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Hydrobiology of Two Solar Saltworks in India — II

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ABSTRACT

Physico-chemical and biological factors of brine water of two man-made solar saltworks have been investigated at six sites, from seawater intake to salt crystallization pans. Water temperature, conductivity, total dissolved salts, total alkalinity and magnesium hardness showed positive correlation with salinity, but dissolved oxygen content, nutrient concentration and ammonia–nitrogen showed negative correlation with salinity at both saltworks. However, calcium salt had undergone fractional precipitation at the salinity range of 100–160 ppt. Twenty-one species of algae dominated by Cyanophyceae, and nine groups of zooplankters dominated by ciliate protozoans and crustaceans were documented. The number of species decreased as the salinity increased; at salinities above 100 ppt only *Dunaliella salina, Coccochloris elabens, Spirulina platensis* and *Artemia* remained. Crystallizer pans were devoid of phyto- and zooplankters.

INTRODUCTION

Of the 9 Mt of common salt produced in India, 75% comes from man-made salt ponds located on the east and west coasts of the continent (Anon., 1990). Saltworks constructed some decades ago are well suited for the manufacture of good quality salt. These saltworks, composed of connected ponds, have widely varying physico-chemical parameters, which induce great physiological modifications in the organisms to adapt themselves to these extremes. It has been shown, however, that hydrobiological activity in solar salt operations largely determines the quantity and quality of the salt produced (Davis, 1980b). It is important to understand how salt of high sodium chloride content is manufactured in these saltworks under natural conditions, and how the presence of common impurities in the salt can best be minimized. This paper reports on the initial composition of seawater from which salt is manufactured, and the changes involved in the chemical and biological composition with progressive evaporation of seawater from feeder canal up to crystallizing pans.

STUDY AREA

The study sites were a saltworks producing edible salt (Station I) and a saltworks producing industrial salt (Station II). Station I (S-I) with an area of 93.08 ha is located at Vedaranyam (10°0.01″N, 79°50″E) which started operating in 1918, and Station II (S-II) is located at Kelambakkam (12°08″N, 80°02″E) with an area of 525.2 ha (Fig. 1). Both stations are in a tropical climate region subject to high evaporation and rainfall only during a short period, i.e. October–December. In both stations the source of seawater is from the Bay of Bengal, which enters a feeder canal by tidal action and is pumped into series of inter-connected earthen ponds (evaporators or reservoirs) of 1–2 ha each. The salinity gradually increases by solar evaporation as water flows from one evaporator to another. After the brine becomes saturated, it is transferred to crystallizing pans. The layout of ponds is such that brine flows by gravity from reservoirs to crystallizers. The salt operation is seasonal and the production period is from January to September. Due to the north-east monsoon, salt operations close from October to December.

The process of edible salt production differs from that of industrial salt. For the manufacture of edible salt, water that attains 15°Bé is transferred to the crystallizers in a layer of 4–5 cm (evaporator:crystallizers = 7:1 by area), and allowed to deposit salt. The salt harvest begins after 3–4 days. For the production of industrial salt, brine of 24°Bé is pumped into crystallizers to a depth of 10 cm. Ten to fifteen days

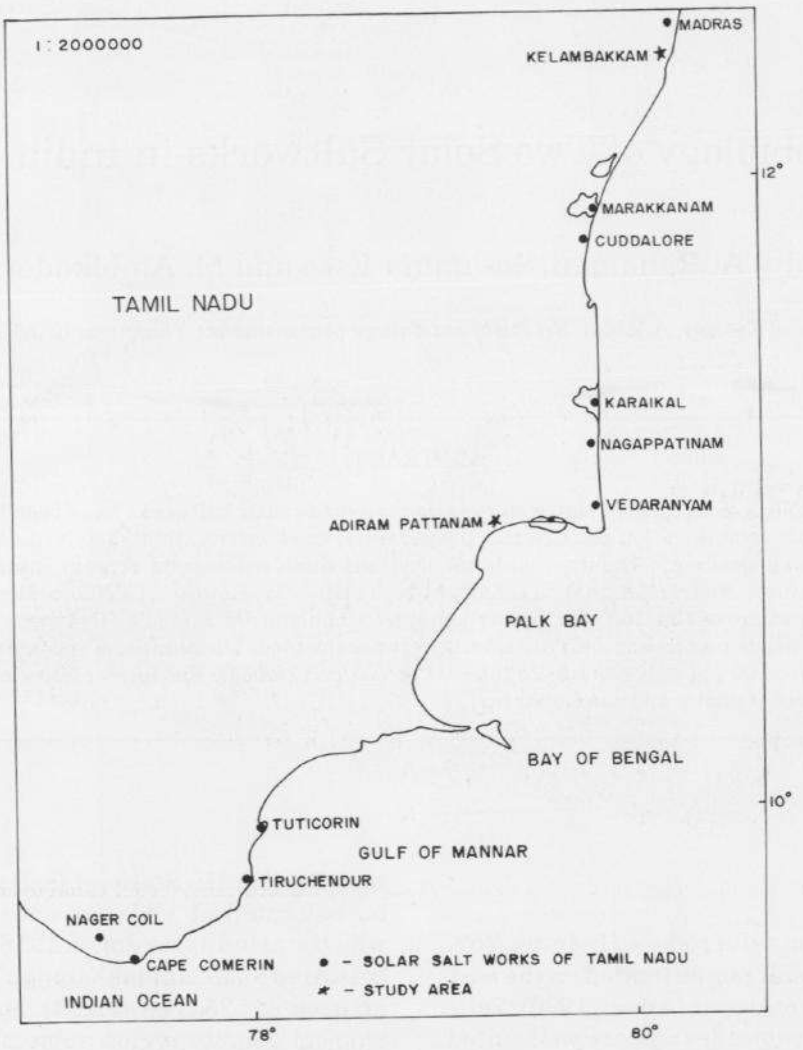


Fig. 1. The study area.

after concentrated brine reaches the crystallizers, the bittern liquor is pumped out, and the salt is harvested and washed.

