

THE INFLUENCE OF THE NUTRIENT ENVIRONMENT ON BIOTA OF SOUTH AFRICAN SALINAS

MONIQUE S. DE LAWRENCE, EILEEN E. CAMPBELL

Department of Botany, P O Box 77000, Nelson Mandela Metropolitan University, Port
Elizabeth, 6031, South Africa

e-mail: monique.delauwere@gmail.com, Eileen.Campbell@nmmu.ac.za

ABSTRACT

Five South African salinas (Veldrift and Kliphoek on the west coast and Missionvale, Swartkops, Missionvale and Tankatara on the south coast) present varying hypersaline environments. These environments pose different ecological challenges to the organisms that live in them. Analysis of nutrient and biotic data from all ponds in all systems over a 12-year period provided generalised insights, despite episodic perturbations. The primary producers in the ponds were evaluated as phytoplankton biomass determined as chlorophyll *a* concentrations, macroalgal biomass as the percentage of the pond covered and *Artemia salina* (brine shrimp) abundance. Macroalgal biomass was not correlated to nutrient concentrations, but they were particularly sensitive to the increasing salinity, being almost entirely excluded by 100 psu. Below this salinity, macroalgae outcompeted the phytoplankton. Phytoplankton thrived where birds provided soluble reactive phosphorus. However, once brine shrimp numbers increased due to increased salinity, their grazing reduced phytoplankton abundance and released nitrogenous nutrients into the water. Once the salinity reached 220 psu, *Artemia salina* numbers were reduced, allowing the halophilic phytoplankton (e.g. *Dunaliella salina*) to flourish. Despite a large range of nutrient loadings, wide fluctuations in nutrient concentrations and resultant perturbations in biotic activity were limited to episodic events. Even the biota of the high nutrient load salinas adjusted and the systems remained ecologically sound.

Keywords: Salinity, nutrients, phytoplankton, macroalgae, *Artemia salina*

INTRDUCTION

The Chinese were the first to relate organisms in salinas to salt production (Baas-Becking, 1931). However, formal documentation of the management of the biota of solar saltworks began as recently as the 1950s with the development of large-pond saltworks. It became clear that the biota of a salina can either have a positive or detrimental effect on the quality and quantity of salt produced (Carpelan, 1957). As technology advanced, the recognition of the value of organisms for clearing brine resulted in the formulation of management procedures aimed at creating biological systems that aid salt production (Davis and Giordano, 1996).

Inorganic nutrients are not essential for the production of salt, however they do play an important role in controlling the biota of salinas (Difford, 2008). Nutrient concentrations vary greatly in solar saltworks: Ammonium concentrations of up to 700 μM (Jones *et al.*, 1981) have been reported, while nitrate in excess of 40 μM has been found (Du Toit, 2001). Phosphate concentrations may also increase to detrimental levels as reported by Sammy (1983) with concentrations of up to 35 μM reported. Target concentrations appear to be around 15 μM NH_4^+ ; 10 μM NO_x^- and 1 μM PO_4^{3-} (Davis and Giordano, 1996) with appropriate biotic activity reported for dissolved inorganic nitrogen levels of 25 μM and less (Carpelan, 1957; Britten and Johnson, 1987). Phosphate concentrations appear to be less important for determining a beneficial salina biota. Orthophosphate in the water column of the

Salin de Giraud was practically absent over most of the salinity range and was only detected in the low salinity ponds, where the maximum concentration was 0.04 μM (Britten and Johnson 1987). Even so, the salina, the largest in Europe, has an efficient biological system (Britten and Johnson 1987) and another biologically highly productive Indian saltworks had phosphate concentrations varying between 0.5 μM to 3.5 μM (Rahaman *et al.*, 1993).

Provision of nutrients to salinas is essential as nutrients promote development of the microphytobenthos (Difford, 2008). This is important to the system as the microbial mats seal the concentrator ponds and limit brine leakage (Difford, 2008). Sufficient nutrients also promote phytoplankton growth in the water column, which colours the brine, thus increasing solar absorption, raising the temperature of the water in the ponds and increasing the rate of evaporation from the system (Javor, 1989). The biological communities of salinas may become limited by nutrients: Davis (1978) noted that the low concentrations of phosphorus in a newly constructed salina resulted in pond leakage and general impairment in functioning of the salina.

Controlled nutrient supplementation by means of fertilisers is required under these conditions to address this imbalance. The addition of nutrients to the Velddrift salina on the west coast of South Africa resolved pond leakage, remedied the insufficient production of biological matter, and improved solar energy absorption.

As saltworks are closed systems, nutrient recycling between the water column and sediment is generally sufficient to maintain an efficient biological system: however, loss of significant quantities of water via seepage can also affect the integrity of the system as well as increase the need for additional fertilisation (Davis, 1978).

By contrast, pumping of nutrient-laden coastal or estuarine waters or direct inflow of rainwater to solar saltworks generally causes hypertrophic conditions in the urban context (MacKay, 1994). Increased runoff during the rainy season often provides substantial nitrogen loading to lagoons, estuaries and coastal waters (Abreu *et al.*, 1995).

Disturbances due to excessive nutrients allow species that are usually constrained by low nutrients and high salinities to reproduce excessively, displacing species beneficial to salt production (Davis and Giordano, 1996). The geographic location of a salina plays an important role in understanding which factors influence the nutrient concentrations of water (Javor, 1989). Proximity to rivers, urban areas, the nutrient status of the incoming seawater and climatic conditions all play a role in determining the trophic status of a salina as are the extent and nature of the fauna and flora in the area and the management practices employed (Javor, 1989).

Excessive nutrient concentrations of water entering the system affect the biota in a variety of ways: substantial masses of pioneer species, predominantly chlorophytes and grasses choke the initial ponds and release dead or decaying matter into higher salinity ponds, suppressing or killing nutrient-stripping organisms (Davis and Giordano, 1996); a rapid increase in brine viscosity may occur, as reported by Jones *et al.* (1981) to be the result of an *Aphanothece* sp. bloom caused by high nutrient conditions in pre-crystallizer ponds. High levels of ammonium may also become toxic to algae (Campbell and Wooldridge, 1994).

Urban saltworks are particularly susceptible to nutrient loading due to their proximity to human settlements. By contrast, the reduced cost of transport makes salinas close to urban areas economically desirable, particularly for a low-price product, such as salt. Evidence indicates that over the past ten years there has been a marked increase in nutrient concentrations in the source water for the urban saltworks close to Port Elizabeth (MacKay 1994, Du Toit 1998, Du Toit 2001). Estuarine ecosystems

and coastal waters (from which the urban salinas derive their brine) are particularly vulnerable to pollution (Winter 1990). Waste, including industrial (hydrocarbons, heavy metals), domestic (phosphates and ammonium), and agricultural (nitrates) has been linked to the disturbance of estuaries and salinas (Morand and Briand 1996, Davis 1990, 1993).

