the porous substrate typical of much of the island must have resulted in a dissolution and washing of guano into the vast groundwater deposits that lie under the island. As we had not anticipated this finding prior to our second expedition, we could only improvise a small well-drilling apparatus which was inadequate to do anything more than give us a general indication that ground water deposits were high in nutrient content. The work of Jenkin and Foale (1968) made extensive nutrient determinations of ground water which showed a relatively high level of plant nutrients, but they did not sample the salt water below the fresh water in the Ghyben-Herzberg lens complex.

In the planning of production facilities during and following the second expedition, a great deal of thought was given to the possibility of utilizing available nutrients, particularly those in the ground water resources near the New Zealand Airfield in the southwest coastal plain at Christmas Island. A combination of our lack of specific knowledge regarding these resources and the high cost of transporting water over a distance of about five miles to the F-series lakes resulted in abandonment of this approach in favor of imported fertilizer. We believe that the utilization of local nutrient sources still has considerable potential and further exploration of the idea should be attempted when other activities are initiated on Christmas Island.

It has been demonstrated by our experiments that phytoplankton can be grown in enriched F-lake waters and that Artemia can be reared upon this phytoplankton. Calculations are presented relative to the nutrient additions needed to stimulate maximum phytoplankton growth, the Artemia productivity that can be expected optimal at phytoplankton densities, as well as the magnitude of egg yields providing the animals are properly fed and manipulated. Much of this information was developed under ideal laboratory conditions, but we are confident that the process can be duplicated in the field at lower levels of productivity.

A plan of production is outlined, involving hatchery, phytoplankton production, rearing, and egg-laying lakes; it provides for expansion as warranted. The scheme has not been worked out in detail because the rather simple requirements for production of Artemia products in the F-lakes allow a number of alternatives and modifications. Thus if difficulties are encountered in modifying the F5 - F6 channel, the operation could be modified to utilize other adjacent bodies of water.

It is envisioned that management of the lakes is going to be the principal challenge in this proposed scheme, requiring an extremely resourceful biologist (production manager) and several assistants. It is obvious from our laboratory and initial pilot studies in Hawaii that in order to maintain a balance between phytoplankton production, adult Artemia population levels, and sustained egg production, careful monitoring and manipulation of the various interacting parameters must be executed. Changes in salinity and the water level of some lakes during periods of heavy rainfall will pose some management problems that should be considered in the initial modification of the lakes for production. Because the proposed scheme involves a rather simple ecosystem, it should be possible to maintain a steady state. An attempt will be made to develop a mathematical model to aid in the management of this production scheme. If this is successful, certain environmental and population parameters could be monitored at Christmas Island and the essential data relayed to Hawaii where predictions on future management practices could be made with the aid of the model and a computer. This implies the maintenance of monitoring and communications systems.

A number of assumptions were made in developing the economic aspects of this study. These are our best estimations but we expect that after further consultation with contractors, suppliers, etc., these figures will be refined. They have been refined since the preparation of the preliminary report (Helfrich et al, 1972).

The Artemia production scheme proposed cannot be undertaken without a recognition of the risks involved. The risks in the proposed brine shrimp culture venture may be viewed as those inherent in the scheme itself and those that relate to other activities that might be undertaken to share in the overhead costs. We have tried to explore most of the elements of risk inherent in the culture scheme deemed important, in order to elucidate and minimize them.

We did not attempt any large-scale enrichment of lakes or production of Artemia in natural bodies of water at Christmas Island because of time limitations. We have proposed a sequence of developmental activities that lead directly into large-scale production. This course was chosen because of the high cost of transporting materials and heavy equipment to the island, but is obvious that it involves a greater element of risk for a more rapid return on the investment made. A more conservative approach might be considered, in which a pilot venture was first established at Christmas Island followed by full production if warranted. This approach would have the added advantage of allowing more detailed site surveys and production plans, but it would probably extend the time until full production was realized by nine months to one year.

In selecting a site, our time and resources were severely limited. We chose a location during our March, 1971, visit (the F-series of lakes) around which we developed a production scheme. An important factor in our consideration was the fact the F-series were interconnected, thus minimizing modifications needed, and that they were of increasing salinity. These positive factors are perhaps outweighed by their remoteness from the supporting facilities such as the port, airfield, and villages. A distinct advantage to undertaking an initial pilot operation lies in the fact that it would allow time for a further evaluation of alternatives in siting.

The role of other enterprises that might share in the cost of transportation, utilities and other overhead items cannot be overemphasized, as a way of reducing the risks on the success of any single venture at Christmas Island. An offshore fishing operation with an ice plant and other support facilities on Christmas Island, coupled with regular air service to Honolulu, are presently being considered. Such ventures would undoubtedly have a significant impact upon the overhead costs of any other enterprise at Christmas Island. Several other business ventures may warrant further investigations, including the following:

- Seaweeds are in high demand by the commercial colloid industry. Seaweeds are cultured for their carrageenans, which are used as emulsifiers in dairy products, prepared foods, and cosmetics. A shallow-water, labor-intensive culture has been successfully carried out in the southern Philippine Islands under a program directed by Dr. Maxwell S. Doty of the University of Hawaii. According to data he presents, yields of 36 tons per hectare are possible (Doty, 1973).

- A marine turtle is reported to nest on Christmas Island (Bryden, personal communication), which suggests that a culture scheme is a distinct possibility. Hatchlings from natural spawnings could be reared in natural lakes equipped with low enclosing barriers. A number of products including the shell, leather, oil and meat are presently being marketed from a turtle culture farm in the Caribbean. If such a culture is undertaken, strict conservation practices should be initiated in order to maintain or increase the natural breeding stock.

- Other aquaculture programs involving species for which the technology is presently being developed might be well suited to Christmas Island. These include penaeid shrimp, mullet, jacks or pompano, homarid lobster, and others. It should be noted that several species of fish might be cultured with surplus Artemia as an important element in their diet.

- A sport fishing resort might be developed. (See Appendix A.)

- Vegetables might be produced in plastic greenhouses. Jenkin and Foale (1968) report that the American forces during World War II successfully cultured vegetable crops at a point north of London village on Christmas Island. Techniques have been developed for the high-yield production of vegetable crops in inflatable greenhouses in the tropics (Hodges, 1969). This technology should be readily adaptable to Christmas Island; whether the produce could be profitably exported to the Hawaiian market would have to be determined.

In an attempt to determine if this type of specialized vegetable crop production was possible at Christmas Island, a small pilot project was initiated in 1972. An enclosed rigid-frame greenhouse was constructed at London village and covered with translucent polyethelene film. With the addition of soluble iron chelate to the porous atoll soil of Christmas

Island, 12 tomato plants produced a total of 300 pounds of tomatoes before the polyethelene ruptured and the experiment was terminated.

- A research center might be operated. The physical location of Christmas Island in the equatorial current system with strong, nearly unidirectional winds and proximity to deep ocean waters all suggest unusual opportunities for research on energy systems. Of course, the most obvious opportunities for biological research relate to the vast lake system, high temperatures, and nutrient potentials for tropical aquaculture.