MATERIALS AND METHODS

The water and phytoplankton samples forming the basis of this study were collected during March 1991, the peak salt producing period. Because all the sampling sites (feeder canal, evaporators, reservoirs and crystallizers) were shallow, surface water was collected and analysed. Analyses included physico-chemical factors like salinity, dissolved oxygen, pH, total alkalinity, conductivity, total dissolved solids, calcium and magnesium hardness, and nutrients like nitrite–nitrogen, nitrate–nitrogen, inorganic phosphate, silicate–silicon and ammonia–nitrogen. The standard methods of Strickland and Parsons (1968) were used to analyse the samples. Samples for phyto- and zooplankton analyses were collected by filtering 50 l of water sample through a plankton net having a mesh size of 10 μ and preserved in 5% formalin. The plankters were identified using published papers and monographs. Statistical analyses were carried out to determine correlation coefficients between different factors (Snedacar and Cochran, 1967).

RESULTS

Physico-chemical factors

Figures 2–4 and 5–7 illustrate the variation in salinity, temperature, dissolved oxygen, total alkalinity, conductivity, total dissolved salts (T.D.S.), calcium and magnesium hardness and nutrients in S-I and S-II. respectively. The depth of water maximum in the feeder canals (F) and in reservoirs varied from 5 to 55 cm at S-I, and 5–60 cm in S-II. The water

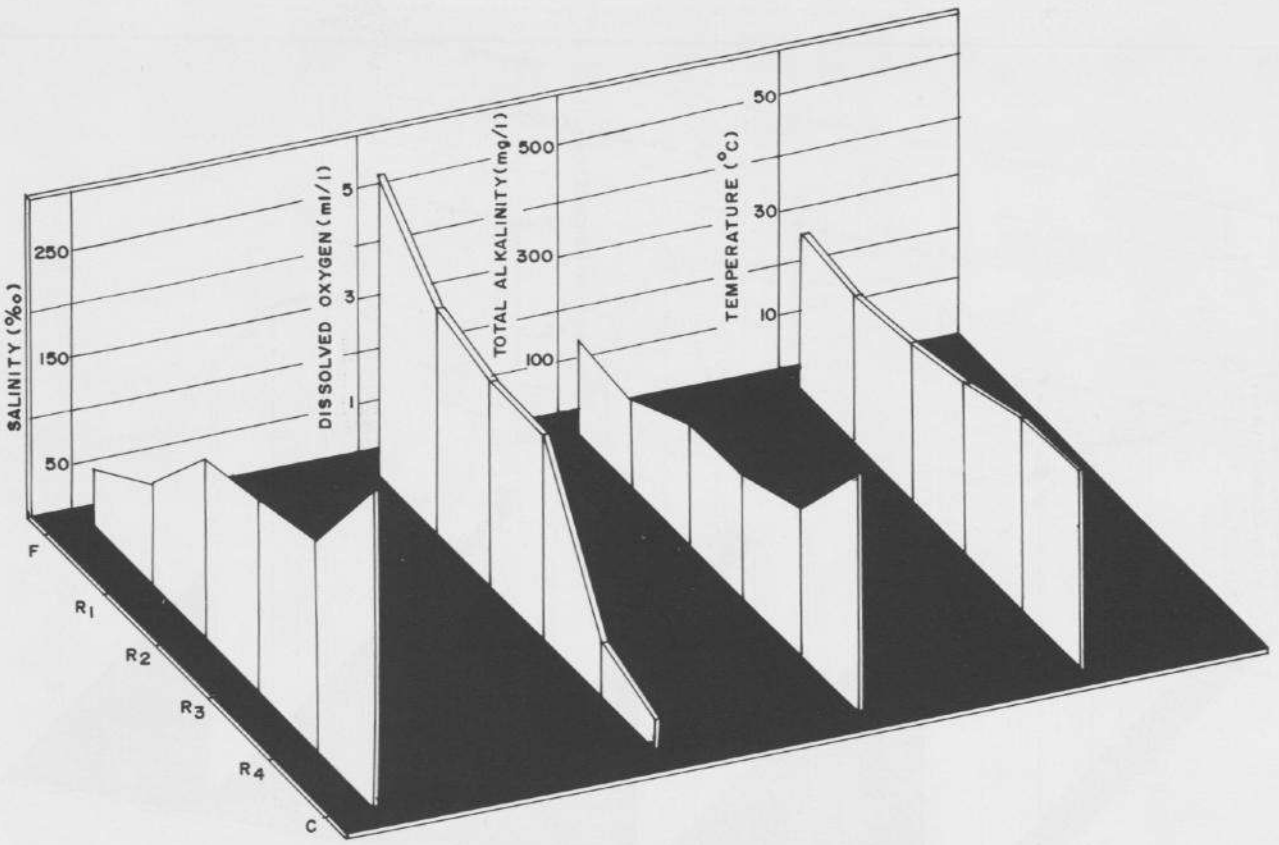


Fig. 2. Variations in salinity, dissolved oxygen, total alkalinity and temperature, from feeder canal to crystallizer, at Station I.

temperature showed a corresponding increase with decrease in water depth from feeder canals to crystallizers (C), i.e. 28.2–37.2°C at S-I, and 26.3–37.4°C at S-II. Because of very shallow water depths, the surface and bottom waters heat up uniformly and quickly attain their maximum temperatures.