Difford (2008) found that the primary controlling factor of the biota of initial ponds was the balance between inorganic nitrogen and phosphorus. He concluded that macroalgal growth was curtailed when nitrogen was in short supply. However when nitrogen was abundant, water clarity became the controlling factor (Difford, 2008). Nitrogen appears to be the critical nutrient in most salinas as reported by Sammy (1983) who reported that the nitrate levels in the Dampier salt fields in Australia were low by comparison to phosphate, indicating rapid utilisation of nitrate by organisms in the system. High nitrate concentrations indicate that there is an imbalance between the inorganic nitrogen supply and biological utilisation (Campbell and Wooldridge, 1994). However, reactive phosphate is often the growth-limiting nutrient for benthic organisms, as the microphytobenthos remove soluble reactive phosphorus from the water (Davis, 1999).

The proportions of ammonium and nitrate are also relevant as it is generally accepted that the uptake of nitrate by phytoplankton is reduced in the presence of ammonium, this being due either to a preference for ammonium or an inhibition of nitrate uptake (Dortch, 1990). In extreme circumstances nitrate will not be taken up above an ammonium threshold of around 1 μM for of marine phytoplankton (Dortch, 1990).

In South Africa, salinas are limited to areas where high evaporative demand occurs in proximity to a seawater supply (Campbell & Davis, 2000). Salinas have been installed on the west coast of South Africa where the rainy season is in winter leaving a long, dry, hot summer ideal for salt production. Low annual rainfall (ca. 325 mm; Mucina and Rutherford, 2006) of the arid north-west coast also contributes to this area becoming productive for salt production. Being relatively close (150 km) to the large market of Cape Town minimises transport costs.

The other productive area for solar harvesting of salt in South Africa is the south-east coast around the city of Port Elizabeth, Nelson Mandela Bay municipality. Here annual rainfall is higher (ca. 480 mm; Mucina and Rutherford, 2006) but evaporation is increased due to high wind frequency and speeds.

Evaluation of the nutrient environment of some of these South African salinas was aimed at providing insight into how nutrient concentrations affect the biota in solar salt harvesting ponds.

METHODS & MATERIALS

Five South Africa salinas were chosen for investigation: three on the temperate south-east coast of South Africa (Missionvale, Swartkops and Tankatara; Figure 1) and two on the arid west coast of South Africa (Velddrift and Kliphoek; Figure 2).

The nutrient environment in salina ponds was measured at various times over the past twelve years. In order to compare the systems, water salinity (measured with an Atago hand-held refractometer) was taken as a measure of in-flow position of the sample along the path-length of the salina.

Water samples for nutrient analysis were collected from ponds and immediately filtered through Schleicher & Schuell GF/C filters. Samples were darkened, cooled and analysed within four hours. Ammonium was determined according to the method

of Solórzano (1969) and soluble reactive phosphorus according to Strickland and Parsons (1972). Nitrate and nitrite were determined together (NO_x^-) according to the method of Greiss (1879) as modified by Ilosvay (1889) following the reduction of nitrate to nitrite using the copper cadmium method recommended by Bate & Heelas (1975).

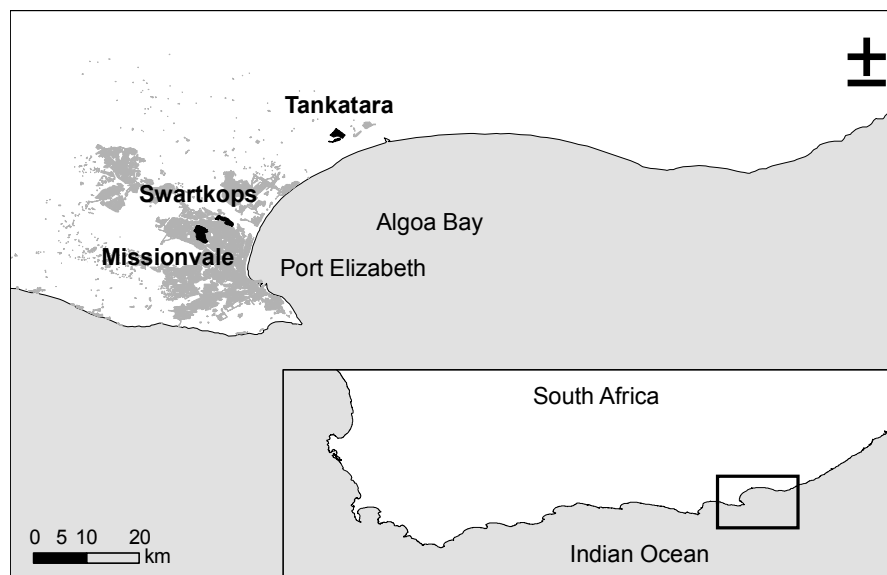


Figure 1. The locality of the salinas sampled on the south coast of South Africa: Missionvale, Swartkops and Tankatara Salinas.

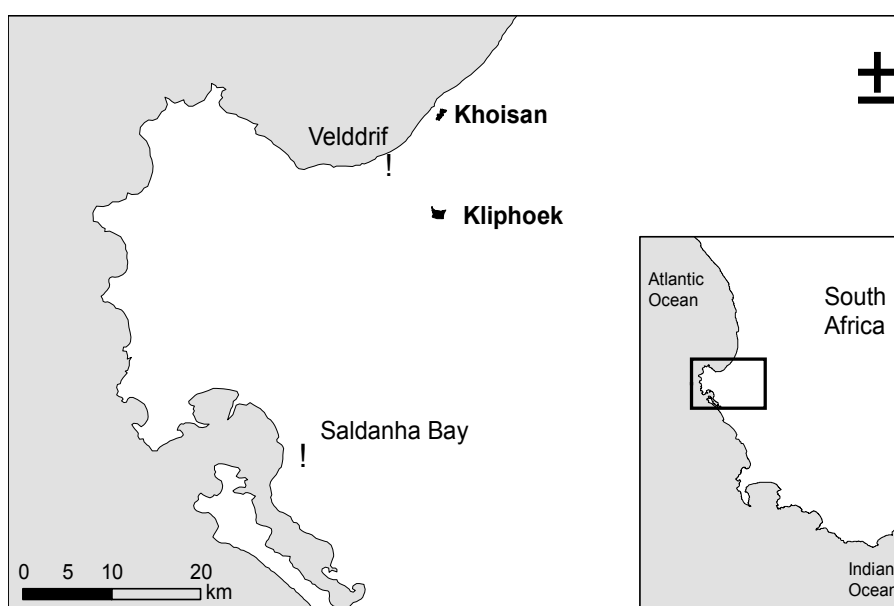


Figure 2. The locality of the salinas sampled on the west coast of South Africa: Velddrif and Kliphoek.

Phytoplankton biomass was determined using chlorophyll *a* concentration measured spectrophotometrically according to the method recommended by Nusch (1980). Macroalgal cover on the water surface of each pond was estimated as a percentage of the pond area.

The number of brine shrimps was used as representative of the zooplankton component of the ecosystem. Samples were collected using a 200 μm mesh tow-net

with a total of 63.8 l of water filtered. Samples were preserved in a 5% formalin solution prior to counting.

Statistical analyses were done using *Statistica* version 10. The Shapiro Wilks test indicated that all data were nonparametric. The Spearman Rank test was used to determine the significance of correlations between variables.