SUMMARY AND CONCLUSIONS

This report on the feasibility of brine shrimp production at Christmas Island was the result of a team effort on the part of a number of people associated with the University of Hawaii and its Sea Grant Program. Funds were obtained from the U.S. Sea Grant Program and from private industry. Individuals from a variety of disciplines contributed to various parts of the study and aided in the preparation of this report. The principal investigator organized and coordinated this effort, edited this document, and bears full responsibility for the statements contained herein.

The initial objectives of this investigation were: (1) to examine data from an ecological reconnaissance of Christmas Island, in order to determine whether the lakes there can support a viable commercial *Artemia* aquaculture scheme; (2) to determine, through laboratory studies, the requirements for the optimal production of *Artemia* under conditions found in potential culture lakes on Christmas Island and on Maui in the Hawaiian Islands; and (3) to conduct product development, marketing, and economic feasibility studies on the production of *Artemia* as a source of protein for human consumption.

Although the emphasis changed slightly (i.e., it proved impractical to conduct lake studies on Maui) the major objectives were largely attained. The use of *Artemia* directly for human consumption was not thoroughly explored; it will be the subject of future investigations.

Following is a summary of the major points covered by this report and conclusions that we feel are warranted at this time:

- *Artemia* is a remarkable organism from the standpoint of its energy-conversion efficiency, levels of productivity, and its ability to withstand environmental stress, particularly high salinities. An increasing world demand for a steady supply of high-quality brine shrimp products, plus recognized advantages afforded aquaculture of some organisms in tropical environs, prompted a search for large hypersaline bodies of water in the tropics. Christmas Island was chosen and this study conducted on it as a potential site for a commercial *Artemia* culture enterprise in recognition of its natural attributes, including the large number of hypersaline lakes, as well as its existing support facilities and labor force.

Christmas Island is located in the Line Islands approximately 1,000 miles south of Hawaii and 105 miles north of the equator. It is sometimes referred to as the largest atoll in the world with a total area (land and lagoons) of 247 square miles. It lies in the equatorial dry zone with an average annual rainfall of about 34 inches and extremes of 103 and 7 inches recorded. Great variability in rainfall is experienced in the equatorial dry zone, relating to the movements of the intertropical front. Heavy rainfall in the summer of 1972 and the spring of 1973 indicate that this may be one of the wettest cycles yet recorded and lead to an expectation of another dry cycle of six or seven years. The diurnal temperature fluctuates between 24°C and 30°C with an average relative humidity of 70%. A relatively constant easterly wind with an average speed of 8.6 knots is experienced at Christmas Island; it is calm less than 2% of the time. The mean annual sunshine was 9.36 hours per day with a range of 7.9 to 11.1 hours.

● The Line Islands are administered by the British Gilbert and Ellice Island Colony from Tarawa, 2,015 miles to the west of Christmas Island. It has no endemic population. A government-owned copra plantation is operated on Christmas Island manned by contract employees from the Gilbert and Ellice Islands. Christmas Island is visited several times a year by supply vessels; it has no scheduled air service.

The island was discovered by Captain James Cook on December 24, 1777, at which time it was uninhabited. Various guano and copra enterprises have been pursued on the island over the years. It was occupied by the military during World War II and during the British and American Nuclear test programs (1956 - 1962). Its present population consists of more than 500 Gilbert and Ellice Islanders and a few Europeans.

● A study of the geology of Christmas Island was undertaken and the processes involved in its geologic development are discussed. The island is presently in the process of having its internal lagoons and lakes filled by aeolian sediment derived from the emerged coastal plain. As the lakes become more isolated from the lagoon, they are becoming more saline. Nearly 50% of the total area of Christmas Island is occupied by some 500 saline lagoons and lagoon lakes. These lagoon lakes are either connected to the main lagoon by channels or they are completely isolated; some of the isolated lakes are fed from groundwater springs.

A series of lakes was chosen for a brine shrimp culture scheme. These lakes, consisting of nine interconnected lakes, were designated the "F-series".

● A detailed study of the physiography of the "F-series" lakes was accomplished. This series of interconnected lakes have a total estimated surface area of 1,306 acres and an estimated volume of 853×10^6 ft^3. The range of salinities in this series is from 48 o/oo to 101 o/oo, and the average depth is about 15 feet.

● Circulation through the F-series of lakes and within individual lakes received special attention in this study. The flushing rates, residence time of water in each lake, and the effect of tides and other factors on flushing were determined. The tidal effect on each lake relates to proximity to the main lagoon; only the higher tides presently penetrate F6 and F7. A plan for altering and controlling the flow of water through the lakes is proposed.

● The biological aspects of Artemia culture are reviewed. Artemia may occupy a rather private ecological niche, in view of their tolerance for high salinities (to 150 o/oo) and other environmental extremes (temperature 9°C - 35°C). A number of studies of Artemia that have resulted in an extensive knowledge of the biology of this organism are reviewed. Brine shrimp thrive in crowded cultures and have a high food-conversion efficiency. They have a rapid life cycle, reaching sexual maturity two weeks or less after hatching, and they may produce up to 200 nauplii every five days. A sizeable market exists for Artemia as food for aquatic pets and for a rapidly expanding aquaculture industry.

Artemia are herbivorous filter feeders that feed on a variety of unicellular algae. Females have a higher food-conversion efficiency and those feeding upon a more nutritious diet produce a higher percentage of female offspring.

Artemia may concentrate substances from their environment including chlorinated hydrocarbons such as DDT. The present levels of DDT in Artemia from San Francisco Bay and the Great Salt Lake make them less acceptable as food for certain kinds of larval fish presently being cultured.

● The present production of brine shrimp and eggs comes from the harvest of wild populations. There are indications that the imposition of proper management could result in a continuous high yield of Artemia and their eggs in the Christmas Island environment. The unique saline lakes, climate, general physiography, and support potential of Christmas Island make it an advantageous location in which to establish large-scale Artemia production.

● An expanding market exists for brine shrimp products primarily among fish hobbyists and in culture of a variety of aquatic organisms. Other potential uses of Artemia might be in the management of sewage ponds, in animal feeds,and for direct consumption by humans. It is expected that the demand for Artemia eggs might exceed 50,000 gallons per year if other uses are developed and the present price is reduced.

● The suitability of a selected lake at Christmas Island for Artemia culture was investigated. Studies made consisted of: (a) a broad survey of Christmas Island lakes to determine in situ plant nutrient concentrations, (b) the phytoplankton biomass in selected lakes, (c) the response of possible Artemia rearing lakes to various nutrient treatments, (d) the level of nutrients in groundwater, and (e) Artemia egg-hatching experiments in F-lake water.

