Biological Systems in North-Western Australian Solar Salt Fields

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ABSTRACT

The principles of salt field biological management as developed by J. S. Davis have been modified and applied to some North-Western Australian solar salt fields. A monitoring programme designed for planktonic organisms and physico-chemical parameters has been implemented for the Dampier solar salt field at weekly intervals for nine years. This intensive monitoring together with laboratory investigations on selected brine organisms has revealed factors controlling biological proliferation in a continuous flow salt field. Results from investigations on brine organisms in the Dampier salt field are widely applicable to North-Western Australian salt fields. The practical aspects for effective biological management are noted and possible corrective measures duly described.

INTRODUCTION

The importance of the algal mat for the solar salt industry was recognised long before the organisms themselves were observed (Baas Becking, 1931). Von Buschmann (1909) in his two volumes on salt described the saltworks at Istria in the Adriatic and stated "Schwarzer Grund, weiszes Saltz". When the bottom is covered with an algal film the salt may be harvested without contamination by the black sulphide muds which lie immediately beneath. The Portuguese salt from the ancient salina at Setubal is of superior quality according to von Buschmann (l.c.) because the algal cover allow for quicker diffusion of magnesium salts than sodium chloride. Great care is taken not to injure the algal carpet during harvest.

Early biological studies concentrated on the ability of organisms to survive increasing salinity and concentrated brine (Teodoresco, 1906; Biswas, 1926; Baas Becking, 1928; Van Neil, 1931; Hof and Frémy, 1933).

The increasing use of mechanisation and further development of salt field process technology saw the construction of larger salt fields (salinas) with large crystallising ponds. In consequence of holding greater depths of salt, the ingress and establishment of organisms across salinity gradients in such an artificially created system presented new areas of study, as blue-green algal mats rarely develop in these newer crystallising areas.

In contrast to many natural saline systems, algal mats in sea water based solar salt fields appear to be dominated by unicellular colonial cyanobacteria (blue-green algae) producing mucilage (Bauld, 1981). Golubic (1980) noted that *Aphanothece* (*Coccochloris*) is the most common genus that forms mucilagenous coatings in the benthos of many salt ponds. Seshadri and Buch (1958) observed that *Aphanothece* and other blue-green algae formed a jelly which adhered to the salt crystals, colouring the salt and imparting a foul smell to it. Rapid solar evaporation of brine from Sambhar Lake in India, resulted in a green pasty mass of crystals with no appreciable change in the colour of the algae (Sapre and Mehta, 1956). Overproduction of this alga also gave rise to undesirably high brine viscosities at Port Alma, Australia (Jones et al., 1981).

The resultant impairment to salt quality and associated problems with processing required a better understanding of the interaction between physical and biological parameters in salinas. Studies by Carpelan (1964), Copeland (1967), Borowitzka (1981), Post (1977, 1981), Bauld (1981), Jones et al. (1981) and Davis (1974, 1978a) elucidated the interactions, while Davis (1978b) discussed biological management of solar saltworks.

THE PHYSICO-CHEMICAL ENVIRONMENT

The positioning of solar salt fields in arid coastal regions has certain design advantages, as the coastal waters already have some degree of hypersalinity. This factor, together with high evaporation and very low rainfall, ensures a year round salt production because established design physico-chemical factors in each pond can be maintained, subject to operational demands.

The solar salt field at Dampier draws coastal marine waters and concentrates the brine through six primary ponds (Figure 1). Associated with the increasing salinity for each successive primary pond are consequential changes in levels of dissolved oxygen, pH, brine temperature and available nutrients (e.g. phosphates and nitrates), which, in turn, directly regulate the propagation of the salt field biota. The significance of these factors is discussed below.

Hydrogen Ion Concentration. Extremes of pH are normally toxic to biological organisms because of the influence on cell surface charges, or the ionic state of metabolites and inorganic ions. Such major fluctuations may result in mass mortality or organisms or a selection for organisms capable of tolerating such changes. Brine pH also demonstrates biological activity such as photosynthesis and respiration. This measurement is, therefore, an important factor for determining the growth and health of brine organisms.

The hydrogen ion concentration of concentrating sea water increases to a value above pH 9 just before saturation with calcium carbonate, and decreases rapidly when carbonate precipitation occurs (Copeland, 1967). A general decrease follows further evaporation until equilibrium is reached at about pH 7.8 when the salinity reaches about 200 ppt (s.g. 1.17).

Carbonate precipitation in the Dampier salt field occurs in Pond 1A, and in subsequent ponds the pH drifts towards neutrality as further evaporation occurs.

Specific Gravity and Salinity. These two measurements reflect water availability which, in the biological sense, selects organisms able to function in low solvent concentration. Changes in solute concentration correspond to changes in water availability resulting in large physiological changes as water is of cricial importance in enzyme catalysis, both as a solvent and a reactant (Jaenicke, 1981). Most organisms have evolved mechanisms for keeping constant the composition of intracellular fluids, known as osmoregulation. The efficiency of this biological mechanism determines the distribution of different brine organisms in a salt field.