At S-I, the salinity of the seawater reached 57 ppt in the feeder canal, and as water flowed through the series of evaporators, it increased to 202 ppt; in the crystallizer salinity was 297 ppt where sodium chloride starts precipitating. At S-II the incoming water had a salinity of 45 ppt in the feeder canal; in evaporators it gradually increased to 216 ppt in and crystallizers it was 326 ppt. The dissolved oxygen values showed negative correlation with salinity and water temperature. Oxygen decreased from 5.76 ml/l at F to 0.67 ml/l at C, and 5.13 ml/l at F to 0.39 ml/l at C in S-I and S-II, respectively.

The pH values did not show much variation, but a slight reduction was noticed at very high salinities at both stations (Table 1). Statistical analysis showed an insignificant negative correlation between salinity and pH. But at the same time, the total alkalinity values were found to increase with increase in salinity. The minimum value of 182 mg/l was recorded at F and it gradually increased and reached its maximum of 437 mg/l in C at S-I and 156 mg/l in F to 358 mg/l in C at S-II, respectively. Total alkalinity values showed a highly significant positive correlation (at 1% level) at S-I and 5% level positive correlations at S-II. Conductivity increased from 22.10 to 29.8 mhos at S-I and 11.2 to 39.8 mhos at S-II, respectively. The T.D.S. varied from 11.9 to 14.9 ppt at S-I and 5.6 to 10.9 ppt at S-II. respectively.

TABLE 1

Variation in pH and salinity at S-I and S-II

	S-I		S-II	
	pH	Salinity (ppt)	pH	Salinity (ppt.)
F	8.3	57	8.75	45
R1	8.9	95	8.9	140
R2	8.8	170	8.8	163
R3	7.3	181	7.26	206
R4	7.2	202	7.17	216
C	7.16	297	7.03	326