The existing distribution of plant nutrients in Christmas Island lakes is quite variable. Several correlations were identified, but generally their distribution is complicated by the long residence time of water circulating in the inner lagoon and in lakes,during which time it is influenced in varying degrees by groundwater infusion and other factors such as periodic heavy rainfall. Phytoplankton biomass is generally low throughout the lagoon system, and associated primary production is less than one would expect in this environment. This is attributed to the high salinities generally encountered which restrict numbers of algal species that can survive in such an environment. Dunaliella salina, an alga that thrives in high salinities and is readily fed upon by Artemia, was found in Christmas Island lakes and its growth was stimulated by nutrient additions. No one area at Christmas Island appeared to have any particular advantage for Artemia culture from the standpoint of existing food substrate concentrations. Addition of nutrients to stimulate phytoplankton growth was clearly indicated. Nutrient enrichment experiments were carried out to determine which nutrients might be expected to limit phytoplankton growth at Christmas Island. Addition of nitrogen and phosphorus significantly increased phytoplankton growth in F-lake waters; total enrichment medium was not particularly advantageous when compared with P and N additions. Groundwater sources contain plant nutrients, but insufficient data exist to predict the results of their use as a sole source of nutrients in an Artemia production scheme.

Artemia egg-hatching experiments were carried out in F-series lake water. Good hatches occurred in water from lakes F1 through F5. Poor hatches in lakes F6 and F7 are attributed to high salinities.

- In laboratory experiments under conditions for optimal growth, Artemia reached sexual maturity in seven to ten days. Experiments confirmed that sexually mature Artemia, when subjected to salinity increases of 32 o/oo to 55 o/oo and 90 o/oo produced eggs within two to three days. In order to insure maximum growth and survival, food concentrations must be maintained in excess of 10^4 cells/ml. Based upon experiments using Dunaliella isolated from Christmas Island lakes, projections on growth rates, reproductive rates, nutrient utilization rates, and energy transformations were calculated. Based upon the possibility of attaining 50% of the laboratory productivity at Christmas Island, and upon a number of assumptions outlined, it was calculated that 2,232 gallons of Artemia eggs could be produced per ton of triple superphosphate and 7.15 tons of urea. These fertilizer requirements are maximal because they do not take into consideration recycling of animal metabolites.

- It is estimated that the more than 14 million birds that nest on Christmas Island deposit 200 tons of nutrient-rich guano per year on the island. No significant guano deposits were discovered there and it is speculated that deposits are washed into the porous soil by periodic heavy rainfall. A reservoir of nutrients may lie in the shallow body of groundwater and this should be investigated.

● A proposed scheme for a brine shrimp production, harvesting, and processing system is presented. It is based upon an expected market demand for high-quality *Artemia* eggs of 40,000 to 50,000 gallons within the next few years. The proposed system is based upon use of the F-series of lakes but it does not preclude the use of other locations on Christmas Island. The basic components of the system are (1) hatchery enclosures, (2) rearing lakes, (3) phytoplankton production lakes, and (4) egg-production lakes.

A pilot operation on Christmas Island is a recommended alternative; a small-scale operation can be attempted while final decisions on the location, modifications, and methods of operating the production facility are being considered.

Two alternate plans for *Artemia* egg production are presented: Plan A (15,000 gals/yr) and Plan B (30,000 gals/yr). These plans involve the employment of different patterns of use for lakes F4 and F7.

● The major steps in the harvesting, processing, grading, and packaging of brine shrimp eggs are presented. In addition the harvesting, processing, and freezing of adult brine shrimp are discussed. The potential of the market for freeze-dried shrimp is also considered. Quality control is emphasized in this scheme, as the entire venture is based upon the premise that only with a superior quality product at a competetive price can a substantial portion of the expanding world market for brine shrimp products be captured.

The proposed levels of egg production for the first three years of operation are as follows: Plan A -- 7,500, 15,000, 15,000 gallons per year; Plan B -- 7,500, 20,000, 30,000 gallons per year.

● Cost projections for brine shrimp production are presented and discussed. An attempt is made to break down costs into that portion which can be appropriately borne by the Gilbert and Ellice Island government and that which can be borne by outside interests. A sequence and schedule of developmental activities is proposed that would allow production to start within six months of a decision to proceed. A number of projected costs and expected profit tables for brine shrimp products are presented.

A preliminary cash flow summary for brine shrimp egg production indicates a positive cumulative balance of $7,521 from the second production year (Plan A) and a positive cumulative balance of $174,932 from the third production year (Plan B). The total cumulative balances from the fourth production year are $315,881 for Plan A, and $522,082 for Plan B.

A detailed breakdown of costs of construction and operation of the project under Plans A and B is presented.

- A number of unused camps and seldom-used airfields, roads, and other support facilities make Christmas Island an attractive site for a commercial venture. Some of the facilities worthy of special note are diesel-powered generators, a bulk fuel-storage facility with a capacity of 149,500 Imperial gallons, a fresh water supply estimated at 7 x 10^9 gallons, a marine railway, and port facilities. The port is presently usable only by shallow-draft barges due to silting of the approach channel. Numerous warehouses and a cold-storage plant with a total capacity of 11,700 cubic feet exist, but all are in need of repair. A 6,000-foot paved airfield exists on the northern portion of the island with an additional paved runway at the eastern end of the island.

- The evolution of the research plan for Christmas Island *Artemia* production and the rationale for utilizing the F-series lakes are discussed. We are confident that with proper nutrient enrichment, monitoring, control, and manipulation, the laboratory-scale operations that resulted in shrimp and egg production in Hawaii can be duplicated at Christmas Island at somewhat lower levels of efficiency. This will require sophisticated management practices by knowledgeable and resourceful individuals.

- Other enterprises pursued simultaneously with the *Artemia* venture at Christmas Island would presumably share the cost of transportation, utilities, and general overhead, and would greatly reduce the risk on the success of a sole venture. A sport-fishing resort development appears to be an attractive possibility as an additional venture, and a tentative proposal for it is presented in the Appendix. Other enterprises suggested include (1) the culture of seaweed for marine colloids, (2) turtle culture, (3) the culture of various species of fish and shellfish, (4) the culture of vegetable crops in plastic greenhouses, and (5) the use of Christmas Island as an equatorial research center.

APPENDIX

TENTATIVE PROPOSAL
FOR SPORT FISHING RESORT DEVELOPMENT

The prospects for sport-fishing resort development at Christmas Island were investigated. The ideas presented here are preliminary in nature. The rationale for this development is to have several concurrent activities that can share costs of transportation, support facilities, and other items of overhead. It is proposed that the facilities at JOC camp be established as the common support camp for the majority of commercial activities at Christmas Island. This choice is made because of its location relative to the proposed Artemia production site, the airport, London village, and Banana Wells village. This would then suggest that an ideal location for a resort development would be the old Sailing Club approximately 1-1/2 miles from JOC camp. (See Figure 33.) The old Sailing Club is adjacent to sheltered waters with access to the open lagoon. The site is served by a road off the main lagoon road, and it is centrally located to all of the major activities outlined above.