Determinations have been conducted on collected brines cooled to 20°C and weighed in s.g. bottles. The measured brine was then used in argentometric titrations

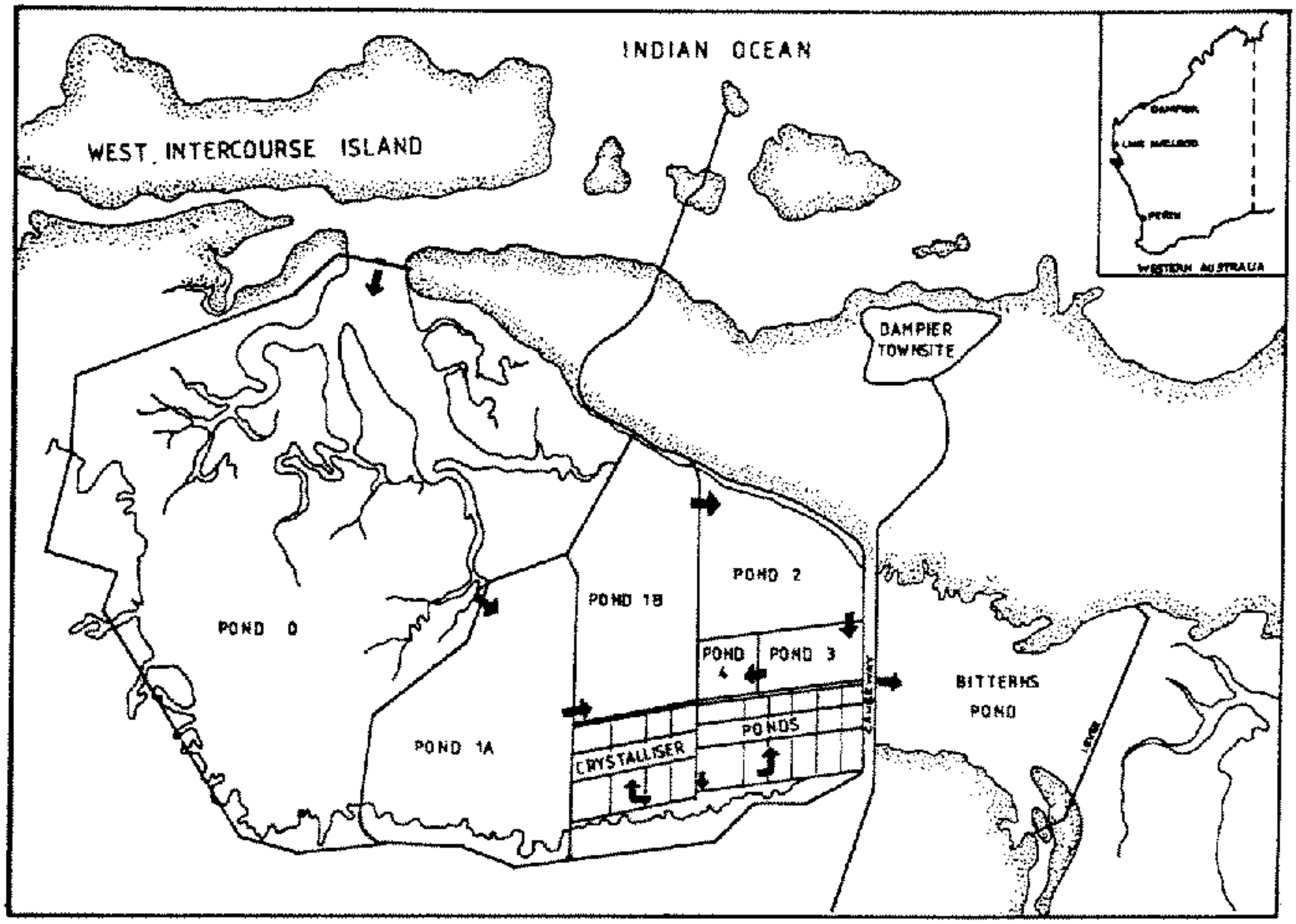

Figure 1. Field layout indicating brine flows for the Dampier solar salt field. Insertion map of Western Australia shows location of Dampier and Lake Macleod.

to estimate salinity (ppt) using the UNESCO (1962) formula. For high density brines, samples were evaporated to dryness and constant weight and then compared to argentometric determinations. These are presented in Table 1.

Dissolved Oxygen. Dissolved oxygen in brine is partly provided from the photosynthesis of chlorophyll-bearing organisms and partly from the atmosphere through diffusion and/or by surface brine turbulence. This element is required for the respiration of organisms, a continuous activity resulting in the production of carbon dioxide. Oxygen is also utilised by aerobic bacteria for the decomposition of organic matter while the presence of soluble iron compounds forming insoluble ferric compounds play an important part in the exhaustion of the dissolved oxygen. Moreover, the solubility of oxygen in brines is dependent on temperature and composition of the electrolyte (Cramer, 1980) with saturated brines and high temperatures recording low dissolved oxygen.