RESULTS

The different nature of the source water resulted in variable salinity profiles of the initial ponds of the five salinas (Figure 3). The Velddrift salina had the highest initial salinity as the water is pumped from an underground aquifer with a salinity of 100 psu (Figure 3). However, this salina had the most consistent initial salinity. The Swartkops salina salinities remained low for longer than the other salinas (the first four sampling points had lower salinity than that measured in the initial ponds of the other four systems; Figure 3). By sampling stations 5 the salinities were similar for all five salinas (Figure 3).

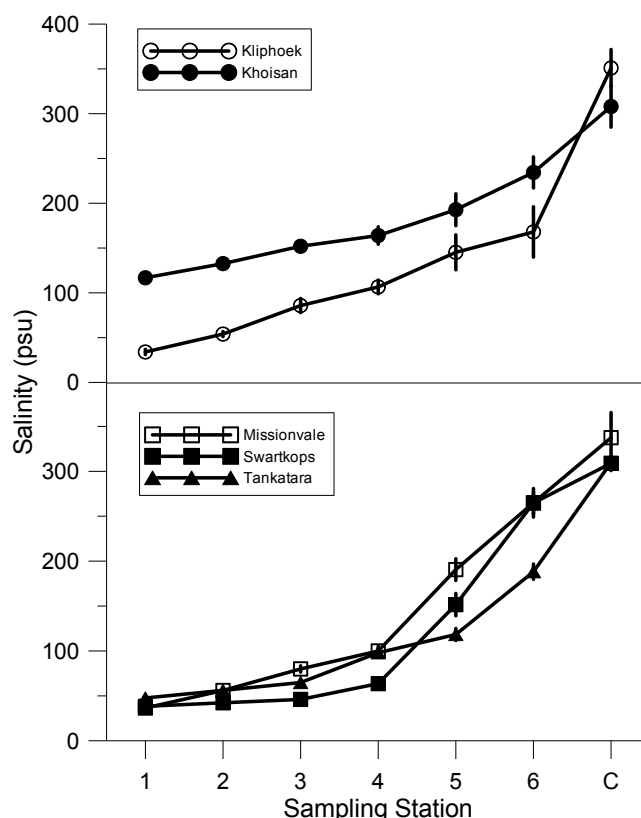


Figure 3. The salinity profiles along the flow path of five salinas sampled on the south and west coasts of South Africa.
South coast: Missionvale, Swartkops and Tankatara salinas;
West coast: Velddrift and Kliphoek salinas.

As much as salinity plays an important role in determining the biotic composition of the salinas, so do the inorganic nutrients of the systems. Nitrogenous nutrients were greatest in the west coast salinas (Velddrift and Kliphoek) and the south coast salina of Missionvale (Figure 4; Table 1). In the two west coast salinas, ammonium contributed less than nitrate and nitrite (Figure 4). More than 80% of the nitrogenous nutrients came from ammonium in the Swartkops and Missionvale systems (the two urban salinas), while the rural Tankatara system had equal contributions between ammonium and the oxidized nitrogen nutrients.

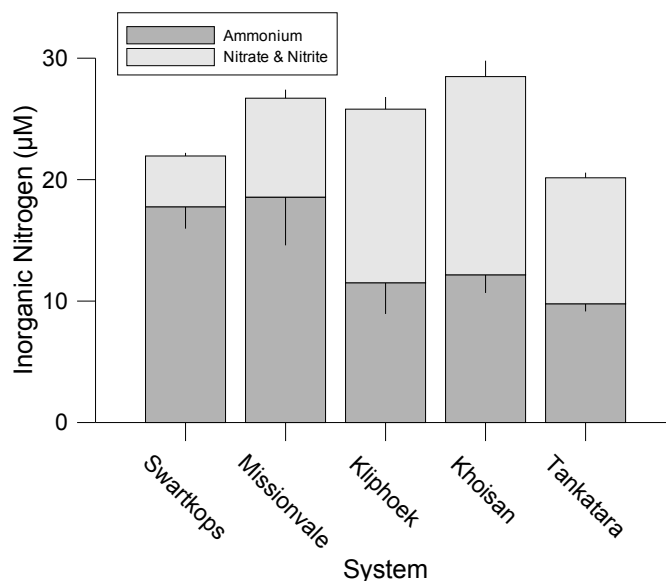


Figure 4. The mean inorganic nitrogen concentrations (± 1 S.E.) of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas.

The inorganic nitrogen concentration of all five salinas falls within or is close to the recommended target of inorganic nitrogen for salinas: 25 μM (Davis and Giordano, 1996).

Table 1. The mean inorganic nitrogen concentrations (± 1 S.E.) of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas.

	Ammonium (μM)				Nitrate and Nitrite (μM)			
	n	median	minimum	maximum	n	median	minimum	maximum
Swartkops	183	10.897	0.927	139.540	219	4.539	0.445	60.897
Missionvale	74	8.263	0.490	196.857	84	7.230	1.718	28.355
Kliphoek	35	7.829	1.980	68.512	35	13.146	3.493	28.874
Velddrift	69	9.516	2.380	76.033	69	17.373	2.313	37.977
Tankatara	482	6.102	0.001	144.153	499	7.311	0.530	60.897

By contrast, the low-nitrogen Tankatara salina had the highest concentration of soluble reactive phosphorus (Figure 5, Table 2) with the high-nitrogen Missionvale having the lowest concentration. All five salinas had higher average concentrations of phosphate than what is ideal (1 μM ; Davis and Giordano, 1996).

Kliphoek and Tankatara had the highest average phytoplankton biomass with Swartkops, Missionvale and Velddrift salinas having low phytoplankton standing biomass (Figure 6; Table 3). The average chlorophyll a concentrations varied greatly, ranging from $<0.01 \mu\text{g l}^{-1}$ to $500 \mu\text{g l}^{-1}$ (Figure 7). To convert this nonparametric data to a trend-line, the running average of the phytoplankton biomass means recorded in 10 psu bin sizes of salinities (i.e. 35-44 psu; 45-54 psu; ...) was added (Figure 7).

This running average for phytoplankton biomass fluctuated between 50 and 100 $\mu\text{g chl } a \text{ l}^{-1}$ (Figure 7).

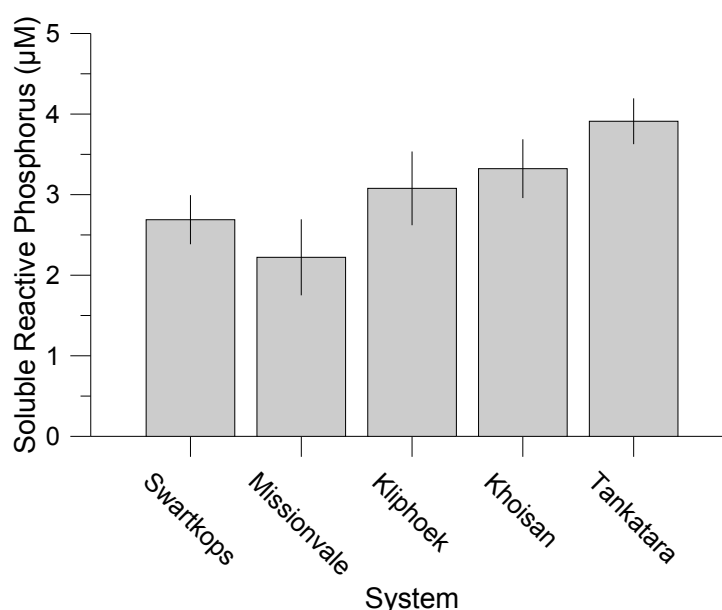


Figure 5. The mean inorganic nitrogen concentrations (+/- 1 S.E.) of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas.