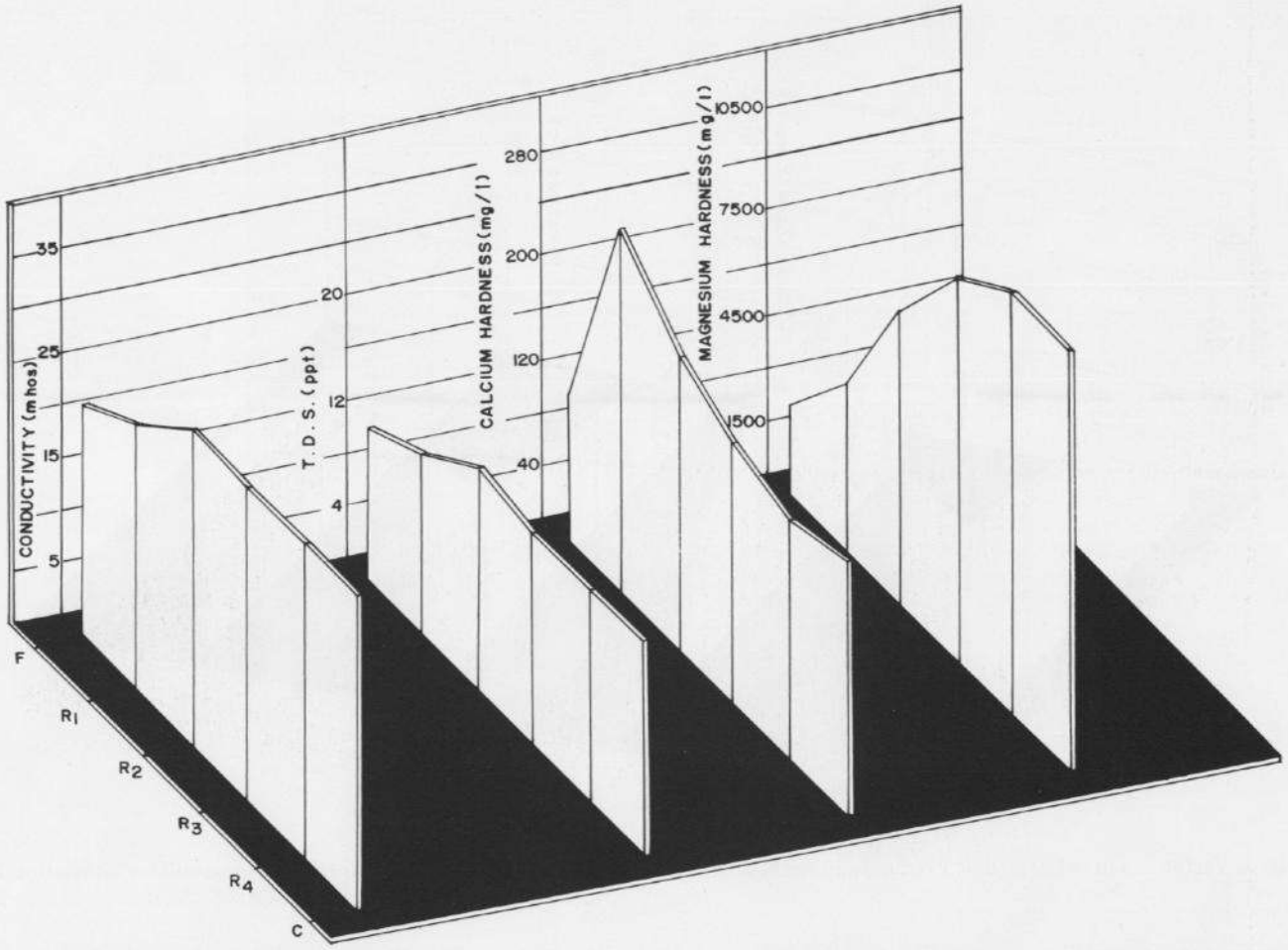


Fig. 3. Variations in conductivity, total dissolved solids, calcium hardness and magnesium hardness, from feeder canal to crystallizer, at Station I.

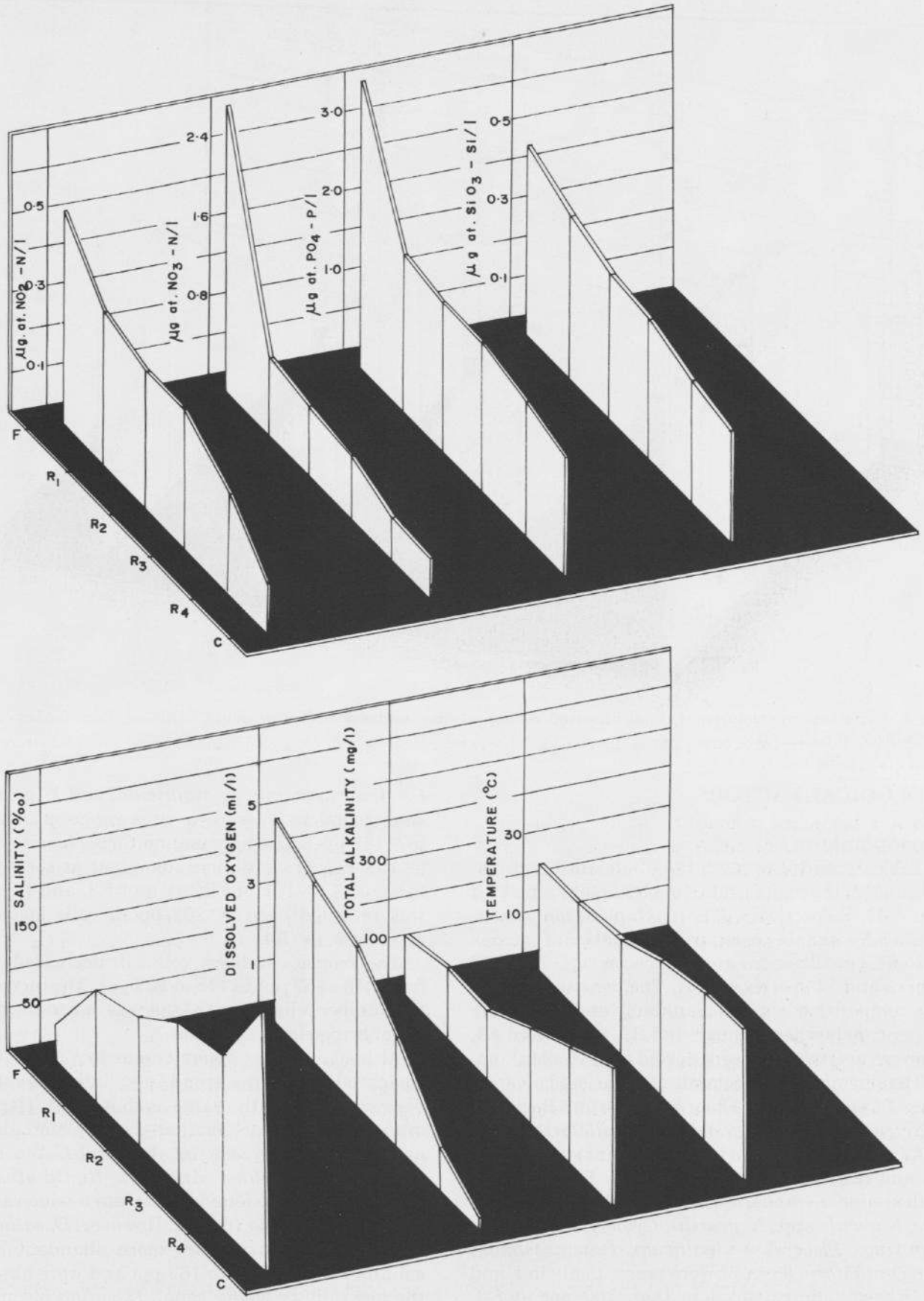
Water hardness is mainly due to the calcium and magnesium content. At S-I the calcium hardness increased from 109.33 mg/l in F to its maximum of 277.54 mg/l at R1 where the salinity of the water was 95 ppt; thereafter, hardness decreased as the salinity increased. In crystallizers its value decreased to 185.03 mg/l. Similar variation was observed at S-II. There the calcium hardness increased from 126.15 mg/l in F to 319.59 mg/l in R2 followed by a reduction to 100.92 mg/l in C. At the same time, the magnesium hardness showed a significant positive correlation with salinity. Its value ranged from 2610.17 mg/l at F to 12234.97 mg/l at C and 1913.85 in F to 12239.08 mg/l in C at S-I and S-II, respectively.