Brine samples were collected in BOD bottles, while in situ dissolved oxygen measurements were taken with a dissolved oxygen meter. BOD bottled samples were determined by the Winkler method with azide modification.

The results in Table 1 clearly confirm reported observations that, as brine concentration increases, conditions become increasingly anaerobic in all except the most turbulent conditions.

Reactive Phosphate. The presence of phosphorus in this form is of prime importance for the growth of organisms as it is incorporated and utilised for protein synthesis, genetic replication and stores of energy.

Reactive phosphate is determined by the molybdate blue method using standard addition. The determinations show very low natural levels in the Dampier field and do not approach the saturation level for any of the different brines (Table 1). These saturation levels were determined gravimetrically.

TABLE 1

Typical Physico-Chemical Recordings for Dampier Solar Salt Field

Source	s.g. @20°C	DO_2 (ppm)	Reactive PO_4 μg-A/l	pH	Salinity (ppt)
Sea	1.026	5.79	0.21	8.20	35.00
Pond 0	1.058	5.29	0.26	8.03	61.77
Pond 1A	1.078	4.51	0.18	8.25	96.50
Pond 1B	1.125	3.25	0.13	8.16	142.79
Pond 2	1.172	2.07	0.05	7.81	177.51
Pond 3	1.198	1.53	0.03	7.62	223.81
Pond 4	1.218	1.28	0.03	7.53	246.96
Cryst. Ser.1	1.224	0.24	ND	7.35	263.16
Ser.2	1.235	0.08	ND	7.20	275.89
Ser.3	1.250	0.05	ND	6.95	293.25

ND—not detected.

Reactive Nitrate. Available nitrate is utilised by organisms mainly in the production of proteins required for the growth process. An actively growing population of organisms will rapidly deplete the brine of nitrate.

A method developed by Prof. M. Avron (Weissman Institute, pers. comm. 1982) proved reliable in application and revealed that brines at the Dampier and Lake Macleod salt fields have low levels of reactive nitrate. This indicates that the population of organisms is utilising this source of nutrient far more rapidly than reactive phosphate.

Dissolved Organic Carbon. Occasionally levels of dissolved organic carbon (DOC) are determined for brine samples using the persulphate reduction method. This measure indicates biological activity whether it be growth or decay. Generally there can be an increase of DOC through the Dampier field with values ranging from 5 to 60 ppm.

Trace Elements. Trace elemental analyses of the salt field brines are also undertaken occasionally using the Inductively Coupled Plasma (ICP) technique in order to monitor changes in levels.

BIOLOGICAL SAMPLING

To understand the process of colonization through the field and possible seasonal effects, plankton samples have been regularly collected at brine transfer locations for a period of nine years. For biological assessment, brine samples are centrifuged and the resultant concentrate examined for species diversity and numbers using a haemocytometer.

Results for all organisms included separate counts of live and dead cells. In the case of blue-green algae, particularly *Aphanothece*, use of nigrosin stain readily distinguishes living and dead cells especially for samples in high salinity brines.

Apart from plankton transport through the field, detailed grid surveys in each of the primary concentrating ponds revealed the structure and composition of benthic communities.

In earlier ponds, fish are sampled using seine nets and by line fishing.

BIOLOGICAL SYSTEMS—DAMPIER SALT FIELD

As typical of salt fields, the increase in brine density from sea water to concentrated brine places a selection pressure on the brine organisms and a succession of organisms is observed in the different ponds. With increasing salinity, species diversity decreases and there is a rapid selection for micro-organisms. This is illustrated in Table 2.

Pond 0. During the construction of the Dampier solar salt field, a very large mangrove-lined tidal creek was enclosed and isolated from the sea. This first primary pond, Pond 0, initially contained a large variety of marine organisms utilising the tidal creek for feeding. As normal

TABLE 2

Species Numbers for the Primary Concentrating Solar Ponds, Dampier

	Primary Solar Ponds					
	0	1A	1B	2	3	4
Sea Grass	1			Not present		
Fish	>65	3		Not present		
Macroalgae	8			Not present		
Diatoms	29	6		Not present		
Dinoflagellates	3	3		Not present		
Blue Green Algae	21	13	7	4	4	4
Brine Fly	2	1		Not present		
Brine Shrimp*	0	1	1	0	0	0
Dunaliella	Not detected	2	2	2	2	2
Crustaceans	6	1		Not present		

*Denotes introduced species.

for tidal creeks in the north-west of Australia, the waters are hypersaline (38 to 42 ppt) all year round, except, of course, during periods of heavy rainfall. The progressive increase in brine density to operational levels caused the death of many marine species and mangroves, thus resulting in the subsequent release of nutrients. This process engendered the growth and proliferation of a limited selection of estuarine species and the establishment of aquatic plants not normally found in abundance in tropical waters.