Table 2. The median, minimum and maximum values for soluble reactive phosphorus of the five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; west coast: Velddrift and Kliphoek salinas.

	Soluble reactive phosphorus (μM)			
	n	median	minimum	maximum
Swartkops	210	1.554	0.038	16.000
Missionvale	83	0.772	0.000	15.950
Kliphoek	34	2.411	0.132	11.678
Velddrift	69	3.419	0.085	40.956
Tankatara	535	1.613	0.032	68.444

Missionvale and Tankatara had the highest average cover of macroalgae (Figure 8, Table 3). With its high initial salinity, the Velddrift salina had no macroalgae (Figure 8, Table 3). In the initial ponds of the other four salinas, the macroalgal cover varied between 0 and 80%, with no macroalgae persisting after the salinity reached 150 psu (Figure 9). The running average of the macroalgal cover means recorded in 10 psu salinity size classes showed a steep decline in macroalgal cover as the salinity increased above 70 psu (Figure 9). Macroalgae did not form a substantial part of the biota above 100 psu (Figure 9).

Missionvale and Tankatara had the highest abundance of brine shrimps (Figure 10, Table 3). Very low numbers of brine shrimp were found at salinities below 60 psu, with the majority of the brine shrimps found at salinities between 100 and 200 psu (Figure 11). The running average of the 10 psu salinity size classes of brine shrimp

abundances indicates that the greatest abundance of brine shrimps were found at 160 psu with values declining to minimal values by 280 psu (Figure 11).

Table 3. The median, minimum and maximum values for phytoplankton biomass, macroalgal cover and *Artemia salina* abundance of the five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; west coast: Velddrift and Kliphoek salinas.

	Phytoplankton ($\mu\text{g chl } a \text{ l}^{-1}$)				Macroalgae (% cover)			
	n	median	minimum	maximum	n	median	minimum	maximum
Swartkops	206	15.5	0.1	220.6	128	0.0	0.0	25.0
Missionvale	72	24.9	2.5	245.8	71	0.1	0.0	35.0
Kliphoek	35	113.8	7.5	385.0	35	0.0	0.0	10.0
Velddrift	58	12.35	0.4	98.0	70	0.0	0.0	0.0
Tankatara	541	74.0	0.5	951.9	190	0.0	0.0	80.0

	<i>Artemia salina</i> (number l^{-1})			
	n	median	minimum	maximum
Swartkops	165	2	0	13320
Missionvale	52	0	0	35240
Kliphoek	35	10	0	13420
Velddrift	50	125	0	9080
Tankatara	341	0	0	118906

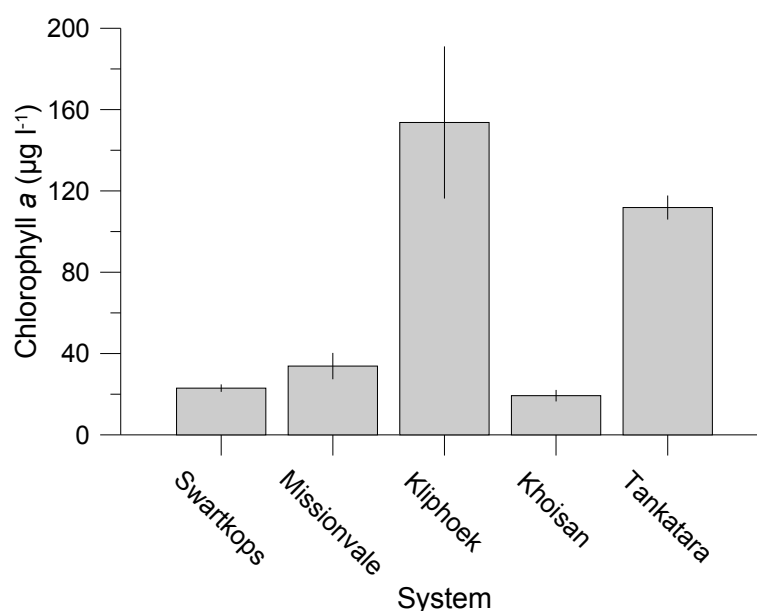


Figure 6. The mean phytoplankton biomass in units of chlorophyll a concentration (± 1 S.E.) of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas.

At the lower salinities (100 psu), there is a significant negative relationship between phytoplankton and macroalgae biomass (Figure 12, Table 4). As the salinity

increases, the brine shrimp abundance increases, with a significant negative correlation between phytoplankton biomass and brine shrimp numbers (Figure 12, Table 4), so that where the brine shrimp numbers are at their highest the phytoplankton concentration is lowest (Figure 12). As the salinity increases beyond the tolerance of the brine shrimps, halophilic phytoplankton flourish (Figure 12).

Phytoplankton biomass was positively correlated to the concentration of soluble reactive phosphorus while macroalgal biomass was not correlated to any of the nutrients (Table 4) *Artemia salina* numbers were positively correlated to the concentration of ammonium as well as nitrate & nitrite (Table 4).

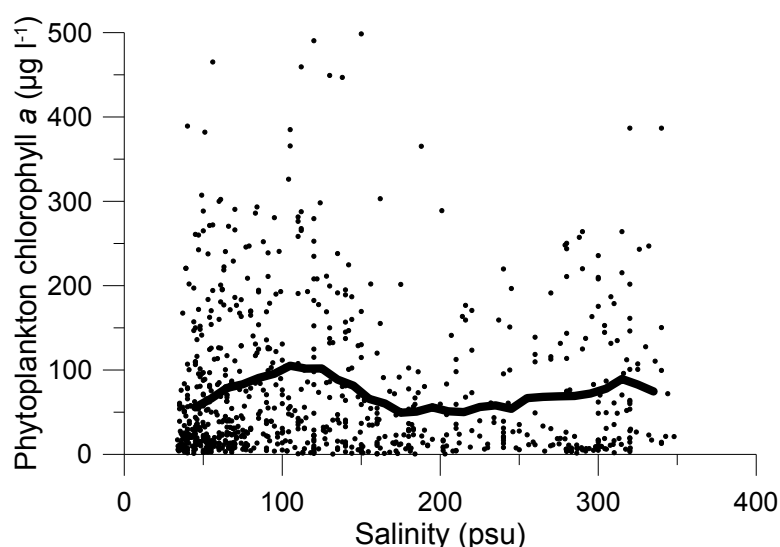


Figure 7. The phytoplankton biomass in units of chlorophyll a concentration measured at different salinities in ponds of five salinas sampled on the south and west coasts of South Africa.