Significant negative correlation was observed in nutrient concentration with salinity. The nitrate–nitrogen values were always higher than nitrite–nitrogen values. At S-I, the NO_2^-–N varied from 0.53 to 0.12 μg at/l, NO_3^-–N from 2.89 to 0.42 μg at/l, PO_4^{3-}–P from 3.63 to 1.48 μg at/l and SiO_3^-–S_i from 0.47 to 0.28 μg at/l.

At S-II the nitrite–nitrogen ranged from 0.48 to 0.08 μg at/l, nitrate–nitrogen from 0.93 to 0.63 μg at/l, inorganic phosphate from 2.37 to 0.93 μg at/l and silicate–silicon from 0.36 to 0.19 μg at/l respectively. The ammonia–nitrogen also showed a negative correlation with salinity. Its values varied between 29.25 and 5.75 μg at NH_4^+–N/l at S-I and 37.7 and 7.25 μg at NH_4^+–N/l at S-II, respectively.

Fig. 4 (*Opposite page, top*). Variations in nitrite–nitrogen, nitrate–nitrogen, phosphate–phosphorus and silicate–silicon, from feeder canal to crystallizer, at Station I.

Fig. 5 (*Opposite page, bottom*). Variations in salinity, dissolved oxygen, total alkalinity and temperature, from feeder canal to crystallizer, at Station II.


µg. at. NO2 - N/l
0·1
0·3
0·5
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0·8
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2·4
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2·0
3·0
µg at. SiO3 - Si/l
0·1
0·3
0·5
F
R1
R2
R3
R4
C
SALINITY (‰)
50
150
DISSOLVED OXYGEN (ml/l)
1
3
5
TOTAL ALKALINITY (mg/l)
100
300
TEMPERATURE (°C)
10
30
F
R1
R2
R3
R4
C

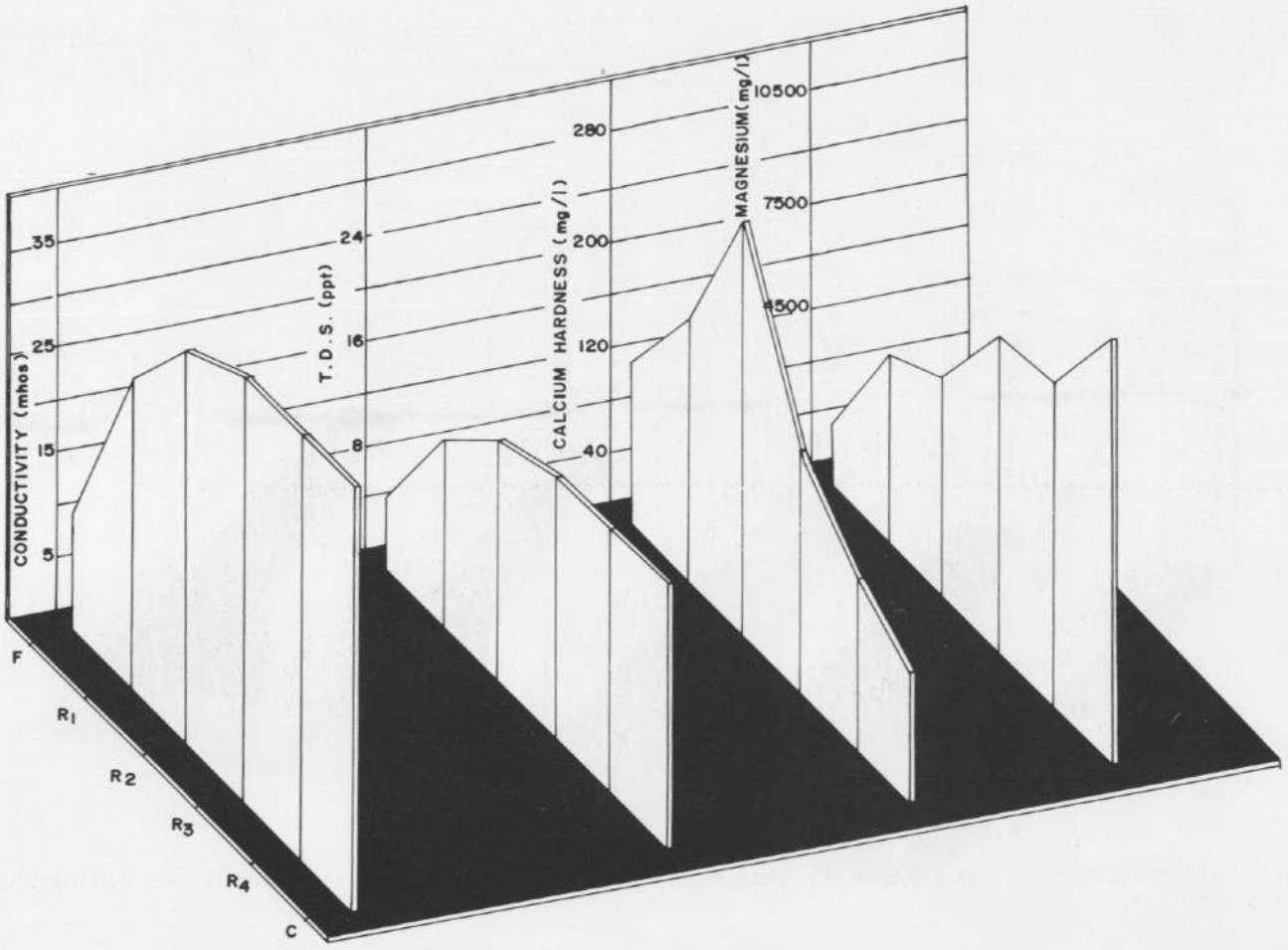

Fig. 6. Variations in conductivity, total dissolved solids, calcium hardness and magnesium hardness, from feeder canal to crystallizer, at Station II.