Large shoals of fish appear periodically and seasonally in the immediate vicinity of the field sea water intake area. However, the change in species congregating in relation to seasons suggested a factor other than brine oxygenation to be operating. Samples of fish removed for gut analysis revealed that the schools were in the reproductive phase with mature eggs and milt. These fish were following their natural annual cycle of seaward migration for reproduction but were hindered by the sea wall. The population structure is, in consequence, maintained by reproduction, death and predator-prey relationship. The stand of dead mangroves along the shallows usually with long strands of the macroalga, *Rhizoclonium*, serve as an efficient nursery area for juvenile fish. Juveniles of carnivorous fish species feed on Amphipod crustaceans or the larvae of midge flies belonging to the families Chironomidae and Ceratopogonidae.

The large species diversity in Pond 0 serve to effectively trap nutrients, releasing them on death by slow decomposition. This large diversity of organisms also indicates the establishment of an artificial ecosystem with nutrient recycling. Inorganic nutrient input occasionally occurs from sources outside Pond 0 through rainfall runoff and from migrating wading birds.

Pond 1A. In this pond, only three species of fish survive but do not appear to be breeding. These fish, *Chanos chanos* (Milkfish), *Elops australis* (Giant Herring) and *Stenantherina sp* (Hardyhead), are stunted in size, especially those of *Elops*, which fall regular prey to sea eagles. The milkfish thrive on a diet of blue-green algae and benthic pennate diatoms. There are no macro-algae present, although there is a continuous firm blue-green algal gelatinous benthic mat which consist predominantly of *Aphanothece stagnina*. Planktonic matter in the brine consist, in the main, of dinoflagellates, but may include small numbers of *Dunaliella* and sporadic benthic diatoms in areas of turbulence. This pond also harbours a breeding population of midge fly (Family Chironomidae), with the algal mats along the pond perimeter being perforated by the blood-red larvae. Protozoans and nematodes are also present as scavengers and predators.

Small numbers of two species of *Dunaliella* are also present within this pond. One species remains green at all salinities while another turns red with increasing salt concentration. The green species is, according to Ginzburg and Ginzburg (1981), a halotolerant species, while the red species is halophilic and may be referred to as *D. salina*.

Brine shrimp (*Artemia salina*) was introduced into this pond in 1971 on the suggestion of J. S. Davis. The purpose of this introduction was to control the possible increase of the mucilagenous producing blue-green algae by the non-selective grazing of the shrimps. This decreases the planktonic component of the brine and prevents algal colonization in subsequent ponds. The excretory wastes of brine shrimps are expelled encapsulated and form a very effective nutrient trap. The cysts introduced into the system came from a mixed stock from Shark Bay, Australia and San Francisco Bay, U.S.A. As a result, a resident population has been established. Geddes (1979) confirmed that *Artemia* occurring at Shark Bay represent a parthenogenetic population of female shrimps. The stock from San Fransisco Bay reproduces sexually.

Three years after introduction, a large quantity of cysts was produced but since then the production has been declining. From field studies, population replacement is mainly by vivipary, i.e. "live-bearing." This strategy was postulated by Browne (1980) that in relative environmental stability, the selective advantage is to produce the majority of offspring viviparously in order to maximise success in intraspecies competition.

Pond 1B. Brine flowing into Pond 1B has very few planktonic components. The bottom mat of Pond 1B consists mainly of *Aphanothece halophytica*. An unidentified fungus survives within the gelatinous matrix and presumably utilises the polysaccharides present as a carbon source. Brine shrimp proliferate in this pond with numbers of 1 to 2 individuals/litre. Although reported as non-selective feeders (Reeve, 1963; Tyson and Sullivan, 1981), brine shrimp have been observed in the field to actively graze bottom algal mats and thus represent a secondary level of control.

Dunaliella is present in the palmelloid form and very often as a benthic "colonial" form sharing a common gelatinous mastrix and is weakly motile. Individuals gradually break away as strongly motile green forms.

Ponds 2, 3 and 4. In Pond 2, the start of calcium sulphate deposition, *Aphanothece halophytica* is the main benthic organism surviving in this pond. This, although viable, is trapped in the gypsum crystal mass where there is little exposure to solar insolation. This alga, when exposed to strong solar radiation rapidly lose their photosynthetic pigment and die. Under this circumstance, the mucilage assumes an orange-brown colouration and is released into the brine. Thus, in normal operational field condition, the gypsum can be said to exercise a form of "biological control."

Dunaliella cells swept into this pond are suspended in the brine column and begin chlorophyll destruction to reveal carotenoid colours.

The final concentration ponds, Ponds 3 and 4, have similar biology to Pond 2.

APPLIED BIOLOGICAL STUDIES

Laboratory investigations are conducted on organisms capable of tolerating high salt concentrations as these may directly or indirectly affect salt production and quality. Such organisms have been discussed by Golubic (1980) and reviewed by Borowitzka (1981). Such studies have been directed to the following organisms.