South coast: Missionvale, Swartkops and Tankatara salinas;
West coast: Velddrift and Kliphoek salinas. The solid line is the running average of the mean of each 10 psu class of salinity.

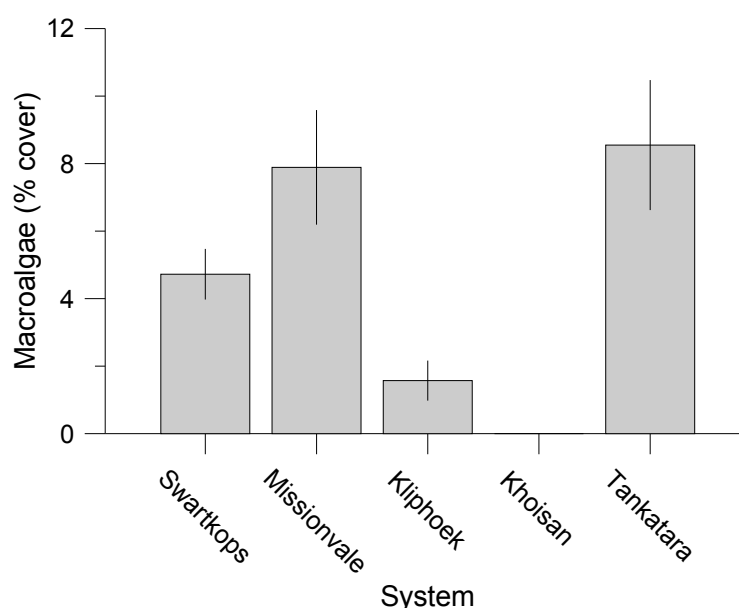


Figure 8. The mean macroalgal cover (± 1 S.E.) of the pond surface of five salinas sampled on the south and west coasts of South Africa.

South coast: Missionvale, Swartkops and Tankatara salinas;
West coast: Velddrift and Kliphoek salinas.

Macroalgae therefore, appear to be controlled primarily by salinity ($|R| = 0.637$; Table 4), phytoplankton by competing macroalgae ($|R| = 0.174$; Table 4) and brine shrimp feeding ($|R| = 0.192$; Table 4); while brine shrimp numbers are determined by the salinity ($|R| = 0.503$; Table 4). The concentrations of nitrogenous nutrients are significantly correlated to brine shrimp numbers indicating that their excretion and feeding controls these concentrations ($|R| = 0.164$ & 0.165 ; Table 4).

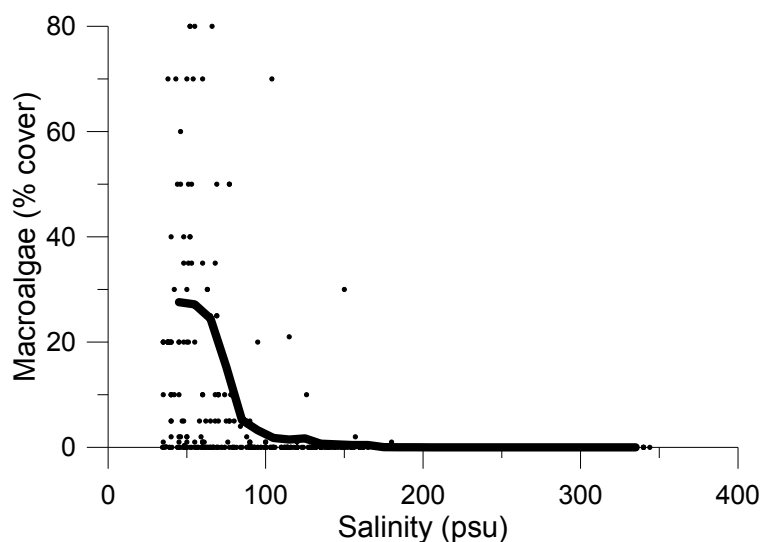


Figure 9. The macroalgal cover of the pond surface measured at different salinities in ponds of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas. The solid line is the running average of the mean of each 10 psu class of salinity.

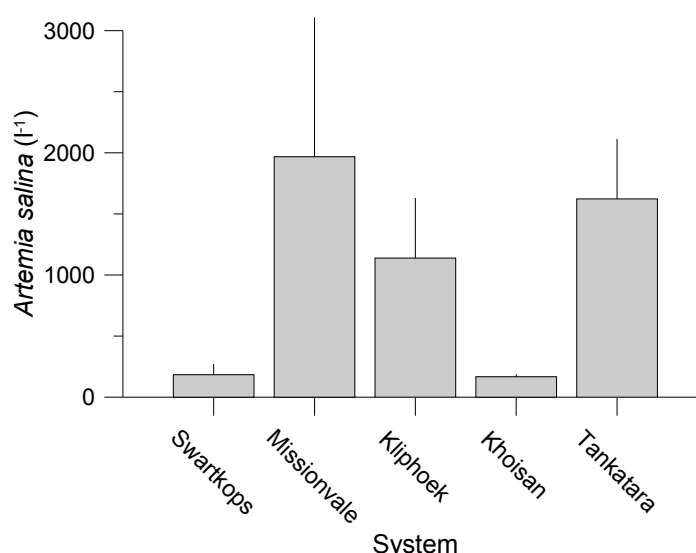


Figure 10. The mean number of *Artemia salina* (brine shrimps; ± 1 S.E.) of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas.

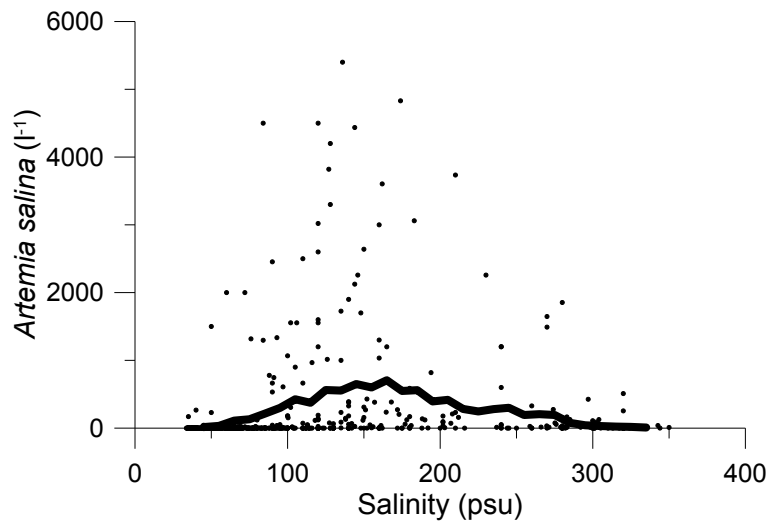


Figure 11. The mean number of *Artemia salina* (brine shrimps) measured at different salinities in ponds of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas. The solid line is the running average of the mean of each 10 psu class of salinity.