A small operation not exceeding 50 guests is envisioned, with "rough it" open-type facilities, catering to the light-tackle enthusiasts such as those who are willing to make substantial expenditures to angle for the 2- to 5-pound bonefish of Florida and the Bahamas. Christmas Island offers not only superb bonefishing but excellent fishing for jacks, tuna, wahoo, barracuda, and a variety of other reef and pelagic species.

Lagoon Fishing

This is a major attraction for the light tackle buff, requiring a minimum of equipment, and is easy sport in which to train natives as guides and boatmen. The key performer would be the bonefish (*Albula vulpes*) which most sport fishermen consider to be one of the gamest fish in the world. The world's record for this fish on 20-pound test line is only 14 pounds. Net catches by Christmas Island natives yielded bonefish in exdess of 25 pounds (Plate 52). Members of our party caught and released specimens in the 12- to 15-pound class. Many of the 500 lakes are connected by channels with the main lagoon, and they harbor an abundance of bonefish, carangids (jacks), and other species providing a rich source of recreation from the generally unobstructed shoreline or from a small boat (Plate 53). A network of trails that could support wheeled vehicles could be laid out to make the inner lakes accessible from land. (Many such trails were laid out during the November, 1971, expedition.) Five outboard-powered skiffs and ten 4-wheel drive "Land Cruisers" plus camp facilities should be adequate to start this operation.

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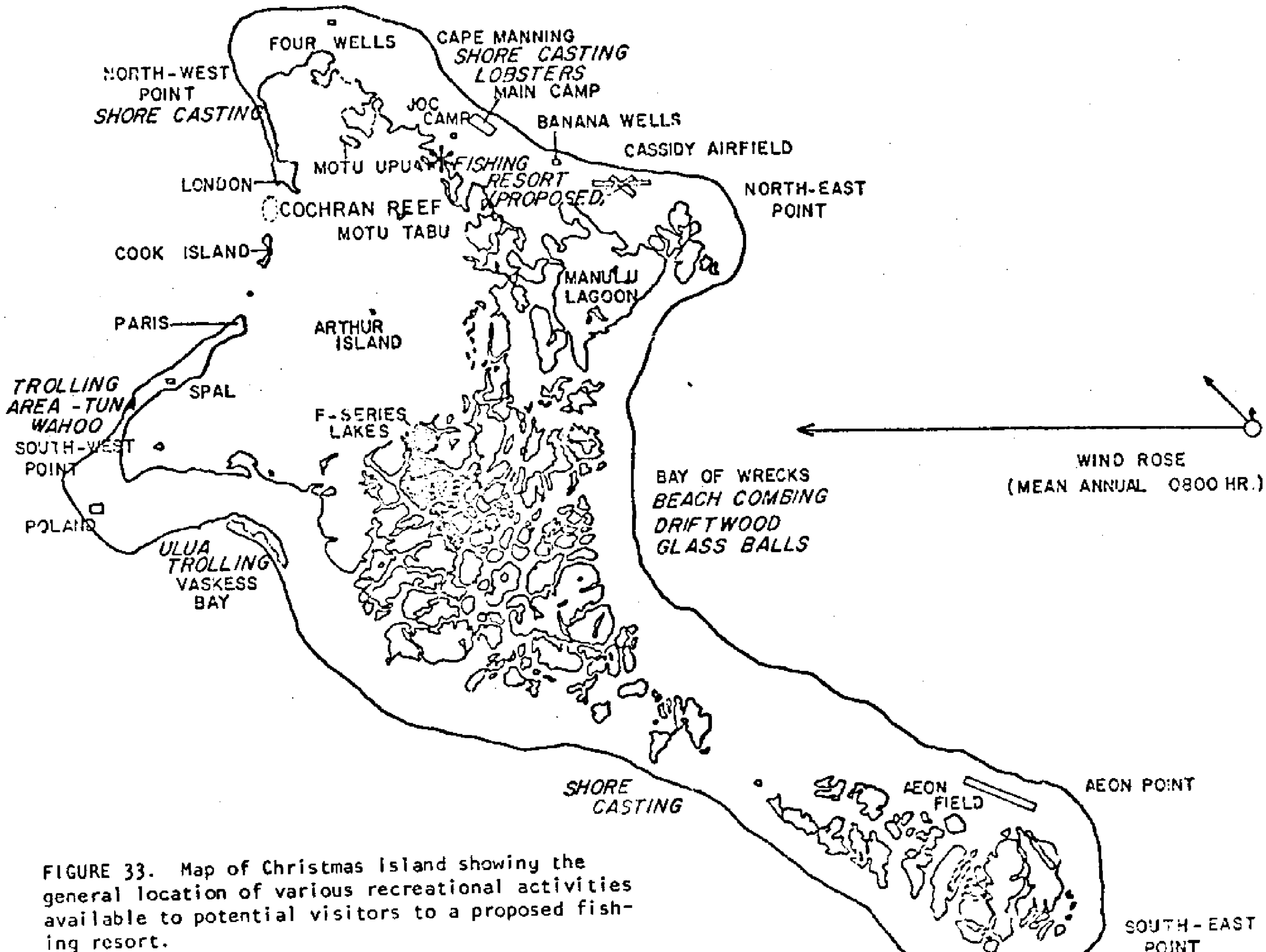

FIGURE 33. Map of Christmas Island showing the general location of various recreational activities available to potential visitors to a proposed fishing resort.

Plate 52. Natives with net catch of bonefish and awa.

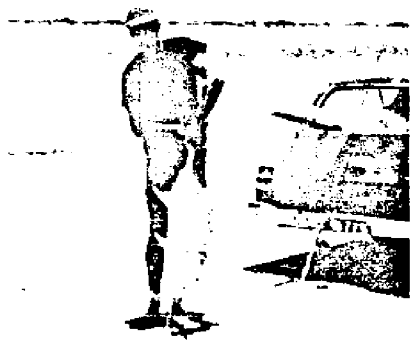

Plate 53. Jack or ulua taken by shore casting.

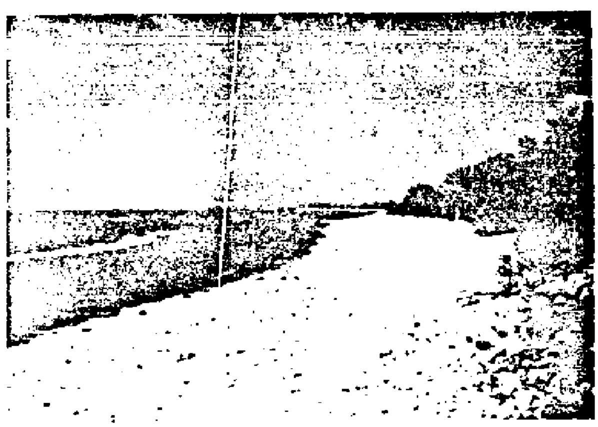

Plate 54. Fringing ocean reef adjacent to main camp area.