Aphanothece Halophytica. Studies were conducted on the mucilage producing blue-green alga, *Aphanothece halophytica* with a view to understanding factors influencing its growth in order to determine methods of field control.

For this study specimens of pure, healthy *Aphanothece* obtained from high salinity were placed in a range of brines with salinities from 62 to 224 ppt with no artificial fertilisers added, and maintained at a temperature range of 25°C to 28°C. The results, as shown in Table 3, indicated that growth continued at all the salinities investigated and ANOVA analysis of the results showed a significant increase in wet weights in all brines tested.

A further experiment was conducted with nutrient addition in Ponds 1B and 2 brines known to support growth in the field. The results are illustrated in Figure 2. Growth with nutrient enrichment was greater in Pond 1B brine than Pond 2 while, in both brines, the increase in wet weight was due to mucilage production rather than an increase in cell number. A longer period than 7 days may result in an increase in cell number.

TABLE 3

Wet Weight of *Aphanothece Halophytica* Clumps in Various Brines after 7 Days

Brine Source	Wet Weight of Algal Clumps (g.)				
	Start		7 Days		
	mean	s.d.	mean	s.d.	Difference
Pond 0	1.333	0.286	1.617	0.578	0.284
Pond 1A	1.083	0.124	1.757	0.301	0.674
Pond 1B	1.083	0.272	1.553	0.174	0.470
Pond 2	0.700	0.0812	1.143	0.357	0.443
Pond 3	0.850	0.041	1.463	0.202	0.613

Dunaliella Species. The ability of *Dunaliella* to survive in saturated brine and the consequential development of carotenoid colouration by this organism could provide increased solar absorption in clear crystalliser brines. Laboratory investigations were conducted at Dampier to determine factors controlling growth and colouration of *Dunaliella*.

These culture experiments with *Dunaliella* show it to be readily grown in the laboratory using the medium of Johnson et al. (1968). The green species requires a low light intensity and remains green irrespective of changes in brine salinity and nutrient levels. In unfavourable conditions, green cysts are produced.

The other species, *Dunaliella salina*, changes to the bright green form in laboratory culture and cannot be distinguished morphologically from the green species. Carotenoid colouration can be induced in low light with nutrient depletion but the colour never reaches the same intensity as those occurring in the field where chlorophyll breakdown is complete.

Halophilic Bacteria. These organisms, like *Dunaliella*, are able to survive in saturated brines. Their presence in large numbers indicate the occurrence of organic matter. A group of halophilic bacteria will develop a red colouration in suitable conditions, and like *Dunaliella*, could serve to increase solar absorption.

Laboratory cultures of halophilic bacteria are readily produced by enriching crystalliser brine according to Colwell et al. (1979). Plate cultures of the bacterial broth in aerobic conditions show initial and rapid development of white colonies during the first week. Red colonies appear during the second week increasing in number to the maximum after four weeks. In anaerobic conditions, there was a rapid growth of the white colonies and during the second week a continuous film was formed. Greatest colony numbers appeared in medium adjusted to pH 8 under aerobic conditions. Low numbers were recorded in pH 6. In anaerobic conditions there was no clear pattern of response to pH with growth being equally good. Red halophilic bacterial growth was inhibited when the medium contained less than 20% sodium chloride.

POTENTIAL BIOLOGICAL FIELD PROBLEMS

Brine Alkalinity. If the pH of brine at the point of carbonate deposition (s.g. 1.08) exceeds 8.5 and is accompanied by brine temperature differential, milky brines result.