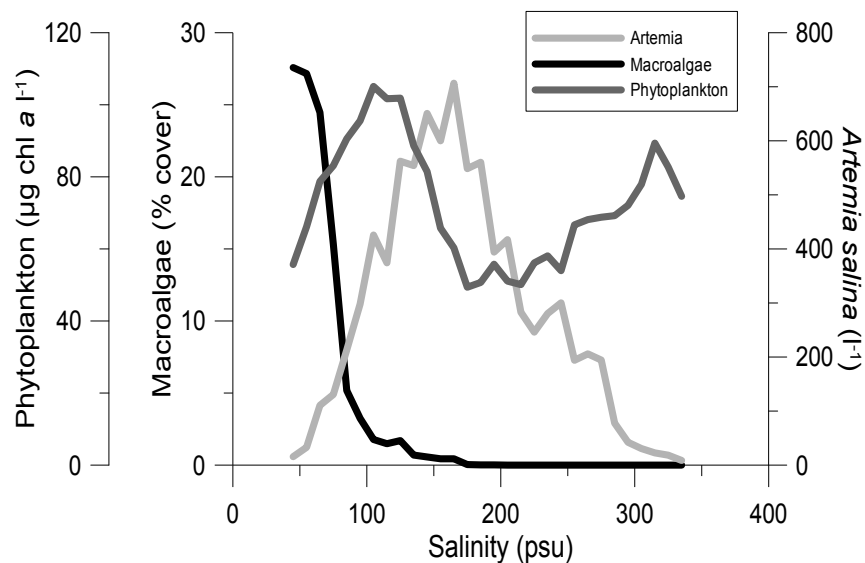


Figure 12. The running average of the mean of major ecosystem measures (phytoplankton biomass as $\mu\text{g chl } a \text{ l}^{-1}$; macroalgae as cover abundance; *Artemia salina* as number l^{-1}) in ponds of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas. Values are the mean of all measures taken in each of 10 psu classes of salinity.

Table 4. Spearman's Rank correlation coefficients comparing water quality and biota of five salinas sampled on the south and west coasts of South Africa. South coast: Missionvale, Swartkops and Tankatara salinas; West coast: Velddrift and Kliphoek salinas. Values in bold are significant at $p < 0.05$. For these the p-value is given in parentheses.

	Phytoplankton biomass ($\mu\text{g chl } a \text{ l}^{-1}$)	Macroalgal biomass (% cover)	<i>Artemia salina</i> (numbers l^{-1})
Salinity	0.071 (0.037)	-0.637 (<0.001)	0.503 (<0.001)
Ammonium	-0.234 (<0.001)	0.063	0.165 (<0.001)
Nitrate & Nitrite	0.008	-0.044	0.164 (<0.001)
Phosphate	0.085 (0.011)	-0.019	0.065
Phytoplankton	-		
Macroalgae	-0.174 (<0.001)	-	
Brine shrimp	-0.192 (<0.001)	-0.298 (<0.001)	-

DISCUSSION

The South African salinas investigated in this study range in biotic productivity. The Swartkops and Missionvale salinas are important salt-producing systems for the Eastern Cape Province and derive their brine from the Swartkops Estuary. The Swartkops River and Estuary and River flows through an area with a variety of heavy industries and nearly a million people within its catchment, many of whom live in informal settlements with little or no formal sewage or rubbish removal services. The result is a steadily increasing level of pollution in the estuary (Binning 1999, Mackay 1994) with a consequent increase in nutrient loading via in the inlet water. To complicate matters, both these salinas are surrounded by informal settlements with poor waste removal and rainfall runoff as well as occasional sewage spillage deposits high-nutrient water into the ponds. As a result, these two salinas are hypertrophic with a thick base of organic deposition as a result of many years of abundant production (Du Toit, 2001; Difford, 2008).

Kliphoek, in the Western Cape Province, is an intermediate system in terms of productivity. It is the smallest and most informal system studied. Salt water is sourced from the Berg River Estuary and the salina forms part of a functioning farm. The Berg estuary is also becoming progressively more polluted (Allanson and Winter 1999), but not to the extent of that in the Swartkops Estuary. The Kliphoek salina has moderate benthic carbon deposits (Du Toit, 2002) supporting the observation that the system is mesotrophic.

Both the Tankatara and Velddrif systems are oligotrophic and required fertilisation to encourage the development of a benthic algal base that would control pond leakage (Campbell et al., 2001 Du Toit, 2002). The Velddrif salina on the west coast of South Africa derives its brine from an aquifer with a salinity of 100 psu, making it an interesting alternative to the other salinas in this study. The aquifer water has low nutrient concentrations, and considering the low rainfall of the area and the sandy soils surrounding the salina, there is no runoff to deliver any nutrients to the system. The only present source of fertiliser is derived from the birds that frequent the ponds. The Tankatara system derives its water from an unpolluted portion of Algoa Bay coastal waters, well away from the discharges of the city of Port Elizabeth. There is

also no nutrient-rich runoff and, as in the case of Velddrif, birds provide most of the nutrients to the salina.

The biology of the five salinas reflects the diverse conditions under which salt is produced. The fifty year old east coast salinas of Swartkops and Missionvale, with their surrounding urban pollution, face particular nutrient loading problems. The oligotrophic Tankatara and Velddrif systems are some distance away from urban pollution but are challenged by low nutrient provision making them susceptible to leakage. Kliphoek, drawing water from the Berg River Estuary, with its ever increasing nutrient load from the agricultural catchment will require careful biological management to ensure an efficient biology. These systems showed high variation in biological production. Average phytoplankton biomass varied by six-fold (Figure 6), macroalgal cover by five-fold (Figure 8) and brine shrimp abundance by ten-fold (Figure 10).

Despite the substantial differences between the inorganic nutrient loads, the nutrient concentrations in the ponds of all five systems were seldom particularly high (Table 1). In 95% of the samples taken ($n = 908$) the ammonium concentration was in the lower 20% of the range (Table 1). For nitrate and nitrite, 83% of the samples taken ($n = 968$) fell in the lower 30% of the range (Table 1). Inorganic nitrogen (ammonium, nitrate and nitrite concentrations) fell in the lower 20% of the range in 90% of the samples. This indicates, that the biota, for the most part take up much of the nutrient load and convert it to biomass.

Despite these differences in nutrient loading, if analysed together, the salinas showed the required replacement of dominant biota as the salinity increased as found by Davis (1990). The early ponds were dominated by algae (macroalgae and phytoplankton; Figures 7 & 8). The more hypertrophic systems had high levels of biomass of macroalgae in the earlier ponds so that they out-competed the phytoplankton. This is a common phenomenon in estuarine (Fong *et al.*, 1996) and hypersaline (Difford, 2008) habitats. Difford (2008) postulated the operation of a “bloom-and-bust” cycle in solar saltworks that occurs when the phytoplankton population collapses in the salina due to macroalgal blooms in the ponds. The macroalgae float on the water surface, and shade the phytoplankton below. This results in the phytoplankton death and decomposition (Difford, 2008). This decay of the phytoplankton biomass leads to an increase of nutrients into the water column and this causes macroalgal blooms again (Difford, 2008). This feed-back loop is supported by this negative correlation between macroalgal cover and phytoplankton biomass (Table 4) overall for the five salinas investigated here.