Ocean-Shore Casting

Lively sport can be obtained with light casting tackle and lures over the well-formed fringing reef flat that surrounds most of Christmas Island. A road that follows most of the ocean shoreline allows easy access to the approximately 100 miles of the encircling fringing reef (Plate 54). The fish most frequently taken in these reefs are carangids (pompano, ulua, papio, jacks) from 1 to 20 pounds (Plate 55).

Ocean Trolling

Christmas Island's location in the equatorial zone of enrichment provides an abundance of offshore game fish including yellowfin tuna, wahoo, ulua, mahimahi, billfish, skipjack tuna, barracuda, and sharks. (The latter are considered by some not to be strictly a game fish.) The attached list of large pelagic species is reported by Murphy and Shimura to be based upon long-line catches, but it includes "...those likely to be captured by trolling or to be seen at the surface" (Table 31).

During military operations at Christmas Island sport fishing was a popular recreational activity, and both the Americans and British operated deep-sea fishing boats which seldom failed to produce good catches. One of the favored fishing locations is off the relatively sheltered southwest point, a mere 11 miles from the port at London village. Record catches from the second period of American Joint Task Froce Operations, April, 1962, to September, 1963, are noted in a "Guide to Fishes of Johnston and Christmas Island". During November of 1971, two trial recreation-fishing expeditions were conducted to assess the potential for sport catches in the vicinity of the SW point at Christmas Island. On November 7, a party of four persons went out on the 26-foot plantation vessel JAMES COOK. Under the direction of Mr. Glen Fredholm, an experienced sport fisherman, three trolling lines utilizing plastic lures were initiated with a trolling speed of approximately 6 to 8 knots. Time fishing was approximately 4-1/2 hours or 13-1/2 line-hours. A second party with an effort of 12 line-hours fished on November 8, 1971. The results of these fishing efforts, conducted largely by inexperienced fishermen, are presented in Table 32 and illustrated in Plates 55 and 56.

One of the problems with sport fishing at Christmas Island relates to the abundance of reef sharks that attack fish on the line before they can be landed. These attacks plus lack of a fighting chair and gimbal caused the party to abandon "rod and reel" fishing after losing a tuna estimated well over 100 pounds to sharks. Heavy handlines were used for the balance of the fishing and only one large wahoo and two tuna about 20 pounds in weight were lost to sharks; however, they were observed pursuing other hooked fish. The work of Tester (1968) in Hawaii indicates that reef sharks probably occupy a territory and that sustained fishing effort can rapidly reduce numbers in a given area. It is conceivable that a special effort to reduce the number of reef sharks could be undertaken, to improve this sport fishery.

Plate 55. Catch of carangids from Vaskess Bay area.

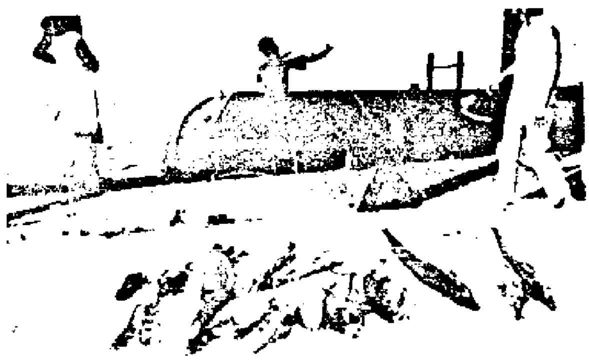

Plate 56. Crewmen unloading catch of wahoo, tuna and variola.

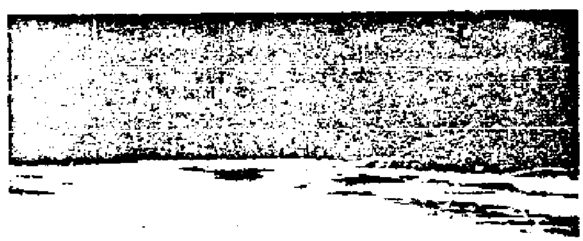

Plate 57. Broad sand beach along southwest coast.

TABLE 31. SPECIES OF FISH LIKELY TO BE CAPTURED BY TROLLING OR OBSERVED NEAR THE SURFACE IN THE VICINITY OF CHRISTMAS ISLAND (after Murphy and Shimura [1972])

Albacore, *Thunnus alalunga* (Bonnaterre)
Barracuda, *Sphyraena barracuda* (Walbaum)
Bigeye tuna, *Thunnus obesus* (Lowe)
Blue marlin, *Makaira ampla* (Poey)
Bonita shark, *Isurus glaucus* (Muller and Henle)
Broadbill swordfish, *Xiphias gladius* (Linnaeus)
Common dolphin, *Corphaena hippurus* (Linnaeus)
Great blue shark, *Prionace glauca* (Linnaeus)
Lancetfish, *Alepisaurus* sp.
Sailfish, *Istiophorus platypterus* (Shaw and Nodder)
Shortnose spearfish, *Tetrapturus angustirostris* (Tanaka)
Silky shark, *Eulamia floridanus* (Bigelow, Schroeder & Springer)
Skipjack tuna, *Katsuwonus pelamis* (Linnaeus)
Striped marlin, *Makaira audax* (Philippi)
Wahoo, *Acanthocybium solandri* (Cuvier & Valenciennes)
White marlin, *Istiompax marlina* (Jordan and Hill)
Whitetip shark, *Pterolamiops longimanus* (Poey)
Yellowfin tuna, *Thunnus albacares* (Bonnaterre)
Rainbow runner, *Elagatis bipinnuatus*
Crevalles (Jacks), *Caranx melampygus*

TABLE 32. SPECIES OF FISH CAUGHT BY TROLLING ON NOVEMBER 5 AND 7, 1971 IN AN AREA APPROXIMATELY 1 MILE OFF SW POINT, CHRISTMAS ISLAND

The total effort was 25-1/2 line-hours.

Species Landed		No. Landed	Approximate number (size in pounds)
Common Name	Scientific Name		
Wahoo	Acanthocybium solanderi	6	1(74), 1(50), 1(40), 2(30), 1(20)
Yellowfin Tuna (Ahi)	Thunnua albacares	11	1(30), 7(20), 3(15)
Oceanic Bonito (Aku)	Katsuwonus pelamis	3	3(5)
Jacks (Ulua)	Caranx melampygus	8	1(40), 1(30), 4(25), 1(20), 1(10)
Jacks (Papio)	Caranx melampygus	5	1(6), 2(4), 1(3), 1(2)
Sea Bass * (Variola)	Variola louti	9	1(20), 5(15), 1(12), 2(10)

Total number landed: 42
Total weight: 795 lb
Average catch/line-hour: 1.65 fish
Pounds fish/line-hour: 31.18 lb

* Caught in shallow water

Note: One large Ahi (over 100 lb), one Ono (30 lb) and two Ahi (20 lb) lost to sharks.

Personal experience during the period 1960 to 1965 attests to the relative constant nature of this localized sport fishery in the lee of Christmas Island. Parties going out several times a week during that period experienced no detectable decline in catches over that period.