This effect is associated with long term modification to

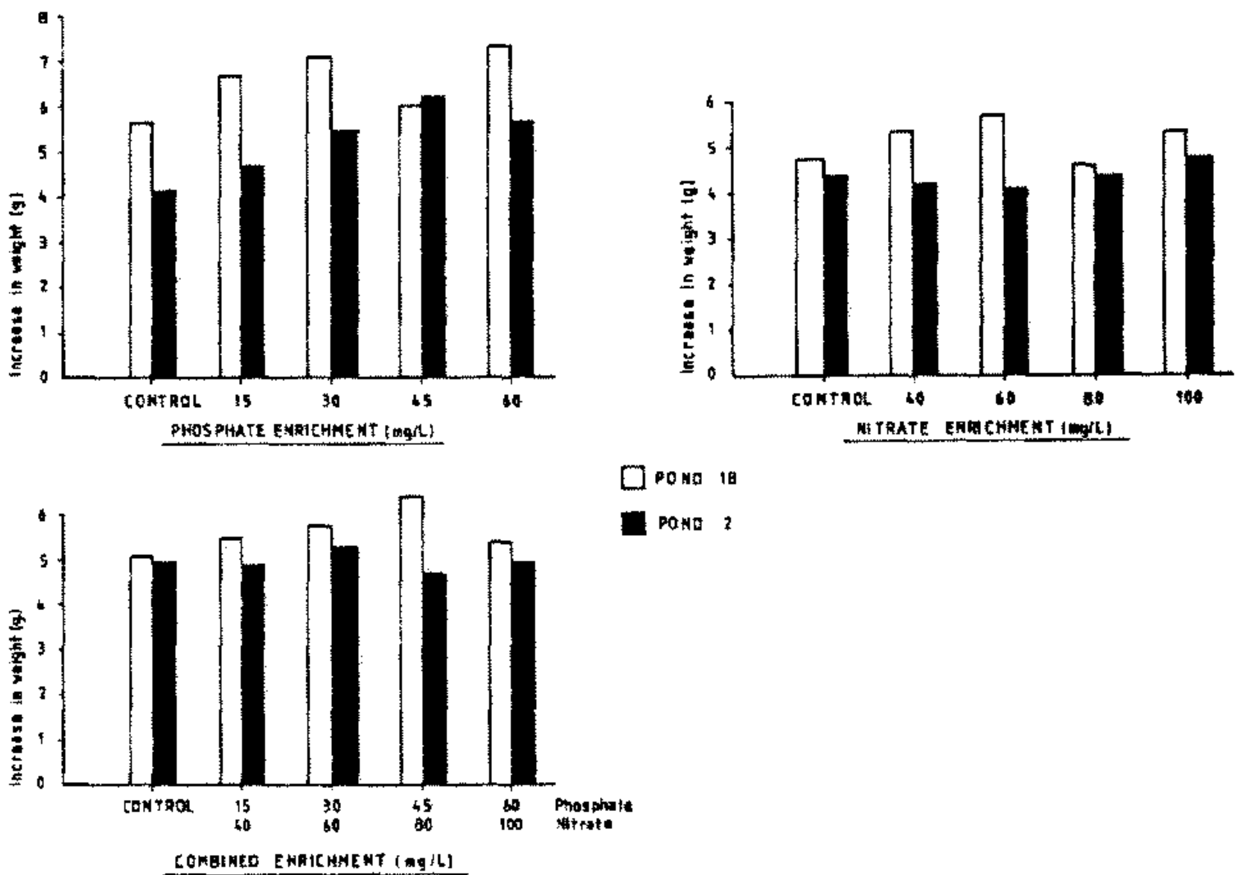

Figure 2. Increase in weight of *Aphanothece halophytica* in Ponds 1B and 2 brines with nutrient enrichment.

the salt field salinity profile (production level) and results from the release of carbon dioxide during bacterial degradation of accumulated organic matter which dissolves in the brine thus increasing carbonate concentration and pH. Such brine coming in contact with warmer brines downstream (2 to 3°C difference) results in a mass precipitation of calcium carbonate and calcium sulphate as tiny spherules (1.5 to 2.5 μM).

Skirrow (1975) stated that precipitation of calcium carbonate from a supersaturated solution depended on kinetic rather than thermodynamic factors, determined by environmental conditions. He quoted a similar natural phenomenon of "whitings" that occurred in the Bahama Bank and Persian Gulf carbonate sedimentation areas where the turbidity was caused by suspended aragonite needles.

The development of milky brines, in a salt field, is rapid and usually lasts for a month during which the spherules gradually decrease in size and disappear. The result is an impairment of salt quality due to higher calcium analysis.

In addition, ingestion of these particles by brine shrimp results in mass mortality. This reduction in shrimp population is usually followed by a proliferation of blue-green algae. Once the salt field reaches a stable equilibrium salinity profile, the deposition of carbonate ceases and a new biological balance is established.

Organic Matter. The accumulation of biological products in a solar salt field is degraded at a slow rate. Factors conducive to biological growth are reflected in accumulation of detritus.

Ward and Brock (1978) in studying the Great Salt Lakes proposed that if production exceeded decomposition, the sediments of hypersaline lakes may be unusually rich in organic matter because of suppression of the rate of metabolism of these compounds. They also concluded that hypersaline lake sediments may be unusually abundant in hydrocarbons.

Observations in the Dampier field indicate that a gradual detrial accumulation is unavoidable and may be a consequence of a salt field aging. An accelerated rate of accumulation, however, would be of concern.

Although other methods are being studied for control of this problem, the best remedial action available to date appears to be pumping should the detrital accumulation be semi-liquid. Solid residues may be mechanically removed, as such accumulations are invariably along the perimeter of ponds.

Blue-Green Algae. Mucilage producing blue-green algae are present in all tropical solar salt fields concentrating sea water. Copious mucilage production is characteristic of *Aphanothece halophytica* (*Coccochloris elabens*). Few analytical studies have been conducted on this mucilage. Fogg et al. (1973) noted that these studies indicated the mucilage to be a highly complex polysaccharide.