Irrespective of the nutrient concentrations, the macroalgae are the first to be affected by the increasing salinity (Figure 12). As found in other systems, the macroalgae do not persist beyond 120 psu (Davis, 1990), but begin to decline above 70 psu (Difford, 2008). Macroalgae cannot survive salinities above 70 psu in the long term and can only withstand higher salinities for short periods. This relationship is supported by the negative correlation between salinity and macroalgal biomass overall (Table 4). Macroalgae reached high standing biomass only infrequently, with 92% of the samples falling in the lower 10% of the range.

The phytoplankton community is affected by salinity at a later stage in the gradient (Rijstenbil, 1987). In these five salinas, phytoplankton biomass declines above 125 psu (Figure 7). Salinity is one of the most variable abiotic factors (Remane, 1955, 1958; Gasiunaite, 2000) and with the specific growth rates of phytoplankton being affected by salinity fluctuations (Rijstenbil, 1987), this effect is predicted. However, this effect may be secondary, as at around 100 psu *Artemia salina* (brine shrimps)

appear (Figure 11). Between 120 and 180 psu there is a decrease in the phytoplankton as the shrimps clear the water. Phytoplankton is the primary food source for brine shrimp (Sammy, 1983). Their reproduction rates, brood size, lipid contents and cyst yields are all determined by the quantity and type of food available (Mohebbi, 2010). Where abundant, the phytoplankton biomass is significantly reduced by *Artemia* grazing (Table 4; Mohebbi, 2010) as manifest in the negative correlation between phytoplankton chlorophyll *a* (biomass) and brine shrimp numbers overall (Table 4). Brine shrimp grazing, in turn results in release of nutrients that further enhance phytoplankton production, leading to a continuous reciprocal interaction (Mohebbi, 2010).

Brine shrimp populations naturally occur in salt lakes, with their salinity tolerances ranges generally being between 100 psu to 250 psu. Difford (2008) found that brine shrimps occur at salinities greater than 70 psu, but do best at salinities of 120 to 140 psu where they have protection from less halotolerant predators. At around 250 psu *Artemia salina* food sources generally become limiting (Sorgeloos *et al.*, 1991) causing their decline. However, in the South African salinas this was not the case. The reduction in brine shrimp numbers as the salinity increased was due to the change in salinity and not the abundance of microalgae, as there was a second phytoplankton biomass maximum (measured as chlorophyll *a* and therefore excluding the halophilic bacteria). Samples showed abundance of *Dunaliella salina* that proliferated at the higher salinities, particularly in the meso- and oligotrophic salinas (Figure 7, Table 3). This unusual phenomenon was not expected according to Davis (1990), but was most likely caused by the reduction in brine shrimp numbers.

The phytoplankton biomass increases in inverse proportion to the abundance of brine shrimps at salinities above 200 psu (Figure 12). This may have implications for the harvesting of the salt from the crystallisers, as there is still a substantial biomass of phytoplankton at this stage (around 80 µg chl *a* l⁻¹, Figure 7).

Brine shrimp are either absent or are present in lesser numbers when there is macroalgae present (Table 4) because they do not share tolerance to much of the salinity range (Figure 12). Difford (2008) found that macroalgae generally have disappeared by 70 psu, whereas in this study they had disappeared by 90 psu with very few exceptions (Figure 8). In this study, the brine shrimps appeared at around 80 psu with very few exceptions (Figure 9) indicating that this negative correlation is unlikely to be due to a direct response of the one to the other, but rather an intolerance of each to the salinity favoured by the other.

The nutrient environment of the salinas is partially controlled by the fauna. *Artemia salina* abundance was correlated to the ammonium concentration of the water as they excrete ammonium (Colvin and Brand 1977, Meyer-Willerer, 1997). Phytoplankton in turn example removed ammonium from the surrounding medium (e.g. in *Dunaliella salina* cells - Thakur and Kumar, 1999).

Nitrate concentrations were, however, correlated to salinity (Figure 4, Table 1). Camargo *et al.* (2004) found that nitrate was released during the decomposition of the numerous organisms that can no longer tolerate the increasing salinity.

Soluble reactive phosphorus was not the limiting nutrient in any of the salinas (Figure 5, Tables 3) as there is a positive relationship between phytoplankton biomass and the concentration of soluble reactive phosphorus (Table 4). The phosphates are generally deposited in abundance by birds in all five salinas (Du Toit, 2001). Avifaunal abundance (data not shown) was significantly correlated with the soluble reactive phosphorus concentrations in the water ($r^2 = 0.79$, d.f. = 48, $p < 0.01$).

CONCLUSION

In conclusion, this study showed that when the data from five South African salinas were analysed collectively, significant correlations were found between inorganic nutrients and the biota, confirming that nutrients play an important role in the overall functioning of systems. Total inorganic nitrogen and soluble reactive phosphorus influenced the total standing biomass of the salinas, showing how beneficial nutrients are to the productivity of a salina. Provided that the exceptional nutrient input events are controlled and/or well managed, the salinas will be productive and remain in equilibrium, and will lead to production of good quality salt.

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REFERENCES

1. Abreu, P.C., Hartmann, C., and Odebrecht, C. (1995), Nutrient-rich Saltwater and, its Influence on the Phytoplankton of the Patos Lagoon Estuary, Southern Brazil. *Estuarine, Coastal and Shelf Science*, **40**, 219-229.
2. Allanson, B. and Winter, D. (1999), Chemistry: The influence of man. In: Allanson, B and Baird, D. (Eds.). *Estuaries of South Africa*. Cambridge University Press, Cambridge. 340 pp.
3. Baas-Becking, L.G.M. (1931), Historical notes on salt and salt manufacture. *Scientific Monthly*, 1931.
4. Bate, G. C., and Heelas, B. V. (1975), Studies on the nitrate nutrition of two indigenous Rhodesian grasses. *Journal of Applied Ecology*, **12**, 941-952.
5. Binning, K.A. (1999), An investigation into the relationship between water quality, sediment, and meiofaunal communities of the Swartkops River system. University of Port Elizabeth, South Africa, MSc dissertation, 147 pp.
6. Britten, R.H. and Johnson, R. (1987), An ecological account of a Mediterranean salina : the Salin de Giraud, Camargue (S. France). *Biological Conservation*, **42**, 185-230.
7. Camargo, W.S., Ely, J.S., Duran-Cobo, G.M., Sorgeloos, P. (2004), Influence of some physicochemical parameters of *Artemia* biomass and cyst production in some Thalassohaline Aquatic Environments in the Columbian Caribbean. *Journal of the World Aquaculture Society*, **35**, 276-283.
8. Campbell, E.E. and Wooldridge, T. (1994), Biological Assessment of the Missionvale and Swartkops Solar Saltworks. Institute for Coastal Research, University of Port Elizabeth. 42 pp.
9. Campbell, E.E. and Davis, J.S. (2000), Diatoms as indicators of pond condition in solar saltworks. In: Geertman, R.M. (Ed.). 8th World Salt Symposium, Elsevier, Volume 2, pp. 855-860.
10. Campbell, E.E., Davis, J.S. and Wooldridge, T. (2001), The biota of newly installed solar saltworks at Tankatara, east of Port Elizabeth, South Africa. Institute for Coastal Research, University of Port Elizabeth. 146 pp.
11. Carpelan, L.H. (1957), Hydrobiology of the Alviso salt ponds. *Ecology*, **38**, 375-390.