BIOLOGICAL FACTORS

Phytoplankton

Tables 2 and 3 present the abundance and distribution of the major groups of phytoplankton at S-I and S-II, respectively. The phytoplankton is taxonomically simple in regard to number of species present, i.e. 12 genera and 21 species at S-I and 12 genera and 14 species at S-II. The density and species composition of phytoplankton were high in the feeder canals when compared to R1, R2, R3 and R4, whereas crystallizers were devoid of phytoplankton.

The phytoplankton community consisted of members of Cyanopnyceae, Chlorophyceae and Bacillariophyceae. *Xenococcus acervatus, Oscillatoria salina* and *Lyngbya majuscula* were dominant species in F, R1 and R2, and *Dunaliella salina* in R2 and R3 at both stations. *Amphora salina, A. ovalis, A. commutate, Navicula* spp., *N. gracilis, Cymbella* spp., *Gleocapsa* sp., *Pleurosigma balticum, P. tenuissimum* and *Oscillatoria formosa* were present only in F and R1 where salinity was less than 100 ppt at S-I. *Oscillatoria salina, L. majuscula*, and *X. acervatus* were found to tolerate a wide range of salinities (57–181 ppt). The hypersaline *Coccochloris elabens* and *D. salina* were more abundant at the salinity range of 170–181 ppt in R2 and R3, and *D. salina* was recorded even in 202 ppt in this last set of reservoirs, i.e. R4.

The biomass indices, cells/ml, decreased at S-I from 345 at 57 ppt to 118 at 202 ppt. The increase in the number cells/ml at 181 ppt was due to the blooming of brine algae, *D. salina*.

Although species diversity was less at S-II when compared to S-I, the trend in salinity tolerance of various species is the same as that of S-I. Here also cyanophycean algae dominated over Chlorophyceae and Bacillariophyceae in abundance. *Xenococcus acervatus, O. salina, Anacystis dimidiatus* and *Navicula* sp. were found to tolerate a wide range of salinity, from 45 to 163 ppt. However, *D. salina* and *Sprirulina platensis* were more abundant at the salinity range of 140 to 163 ppt and were absent in the low salinity feeder canal. *D. salina* blooms, ob-