Observations in the field revealed that the polysaccharide matrix of *Apanothece* is not firm but a very soft ooze, partly dispersable in brine. As referred above, site studies have shown that increased nutrient input increases the numbers of alga which, with the corresponding increase in mucilage, has the potential effect of increasing the brine viscosity. This phenomenon has also been observed by Jones et al. (1981) where a dramatic increase in brine viscosities was recorded.

Observations made during such an event showed increased brine temperature and increased production of fine drift salt. Attendant problems associated with these were failure of salt pavement because of "soft" salt produced and possible brine pumping problems.

A number of physical methods for remedying the situation are known.

1. Removal of algal colonies by pumping
2. Increasing brine depths to kill the algal blooms
3. Decreasing brine depths to consolidate the algal growth as a benthic community
4. Closure and total purging of the ponds

A good preventative practice is to monitor levels of nutrients as suggested by Davis (1978b) and should the presence and persistence of a high phosphate level be detected, usually leading to blue-green algal bloom, an appropriate corrective measure could be devised.

One approach, in terms of pure biological control for the rectification of high viscosity brine, could be investigations for the isolation of viruses (cyanophages) and bacterial pathogens capable of destroying blue-green algae. Although pathogens are yet to be reported for salt fields, the dramatic effects described in Fogg et al. (1973) are too encouraging to ignore.

BIOLOGICAL APPLICATIONS

The natural occurrence of brine organisms capable of tolerating and propagating in high density brines may be exploited in a number of ways.

Pond Seepage. The use of blue-green algae to minimise brine loss by reducing leakage was proposed by Davis (1974) and later implemented (Davis, 1978a). The experimental work conducted by Jones et al. (1981) on a mixed blue-green algal mat demonstrated that a mat of filamentous genera had a permeability slightly higher than clay but much less than that of shell grit. They discovered that an algal mat of 1 mm thickness could decrease the permeability of a 1 m shell grit substratum by a factor of approximately 10.

Brine Colouration. The green alga, *Dunaliella*, and some genera of halophilic bacteria have the ability to colour brine by the production of carotenoids.

Dunaliella can live in saturated sodium chloride brine, although its enzymes are sensitive to high concentrations of salts (Jaenicke, 1981). In this case, Ben-Amotz and Avron (1978, 1979) have found a rapid metabolic adaptation is provided by the *de novo* synthesis of high concentrations of glycerol which protects the organism from bursting under hypotonic osmotic stress and breakdown of chloroplastic and cytoplasmic enzyme activity.

According to Lerche (1937) the combination of high salt concentration, high light intensity and high temperature induces *D. salina* to accumulate carotenoids. Above 5% sodium chloride, beta-carotene is the main compound responsible for this increase.

Jones et al. (1981) have clearly shown that a natural red brine colouration is only slightly less efficient than commercial dyes in relation to solar absorption. Observations in the solar ponds at Dampier indicate that a bloom of *Dunaliella* (1.7×10^9 cells/litre) can raise the crystalliser brine temperature 6°C.

Halophilic bacteria are common in crystalliser brines. The red colouration produced by *Halobacterium* is induced in laboratory experiments by the addition of peptone hydrolysate according to Colwell et al. (1979). Such cultures were maintained at a temperature of 37°C.

Isolates of halophilic bacteria from the Great Salt Lakes have been reported by Post (1977) to have an optimum growth temperature of 45°C with extremes of 50°C and 37°C. These findings imply that although halophilic bacteria are naturally present, the relatively low crystalliser brine temperatures in north-western Australian salt fields with a summer range of 27°C to 33°C and winter range of 16°C to 20°C are not conducive for prolific growth of red *Halobacterium*.

Ngian et al (1980) postulated that an increased population of brine shrimp drifting into crystallisers would be a protein source for halophilic bacteria eventually resulting in red brine colouration. This concept is a logical extension of understanding biological relationships in a solar salt field.

Studies conducted at the Lake Macleod salt field where saturated brine (s.g. 1.21) is drawn from an underground aquifer show a simple interaction between *Dunaliella* and halophilic bacteria (Figure 3), typical of the Australian salt fields crystalliser ponds. However, unlike solar salt fields concentrating sea water, the aquifer brine has very high levels of phosphorus up to a maximum of 35 μg-A/litre. The available phosphorus encourages the growth of *Dunaliella* with a maximum cell count of 46 cells per cubic millimeter, colouring the brine a distinct red. Removal of *Dunaliella* from the brine results in a pale pink