12. Colvin, P.M. and Brand, C.W. (1977), The protein requirements of penaeid shrimp at various life cycle stages in controlled environment systems. *Journal of World Mariculture Society*, **8**, 821–840.
13. Davis, J. S. (1978), Biological communities of a nutrient enriched salina. *Aquatic Botany*, **4**, 23–42.
14. Davis, J.S. (1990), Biological Management for the Production of Salt from Sea water. In: Akutsuka, I. (ed). *Introduction to Applied Phycology*. pp 479-488.
15. Davis, J.S. (1993), Biological Management for Problem Solving and Biological Concepts for a New Generation of Solar Saltworks. *Seventh Symposium on Salt*. Elsevier Science Publishers B.V., Amsterdam, pp. 611-616.
16. Davis, J.S. (1999), Solar Saltwork - An environmentally industry - Text of an invited post-conference contribution presented orally at Pythagorion, Samos, Greece. Department of Botany, University of Florida, Gainesville, Florida.
17. Davis, J.S. and Giordano, M. (1996), Biological and physical events involved in the origin, effects, and control of organic matter in solar saltworks. *International Journal of Salt Lake Research*, **4**, 335-347.
18. Difford, M. (2008), Towards the Bioremediation of the Hypertrophic Swartkops Solar Salt-works. PhD Thesis. Nelson Mandela Metropolitan University. 296 pp.
19. Dortch, Q. 1990. The interaction between ammonium and nitrate uptake in phytoplankton. *Marine Ecology Progress Series*, **61**, 183-201.
20. Du Toit, S.R. (1998), Artificial wetlands in the management of solar saltworks. Unpublished M.Sc. dissertation, Department of Botany, University of Port Elizabeth. 117 pp.
21. Du Toit, S. R. (2001), Biological management of South African solar saltworks. PhD thesis, University of Port Elizabeth, 260 pp.
22. Fong, P., Boyer, K.E., Desmond, J.S., and Zedler, J.B. (1996), Salinity stress, nitrogen competition, and facilitation: what controls seasonal succession of two opportunistic green macroalgae?. *Journal of Experimental Marine Biology and Ecology*, **206**, 203-221.
23. Gasiunaite, Z.R. (2000), Coupling of the limnetic and brackishwater plankton crustaceans in the Curonian lagoon (Baltic Sea). *International Review of Hydrobiology*, **85**, 649-657.
24. Gasiunaite, Z.R., Cardoso, A.C., Heiskanen, A.-S., Henriksen, P., Kauppila, P., Olenina, I., Pilkaityte, R., Purina, I., Razinkovas, A., Sagert, S., Schubert, H., and Wasmund, N. (2005), Seasonality of coastal phytoplankton in the Baltic Sea: Influence of salinity and eutrophication. *Estuarine, Coastal and Shelf Science*, **65**, 239–252.
25. Griess, P. (1879), Bemerkungen zu der abhandlung der H.H. Weselsky und Benedikt Ueber einige azoverbindungen. *Berichte der Deutschen chemischen Gesellschaft*, **12**, 426–428.
26. Ilosvay, M.L. (1889), L'acide azoteux dans la salive et dans l'aire exhale. *Bulletin de la Société Chimique de France*, **2**, 388-391.
27. Javor, B. J., (1989), Hypersaline Environments : Microbiology and Biogeochemistry. Springer Series in Contemporary Bioscience. Springer-Verlag, Berlin. 195 pp.
28. Jones, A.G., Ewing, C.M. and Melvin, M.V. (1981), Biotechnology of solar saltfields. *Hydrobiologia*, **82**, 391-406.
29. MacKay, H.M. (1994), Management of water quality in an urban estuary. PhD thesis. University of Port Elizabeth, Port Elizabeth, South Africa. 242 pp.
30. Meyer-Willerer, A.O. (1997), Effects of age, temperature, light, and starvation time on ammonia excretion of white shrimp *Penaeus vannamei* (Boone) during transport. World Aquaculture '97. Book of Abstracts. World Aquaculture Society. Seattle, Wa.USA, pp 329.

31. Mohebbi, F. (2010), The Brine Shrimp *Artemia* and hypersaline environments microalgal composition: a mutual interaction. *International Journal of Aquatic Science* **1**: 19-27.
32. Morand, P. and Briand, X. 1996. Excessive growth of macroalgae: A symptom of Environmental Disturbance. *Botanica Mararina*, **39**, 491–516.
33. Mucina, L. and Rutherford, M.C. (eds). (2006), The vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19. South African National Biodiversity Institute. Pretoria. 807 pp.
34. Nusch, E.A. (1980), Comparison of different methods for chlorophyll and phaeopigment determination. *Archiv fur Hydrobiologie Beih. Ergebn. Limnologie*, **14**, 14-36.
35. Rahaman, A.A., Ambikadevi, M., and Ezzo, S. (1993), Biological management of Indian solar saltworks. *Seventh Symposium on Salt*. Elsevier Science Publishes B.V., Amsterdam, **1**, 633–643.
36. Remane, A., (1955), Die Brackwasser - Submergenz und die Unkomposition der Coenosen in Belt- und Ostsee. *Kieler Meeresforschung*, **11**, 59-73.
37. Remane, A., (1958), Ökologie des Brackwassers. In: Remane, A., Schlieper, C. (Eds.), *Die Biologie des Brackwassers*. Schweizerbartsche Verlagsbuchhandlung, Stuttgart, p. 216.
38. Rijstenbil, J.W. (1987), Phytoplankton composition of stagnant in tidal ecosystems in relation to salinity, nutrients, light and turbulence. *Netherlands Journal of Sea Research*, **21**, 113–123.
39. Sammy, N. (1983). Biological Systems in north-western Australian solar salt fields. In: Schreiber, B.C. and Harner, H.L. (eds.) *sixth Symposium on Salt*. Vol 1. The Salt Institute, Alexandria, Virginia, pp. 207-215.
40. Solórzano, L. (1969), Determination of ammonia in natural waters by the phenylhypochlorite method. *Limnology and Oceanography*, **14**, 799-801.
41. Sorgeloos, P and Tackaert, W. (1991), Roles and Potentials of *Artemia* in coastal Saltworks. In *Proceedings of International Symposium on Biotechnology of Saltponds*, Tanggu, Tianjin, PR China. Cheng, L. (Ed.) Salt Research Institute, Tanggu, Tianji, PR China, 283 pp.
42. Strickland J.D.H. and Parsons, T.R. (1972), A practical handbook of seawater analysis. 2nd Edition, Bulletin 167. Fisheries Research Board of Canada, Ottawa.
43. Thakur, A. and Kumar, H.D. (1999), Nitrate, ammonium and phosphate uptake by immobilized cells of *Dunaliella salina*. *Bull. Environmental Contamination and Toxicology*, **62**, 70–78.
44. Winter, P.E.D. (1990), The estuarine-marine exchange of dissolved and particulate material at the Swartkops River estuary, Algoa Bay, South Africa. PhD thesis, University of Port Elizabeth, South Africa. 106 pp.