Trolling in other areas around Christmas Island was not assessed, but reports from local residents indicate that SW point yields consistently good catches, possibly due to oceanographic conditions in the area. During the 1962 military operations, it was named "Wahoo Alley".

Ocean-Bottom Fishing

Bottom fishing for red snappers, groupers, and other reef fishes off Cochran reef, within 1/2 mile of London village wharf, can provide good recreation if light tackle is used, but catches are quite variable. On several occasions catches of baout 120 fish per hour were made of the red snappers *Lutjanus bohar* and *L. gibbus*. (The catches were limited by the time required to remove the fish and rebait the hook.) On other occasions many hours were spent fishing in the same area, yielding only a few fish. For further details of this fishery and problems relating to possible ciguatera fish poisoning in reef species see Helfrich *et al* (1968).

Other Recreational Activities

Although sport fishing would have to be the principal activity of a resort development on Christmas Island, a number of other activities could be pursued by the visiting sportsman. These include collecting of spiny lobster (also called sea crayfish or langouste) which can be collected on the fringing reefs around Christmas Island on certain tides. Snorkeling and SCUBA diving in some of the rich coral areas off the west side of the island, and in Vaskess Bay, are attractive prospectives. These activities would allow the visitor to indulge in underwater photography, shell collecting, and spear fishing in the clear, warm waters around Christmas Island.

Sailing was a popular sport during the late 1950's and early 1960's when the British Royal Air Force established a sailing club to take advantage of the persistent winds that blow across Christmas Island. Water skiing and cycling were also popular sports at that time. Other activities that may be of interest to the tourist-sportsman include beachcombing along the extensive beach areas for glass floats, driftwood, etc., and observing the vast bird populations nesting on the island (Plate 57).

Preliminary Economic Analysis

Charter aircraft would be used to convey fishermen on a weekly schedule to and from Christmas Island for a week's sport fishing. Since lagoon and shoreline fishing are judged to be the most interesting and feasible sports activities, the week's attention should be focused on these. Until an adequate shark-control program in initiated, open-ocean trolling should be confined to handlines. One day could be devoted to the very lively open-ocean trolling.

The employment of the local people would be a major value of the sport fishing development. In addition, it is viewed as a very valuable complement to the existing enterprises on Christmas Island. With regular air service to and from the island, a vast improvement is possible in the variety of services, such as supply, personnel movement, and medical services, that are dependent upon transportation.

Preliminary estimates of start-up costs (Table 33), weekly expenses and income (Table 34), and a manning schedule (Table 35) are presented. As with every other new endeavor that is contemplated for Christmas Island, there are significant economies in shared costs from several operations. If a local boat-building and fishing industry were to develop, there are obvious benefits to both the brine shrimp project and sport fishing, such as general construction and shop capabilities, freezer storage, and trained small-boat handlers.

TABLE 33. STANDUP COSTS - SPORTS FISHING DEVELOPMENT

Initial reconnaissance and planning	$ 20,000
Camp preparation	20,000
Ocean sports fishing vessel (1)	40,000
Lagoon sports fishing vessels (5)	20,000
Outboard engines, trailers, fishing gear (10)	9,000
Radio and electronics (7 sets)	7,500
Vehicles (10)	25,000
Other recreation equipment	5,000
Promotion (initial)	40,000
Logistics coordination and management	10,000
Estimated Initial Investment	$196,500

TABLE 34. ESTIMATED WEEKLY EXPENSES AND INCOME FROM SPORTS FISHING DEVELOPMENT

Based upon full occupancy.

	Full Occupancy (50 guests)		60% Occupancy (30 guests)	
EXPENSES				
Transportation		$12,000		$12,000
Food		2,100		1,260
Fuel		250		250
Maintenance supplies		200		120
Expendables (fishing gear, etc.)		100		60
Labor		840		840
Management and coordination		1,625		1,625
Promotion		1,000		1,000
Total Estimated Expenses		$18,115		$17,155
Expenses/fisherman	$363		$572	
INCOME				
Transportation charge:				
Total		$15,000		$ 9,000
Per fisherman	300		300	
Support @ $50/day:				
Total		17,500		10,500
Per fisherman	350		350	
Total Estimated Income		$32,500		$19,500
Income/fisherman	$650		$650	
INCOME less EXPENSES				
Total		$14,385		$ 2,345
Per fisherman	$287		$ 78	

TABLE 35. MANNING SCHEDULE FOR SPORT FISHING DEVELOPMENT

Source of Personnel	Job Description	No. of Individuals	Weekly Salary	Total Wages Per Week
O.C.	Manager	1	$300	$ 300
O.C.	Facilities & Food Supv.	1	250	250
O.C.	Equipment & Vessels Supv.	1	250	250
O.C.	Tour Guides	2	250	500
O.C.	Logistics & Promotion Coordinator (1/2 time)	1	175	175
O.C.	Secretary	1	150	150
		Total O.C.		$1,625
			(@ $3/day)	
L.C.	Boat Handlers & Guides	15	21	$ 315
L.C.	Drivers & Guides	10	21	210
L.C.	Facilities & Food	5	21	105
L.C.	Equip. & Vessel Maintenance	5	21	105
L.C.	Support	5	21	105
		Total L.C.		$ 840

BIBLIOGRAPHY

Antia, N.J. and J. Kalmakoff. 1965. Growth rates and cell yields from axenic mass culture of fourteen species of marine phytoplankton. *Fish. Res. Bd. Can. Manuscript Rept.* (Limnol. & Oceanogr. Series) No. 203.

Arrow, T. 1954. *The hydrology of the Northern Marshall Islands.* Atoll Research Bulletin 30.

Baker, Mary Jane. 1966. *An ecology of Artemia: factors influencing hemoglobin synthesis and cyst production.* M.S. Thesis, San Francisco State College.

Bardach, John E. 1968. Aquaculture. *Science* 161:1098-1106.

Bardach, John E. and J. Ryther. 1968. *The status and potential of aquaculture.* Prepared for National Council Marine Resources and Engineering Development. Clearinghouse for Fed. Sci. and Tech. Information. Springfield, Va. #PB177671B. 2 Vols. 480 pp.

Bardach, John E., John H. Ryther, and William O. McLarney. 1972. *Aquaculture: the farming and husbandry of freshwater and marine organisms.* Wiley-InterScience. New York. 868 pp.

Bookhout, C.G. and J.D. Costlow, Jr. 1970. Nutritional effects of Artemia from different locations on larval development of crabs. *Helgoländer wiss. Meeresunters* 20:435-442.

Boone, Eleanor and L.G.M. Baas-Becking. 1931. Salt effects on eggs and nauplii of Artemia salina. *J. Gen. Physiol.* 14(6):753-763.

Bowen, Sarane T. 1965. The genetics of Artemia salina. V. Crossing over between the X and Y chromosomes. *Genetics* 52:695-710.

Bowen, Sarane T., J. Hanson, P. Dowling, and M.C. Poon. 1966. The genetics of Artemia salina. VI. Summary of mutations. *Biol. Bull.* 131:230-250.