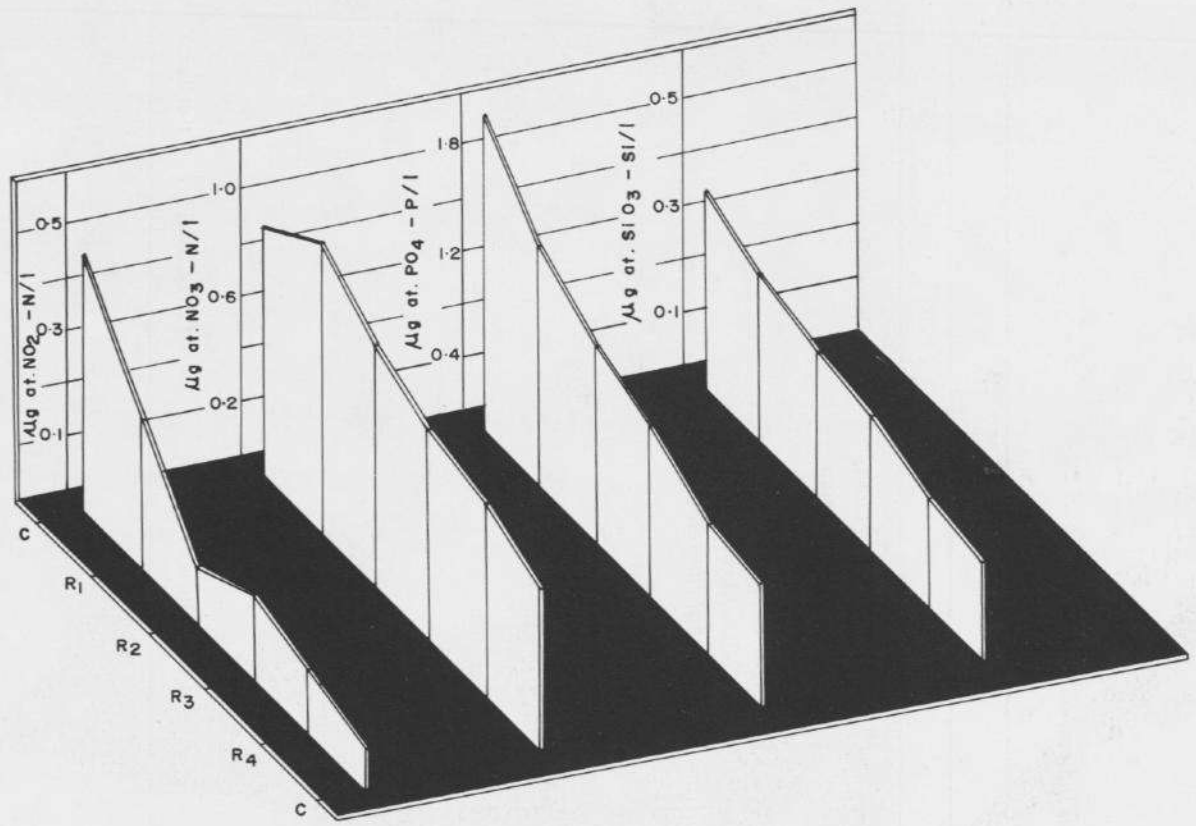

Fig. 7. Variations in nitrite–nitrogen, nitrate–nitrogen, phosphate–phosphorus and silicate–silicon, from feeder canal to crystallizer, at Station II.

served in the reservoirs at 206 ppt, were found to tolerate up to 210 ppt, a salinity where all other phytoplankters were absent. The crystallizers were devoid of any of these primary producers.

The biomass decreased from 21120 cells/l in F to 91 cells/ml at R4 in S-II.

Zooplankton

The relative abundance and species composition of zooplankton at S-I and S-II are given in Tables 4 and 5, respectively. Zooplankters were fewer in composition and abundance than phytoplankton. The zooplankters consisted mainly of ciliate protozoans, rotifers, copepods, amphipods and *Artemia* at both stations. The brine shrimp *Artemia* sp., the dominant zooplankter in reservoirs, was found to tolerate salinities up to 202 ppt at S-I and 206 ppt at S-II.

At S-I, *Diacypris* sp., *Brachionus plicatilis, B. rubens*, larvae of insects, larvae of crustaceans, and the protozoans *Bodo* sp. and *Nassula* sp. were present to the salinity level 95 ppt only, but calanoid and harpacticoid copepods were found to tolerate 181 ppt. At S-II, *Bodo* sp., and harpacticoid copepods were found to tolerate salinities up to 163 ppt. Medusa, *Brachionus* sp., and larvae of bivalves were present only in the feeder canal where salinity was only 45 ppt.

An increase in the total number of zooplankters per litre in reservoirs was mainly due to the presence of hypersaline organisms, especially *Artemia*.

DISCUSSION

The present study reveals the composition and variation of physico-chemical and biotic factors and evaluates which species are well adapted to limiting factors in solar saltworks ecosystems, in particular to high salinity.

The low salinities recorded in the feeder canals were due to tidal flow of seawater for storage in reservoirs for salt production. However, as the saline water flows from the first reservoir through the series of interconnected evaporators, the salinity increases gradually by solar evaporation and reaches saturation level before it enters the crystallizer pans. High salinity brine and high brine temperatures in shallow ponds restrict the solubility of gases such as oxygen, which explains the low oxygen values in reservoirs and crystallizers when compared to the feeder canals (Bayly, 1970).

TABLE 2

Species diversity and biomass indices of phytoplankton at Vedaranyam. Salinity ‰; biomass indices, cells/ml

Salinity (‰)					
57	95	170	181	202	297
1. *Coccochloris elabens*	1. *Coccochloris elabens*	1. *Coccochloris elabens*	1. *Coccochloris elabens*	*Dunaliella salina*	
2. *Lyngbya majuscula*	2. *Lyngbya majuscula*	2. *Lyngbya majuscula*	2. *Lyngbya majuscula*		
3. *Oscillatoria formosa*	3. *Oscillatoria formosa*	3. *Oscillatoria salina*	3. *Spirulina platensis*		
4. *O. salina*	4. *O. salina*	4. *Spirulina platensis*	4. *Xenococcus acervatus*		
5. *Spirulina platensis*	5. *Spirulina platensis*	5. *Xenococcus acervatus*	5. *Nitzschia* sp.		
6. *Gleocapsa*	6. *Gelocapsa* sp.	6. *Nitzschia* sp.	6. *Dunaliella salina*		
7. *Xenococcus acervatus*	7. *Xenococcus acervatus*	7. *Dunaliella salina*			
8. *Amphora commutate*	8. *Amphora marina*				
9. *A. marina*	9. *A. ovalis*				
10. *A. ovalis*	10. *A. salina*				
11. *A. salina*	11. *Amphora* sp.				
12. *Amphora* sp.	12. *Navicula* sp.				
13. *Cymbella* sp.	13. *Nitzschia longissima*				
14. *Navicula gracilis*	14. *Nitzschia* sp.				
15. *Navicula* sp.	15. *Pleurosigma salinarum*				
16. *Nitzschia longissima*	16. *Dunaliella salina*				
17. *Nitzschia* sp.					
18. *Pleurosigma balticum*					
19. *P. salinarum*					
20. *P. tennussimum*					
34,500 cells/ml	15,120 cells/ml	780 cells/ml	1,680 cells/ml	118 cells/ml	0 cells/ml

TABLE 3

Species diversity and biomass indices of phytoplankton at Kelambakkan. Salinity ‰; biomass indices, cells/ml