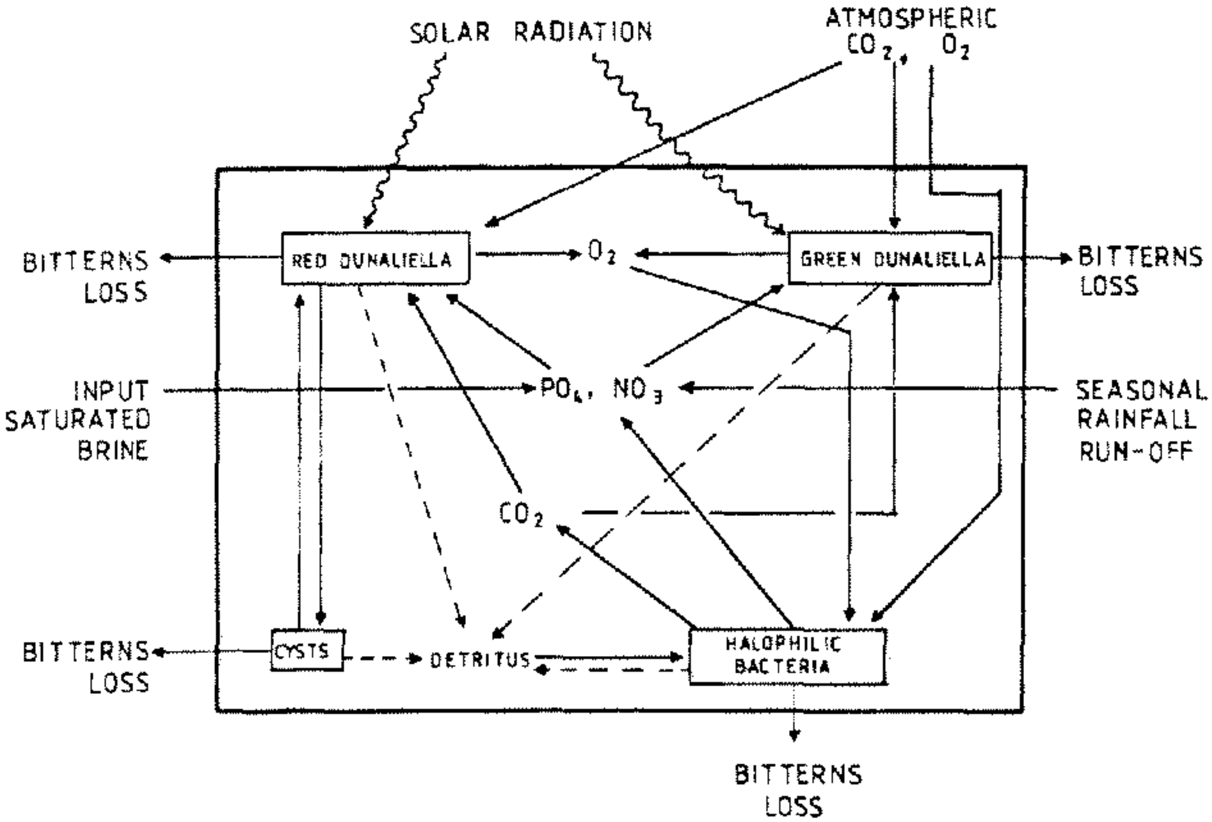

Figure 3. Major inter-relationships of organic and inorganic elements in production crystalliser ponds.

colouration, and three species of aerobic halophilic bacteria have been isolated from this fraction. The pink colouration is due to *Halobacterium*.

The combined factors of increased solar absorption and increased brine temperature may be utilised to enhance salt production.

Mariculture. The culture of certain naturally occurring organisms may be of use to solar salt fields as a means of replenishing the decline of favoured organisms or in the event of an overproduction for commercial sale.

The culture of algae in saline waters is attracting attention (Williams, 1981). *Spirulina* has provided food in certain regions and like *Aphanothece halophytica* is known to contain a significantly high protein content (Tindall et al., 1977).

Nair et al. (1975) explored the possibility of marine fish culture in lower salinity ponds. This possibility may also be extended to north-western Australian salt fields where there is an overabundance of fish and crustaceans in low salinity ponds (35 to 68 ppt). However, for some salt fields, the high cost of processing and freight renders this venture unattractive for the marketing of fish.

Brine shrimp and cysts produced have been exploited commercially in a purely natural system without the need for artificial feeding.

SUMMARY

The salt field biology at Dampier shows the classical balanced inter-relationships in each pond. Nutrients from sea water are enhanced by natural evaporation and then rapidly utilised and demobilised by the biota in succeeding ponds. This rapid decline in available phosphorus limits the growth of the nuisance species *Aphanothece halophytica*. Blue-green algae competition for nutrients and predator pressure by brine shrimp in the lower salinity ponds limit the proliferation of *Dunaliella salina*. This is evidenced by clear crystalliser brines.

The requirement for coloured crystalliser brines demands the use of artificial fertiliser in the early primary ponds where *Dunaliella* is generated. This action will not only encourage the growth of *Dunaliella* but also that of *Aphanothece halophytica* with the associated problems in salt production and quality. An upset to the biological equilibrium can result from artificial manipulation of nutrient levels or induced variations in nutrient levels by salt production demands where the process is either rapidly stepped up or down. The regular measurement of brine pH, phosphate level and brine viscosity are good indicators of such upsets to the biological equilibrium and provide the facility to predict potential problems.

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