Bowen, Sarane T. 1968. Thoughts on the aquaculture of Artemia. Unpublished manuscript. 15 pp.

Bryan, E. 1942. *American Polynesia and the Hawaiian Chain.* Tongg Publishing Co., Honolulu. 253 pp.

Caperon, John, S.A. Cattell, and G. Krasnick. 1971. Phytoplankton kinetics in a sub-tropical estuary: eutrophication. *Limnol. & Oceanogr.* 4:599-607.

Carpelan, L.H. 1964. Effects of salinity on algal distribution. *Ecology* 45:70-77.

Cole and Brown. 1967. The chemistry of Artemia habitats. *Ecology* 48(5): 858-861.

Cox, D.C. 1951. *The hydrology of the Northern Marshall Islands.* Atoll Research Bulletin 8.

Croghan, P.C. 1958a. The survival of Artemia salina L. in various media. *J. Exp. Biol.* 35(1):213-218.

Croghan, P.C. 1958b. The osmotic and ionic regulation of Artemia salina (L). *J. Exp. Biol.* 35(1):219-233.

Croghan, P.C. 1958c. The mechanism of osmotic regul:tion in Artemia salina (L): the physiology of the branchiae. *J. Exp. Biol.* 35(1): 234-242.

Croghan, P.C. 1958d. The mechanism of osmotic regulation in Artemia salina (L): the physiology of the gut. *J. Exp. Biol.* 35(1):243-249.

Croghan, P.C. 1958e. Ionic fluxes in Artemia salina (L). *J. Exp. Biol.* 35(2):425-436.

Dees, Lola T. 1961. Brine shrimp. Fishery leaflet 527, U.S.D.I., Washington, D.C.

Delga, J., J.L. Meunier, C. Pallaget, and J. Carious. 1960. Les mangeurs de vers. *Annales des Falsifications et de l'Expertise Chimique* No. 617.

Doberitz, R., H. Flohn, and K. Schütte. 1967. Statistical investigations of the climatic anomalies of the Equatorial Pacific. *Bonner Meteorologische Abhandl.* 7:1-78.

Doty, Maxwell. 1973. Eucheuma farming for carrageenan. UNIHI-SEAGRANT-AR-73-02. Sea Grant Program, University of Hawaii, Honolulu.

Dunn, J.R. 1953. The origin of the deposits of tufa in Mono Lake. *J. Sediment. Petrology* 23:18-23.

Dutrieu, J. 1960. Observations biochemiques et physiologiques sur le developpment d'Artemia salina Leach. *Archives de Zoologie Experimentale et Generale* 99:1-135.

Dutrieu, J. and D. Cresta-Blanchine. 1966. Resistance des oeufs durables hydrates d'Artemia salina a l'anoxie. *C.r. hebd. Seanc. Acad. Sci. Paris* (Serie D) 263:998-1000.

Ehrlich, Paul R. 1968. *The Population Bomb.* Sierra Club-Ballantine Book, New York. 23 pp.

Eppley, R.W., J.N. Rogers, and J.J. McCarthy. 1969. Half-saturation constants for uptake of nitrate and ammonium by marine phytoplankton. *Limnol. & Oceanogr.* 14:912-920.

Fairbridge, R.W. 1952. Multiple stands of the sea in post-glacial times. *Proc. of the Seventh Pac. Sci. Cong.*, Vol. 3.

Folk, R.L. 1965. Petrology of Sedimentary Rocks. Hemphill's, Austin, Texas. 159 pp.

Fuhs, G.W. 1969. Phosphorus content and rate of growth in the diatoms Cyclotella nana and Thalassiosira fluviatilis. *J. Phycol.* 5:312-321.

Fujinaga, Motosaku. 1969. Method of cultivation of penaeid shrimp. U.S. Patent Office 3,477,406. U.S. Cl. 119-2, Ser. No. 650,067. 14 pp.

Gallagher, B. and W. Munk. 1971. Tides in shallow water: spectroscopy. *Tellus* 23:346-363.

Gallagher, B., K. Shimada, F. Gonzalez, and E. Stroup. 1971. Tides and currents in Fanning Atoll Lagoon. *Pac. Sci.* 25:191-205.

Gentilli, J. 1952. Climatology of the Central Pacific. *Proc. Pacif. Sci. Congr. 1952*, 3:92-100.

Gibor, Aaron. 1956a. The culture of brine algae. *Biol. Bull.* 111: 223-229.

Gibor, Aaron. 1956b. Some ecological relationships between phyto and zooplankton. *Biol. Bull.* 111:230-234.

Gibor, Aaron. 1957. Conversion of phytoplankton to zooplankton. *Nature* (London) 179:1304.

Gilchrist, B.M. 1954. Hemoglobin in Artemia. *Proc. Royal Soc. London* Series B 143(910):136-146.

Gilchrist, B.M. 1956. The oxygen consumption of Artemia salina (L) in different salinities. *Hydrobiologia* 8:54-65.

Gilchrist, B.M. 1958. The oxygen consumption of Artemia salina. *Hydrobiologia* 12:26-37.

Gilchrist, B.M. 1960. Growth and form of the brine shrimp Artemia salina (L). *Proc. Zool. Soc. London* 134(2):221-235.

Grosch, D.S. 1967. Poisoning with DDT: effect on reproductive performance of Artemia. *Science* 155:592-593.

Hammond, L.L. 1969. *The characterization and classification of the soils of Christmas Island.* M.S. Thesis, University of Hawaii. 109 pp.

Heldt (Mme.), Henri. 1926. Sur la presence d'un crystuceriude chez Artemia salina L. Station Oceanographique de Salammbo. *Notes Tunis* 5:3-8.

Helfrich, P., T. Piyakarchana, and P. Miles. 1968. Ciguatera fish poisoning. Part I. The ecology of ciguatera reef fish in the Line Islands. Occasional Papers of B.P. Bishop Museum, Honolulu, 23(14): 305-369.

Helfrich, Philip. 1972. A preliminary report on the feasibility of brine shrimp production on Christmas Island (Central Pacific). University of Hawaii. 233 pp.

Herlad, E.S. and R.P. Dempster. 1965. Brine shrimp vs. copper solutions. *Aquarium Journal* 36:334-336.

Hodges, Carl and Carle O. Hodge. 1971. An integrated system for providing power, water and food for desert coasts. *Hort. Science* 6(1):10-16.

Hutchinson, G.E. 1950. Survey of existing knowledge of biogeochemistry 3: the biogeochemistry of vertebrate excretion. *Bull. Amer. Mus. Natur. Hist.* 96:182.

Jenkin, R.N. and M.A. Foale. 1968. An investigation of the coconut-growing potential of Christmas Island. Ministry of Overseas Dev., Resources Division, Directorate of Overseas Surveys, Tolworth, Surrey, England. Land Resources Study 4, Vol. 1.