Salinity (‰)					
45	140	163	206	216	326
1. *Anacystic dimidiatus*	1. *Anacystic dimidiatus*	1. *Anacystic dimidiatus*	*Dunaliella salina*	*Dunaliella salina*	
2. *Coccochloris elabens*	2. *Coccochloris elabens*	2. *Coccochloris elabens*			
3. *Lyngbya majuscula*	3. *Lyngbya majuscula*	3. *Lyngbya majuscula*			
4. *Oscillatoria salina*	4. *Oscillatoria salina*	4. *Spirulina platensis*			
5. *Spirulina platensis*	5. *Spirulina platensis*	5. *Xenococcus acervatus*			
6. *Xenococcus acervatus*	6. *Xenococcus acervatus*	6. *Amphora salina*			
7. *Amphora ovalis*	7. *Amphora ovalis*	7. *Navicula* sp.			
8. *A. salina*	8. *A. salina*	8. *Nitzschia* sp.			
9. *Navicula mutica*	9. *Navicula mutica*	9. *Dunaliella salina*			
10. *Navicula* sp.	10. *Navicula* sp.				
11. *Nitzschia* sp.	11. *Nitzschia* sp.				
12. *Pleusigma salinarum*	12. *Pleusigma salinarum*				
13. *Surirella ovalia*	13. *Dunaliella salina*				
21,120 cells/ml	835 cells/ml	590 cells/ml	360 cells/ml	91 cells/ml	0 cells/ml

TABLE 4

Species diversity and biomass indices of zooplankton at Vedaranyam. Salinity, ‰; biomass indices, no./l

Salinity (‰)					
57	95	170	181	202	297
1. *Brachionus plicatilis*	1. *Bodo* sp.	1. Calanoid copepod	1. Harpacticoid copepod	*Artemia*	
2. *B. rubens*	2. *Nassula* sp.	2. Harpacticoid copepod	2. *Artemia*		
3. Calanoid copepod	3. *Brachionus plicatilis*	3. *Artemia*			
4. Calanoid copepod	4. *B. rubens*				
5. Harpacticoid copepod	5. *Diacypris* sp.				
7. Crustacean larvae	7. Harpacticoid copepod				
	8. *Artemia*				
	9. Insect larvae				
280/l	1,057/l		360/l	22/l	0/l

TABLE 5

Species diversity and biomass indices of zooplankton at Kelambakkam. Salinity, ‰; biomass indices, no./l

Salinity (‰)					
45	140	163	206	216	326
1. *Bodo* sp.	1. *Bodo* sp.	1. *Bodo* sp.	*Artemia*		
2. *Nassula* sp.	2. *Nassula* sp.	2. Harpacticoid copepod			
3. *Medusa*	3. Calanoid copepod	3. *Artemia*			
4. *Brachionus* sp.	4. Harpacticoid copepod				
5. Calanoid copepod	5. *Artemia*				
6. Harpacticoid copepod					
7. Larvae of bivalves					
365/l	1662/l	1019/1	8/l	0/l	0/l

Our pH values show that water is always alkaline, but a slight reduction in pH in higher salinity may be due to the apparent dissociation constants of carbonic acid in brine (Sars and Ben-Jaakov, 1977). The values of total alkalinity and magnesium hardness were found to increase with salinity. Highly saline waters contain high concentrations of Mg^{2+}, SO_4^{2-} and HCO_3^- (Volcani, 1944; Bayly and Williams, 1966; Oren and Shilo, 1982). The positive correlation of salinity with conductivity and T.D.S. has been already reported (Williams, 1966).

Fractional precipitation of salts that occurs at specific salinities and temperatures deposits vertically or horizontally the various ionic constituents of the water in fairly discrete strata. This explains the initial increase in the calcium concentration at salinity of 163 ppt followed by gradual decrease in its concentration.

High salinity and low nutrient availability are characteristic features of solar saltworks (Javor, 1983). On a more biological note, comparatively large numbers of species and high abundance have been noticed in low salinities. As the salinity increases, the species diversity decreases, mostly due to environmental stress, while the population density of hypersaline species flourish. In the final stages only 2 or 3 algal species have been able to establish themselves at high salinities (Volcani, 1944; Davis, 1978 and 1980a). The check list of fauna and flora of these saltworks are typical for salterns and hypersaline water bodies (Carpelan, 1957; Nissenbaum, 1975; Davis, 1978; Post et al., 1983).

The distribution profile of phyto- and zooplankton also revealed that the process of concentration of brine or salt is not only a physical process, but that there is an organic contribution from the biological

activity within the pond system. For example, the beneficial role of *Artemia* in purifying the brine through its filter feeding activity has already been an established factor (Sorgeloos, 1986). Algal blooms, which prevent early precipitation of gypsum and in extreme situations may even hamper salt crystallisation, are kept under control by the grazing *Artemia*. The halophilic bacteria which grow on metabolites produced by *Artemia* assure red coloration to the brine in crystallizers. This colour enhances the quick evaporation of brine (Jones et al., 1981).

The *D. salina* blooms occur only in hypersaline, warmer waters during the high light intensity period (Lerche, 1937). Such blooms often give a characteristic red colour to the water. During the present study *D. salina* blooms were also observed at hypersaline conditions only at the third set of reservoirs.

CONCLUSION

In short, this preliminary investigation provides a basis for studies concerning the chemistry and biology of man-made salterns. The present cross section of the solar saltworks throws light on the biological diversity of organisms in relation to various environmental factors that are operative from feeder canal to crystallizers. Further ecological study on the factors that enhance and limit successional colonization and growth of various organisms is needed to corroborate evidence from laboratory investigations.

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