Jenne, Fred. 1960. Story of the brine shrimp. *Aquarium Journal* 31: 7, 331-335.

Jones, F.R.H. 1972. An inexpensive apparatus for the large-scale hatching of Artemia salina L. *J. du Conseil* 34(3):351-356.

Kamienski, T. 1899. Notice preliminaire sur la nouvelle espece de Metschnikcwia. (Monospora Metschn.) *Trav. Soc. Imp. Natural. S. Petersb.* 30:363-364.

Khmelva, N.N. 1968. The expenditure of energy on respiration, growth, and reproduction in Artemia salina (L). Biologiya Morya. *Fiziologicheskie osnovy ekologii vodnykh zhivotnykh* 15:71-97.

Krasnick, G. and J. Caperon. 1973. Primary productivity in a nutrient-limited tropical estuary. In press.

Mason, David T. 1963. The growth response of Artemia salina (L) to various feeding regimes. *Crustaceana* 5:138-150.

Mason, David T. 1967. Limnology of Mono Lake, California. *University of California Publications in Zoology* 83:1-103.

Mathias, P. 1934. Sur la biologie de l'Artemia salina L. (Crustace Phyllopode). Annales des sciences naturelles. *Zoologie. Paris.* Ser. 10, Tome 17:433-439.

Menard, H.W. 1964. *Marine Geology of the Pacific.* McGraw-Hill Book Co., London. pp. 79-92.

Murphy, G.I. and R.S. Shomura. 1972. Pre-exploitation abundance of tunas in equatorial Central Pacific. *Fish. Bull.* 70(3):875-913.

Murphy, R.C. 1936. *Oceanic Birds of South America* 2:841.

Murphy, R.C. 1964. *In a New Dictionary of Birds.* (A.L. Thomson, ed.). McGraw-Hill Book Co., New York.

Nimura, Yoshkachiro. 1963. Effects of different concentrations of Chlamydomonas on the grazing and growth of Artemia with reference to the salinity of its living medium. *Bull. Jap. Soc. Sci. Fish.* 29: 424-433.

Nimura, Y. 1967. Biology of the brine shrimp - Review. *Bull. Jap. Soc. Sci. Fish.* 33:690-702.

Northrup, John. 1962. *Geophysical observations on Christmas Island.* Atoll Research Bull. 89:1-2.

Odum, E.P. 1971. Fundamentals of ecology. 3rd ed. W.B. Saunders, Co., Philadelphia. 574 pp.

Parker, G.H. 1900. Lake Urmi. *The American Naturalist* 34:315.

Provasoli, L., K. Shiraishi, and J.R. Lance. 1959. Nutritional idiosyncrasies of Artemia and Trigriopus in monoxenic culture. *Ann. New York Acad. Sci.* 77:250-360.

Reeve, M.R. 1963a. The filter-feeding of Artemia: I. In pure cultures of plant cells. *J. Exp. Biol.* 40:195-205.

Reeve, M.R. 1963b. The filter-feeding of Artemia: II. In suspensions of various particles. *J. Exp. Biol.* 40:207-214.

Reeve, M.R. 1963c. The filter-feeding of Artemia: III. Fecal pellets and their associated membranes. *J. Exp. Biol.* 40:215-221.

Reeve, M.R. 1963d. Growth efficiency in Artemia under laboratory conditions. *Biol. Bull.* 125:133-145.

Ritchie, G.S 1958. Sounding profiles between Fiji, Christmas, and Tahiti Islands. *Deep Sea Res.* 5:162-168.

Roy, K.J. and S.V. Smith. 1970. Sedimentation and coral reef development in turbid water: Fanning Lagoon. Hawaii Institute of Geophysics Report HIG-70-23:61-76.

Schreiber, R.W. and N.P. Ashmole. 1970. Sea-bird breeding seasons on Christmas Island, Pacific Ocean. *Ibis* 112:363-394.

Seelye, C.J. 1950. Rainfall and its variability over the central and south western Pacific. *N.Z. Jl. Sci. Technol.*, Sect. B, 32:13-24.

Sick, Lowell V. 1968. The nutritional effect of five species of marine algae on the growth, development and survival of the brine shrimp Artemia salina. M.S. Thesis.

Solorzano, L. 1969. Determination of ammonia in natural waters by the phenolhypochlorite method. *Limnol. & Oceanogr.* 14:799-801.

Spencer, J.T.F., H.J. Phaff, and N.R. Gardner. 1964. Metschnikowia kamienskii, Sp.N., a yeast associated with brine shrimp. *J. bacteriol.* 88:758-762.

Strickland, J.D.H 1965. Production of organic matter in the primary stages of the food chain. In J.P. Riley & G. Skirrow (ed.). *Chemical Oceanography*, Vol. I. Academic Press, New York.

Strickland, J.D. and T.R. Parsons. 1968. A practical handbook of seawater analysis. *Fish. Res. Bd. Can. Bull. 311.* 167 pp.

Sushchenya, L.M. 1962. Quantitative data on the nutrition and energy balance in Artemia salina (L) (In Russian). *Doklady Akademii Nauk. U.S.S.R.* 143(5):1205-1207.

Sushchenya, L.M. 1964. Quantitative data on filter-feeding of Artemia salina. *Trans. of Sevastopol Biological Station* 15:434-445.

Teramoto, Kenichiro and Shukuo Konoshita. 1961. Some Information on the culture of Artemia. *Bull. Jap. Soc. Sci. Fish.* 27:801-804.

Tester, A. 1968. Cooperative shark research and control program. Annual Report 1967-1968.

Tudor, J. 1972. Pacific Islands Yearbook. 11 ed. Pacific Publications. Sydney, Australia. 542 pp.

von Hentig, R. 1971. Einfluss von Salzgehalt und Temperatur auf Artemia. *Mar. Biol.* 9(2).

Wentworth, C.K. 1931. Geology of the Pacific Equatorial Islands. Occasional Papers of Bernice P. Bishop Museum, Honolulu, IX, 15:3-25.

Wentworth, C.K. and H.S. Ladd. 1931. Pacific island sediments. *Stud. Nat. histo.*, Iowa University, 13:1-47.

Weins, H.J. 1962. Atoll Environment and Ecology. Yale University. 532 pp.

Wickins, J.F. 1972. The food value of brine shrimp (Artemia salina) to larvae of the prawn, Palae. seratus. *J. Exp. Mar. Biol. and Ecol.* 10(2):151-170

Wolfe, D.A., and C.L. Schelske. 1967. Liquid scintillation and Geiger counting efficiencies for C^{14} incorporated by marine phytoplankton in productivity measurements. *Journal du Conseil permanent international pour l'exploration de la mer* 31:31-37.

Young, R.T. 1952. The larva of Hymenoplepis californicus in brine shrimp (Artemia salina). *Journal of the Washington Academy of Sciences* 42:385-388.

Zein-Eldin, Zoula P. 1963. Effect of salinity on growth of post larval penaeid shrimp. *Biol. Bull.* 125:188-196.