Diatoms as indicators of pond condition in solar saltworks

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One of the trends in water quality studies is to use bioindicators to determine time-integrated conditions. Dominant benthic diatoms have been shown to be useful for this purpose. This is in contrast to instantaneous conditions determined by direct water quality measurement. It is hypothesised that the history of environmental conditions will be reflected in diatom species dominance. Both benthic and planktonic diatoms may be useful bioindicators in solar saltworks because of the controlled nature of water flow and the compartmentalisation afforded by the pond system. Multivariate analysis was used to analyse diatom communities and environmental variables.

Salinity was the most stable environmental variable in the system over the long term. Phosphate concentrations also showed little fluctuation. Temperature, light penetration, nitrate and ammonium concentrations fluctuated seasonally but nitrate and ammonium also varied on a shorter time scale from month to month.

Ordination of dominant planktonic and benthic diatom species separated them into two communities: the diatoms in the first three ponds were different from the rest. The greatest variation in dominant diatom composition was accounted for by salinity. However, a secondary gradient controlling both benthic and planktonic diatoms was nitrate and light penetration. This implies that benthic and planktonic diatoms are suitable indicators of both short-term (month to month) and long-term (seasonal) variations in pond condition of solar saltworks. Benthic diatoms, however, indicate a larger suite of environmental conditions than planktonic diatoms do.

1. INTRODUCTION

Harvesting salt following solar-driven evaporation provides one third of world production [1]. Crude harvesting of salt from evaporation-dried pools of seawater was most probably the oldest form of salt harvesting [2]. This opportunistic harvesting developed, via simple artificial ponds, to complex large systems able to produce tons of high quality salt per year. Modern solar saltworks consist of a series of connected, shallow (10 to 50 cm deep) concentrating and crystalliser ponds used for the solar evaporation of seawater to extract sodium chloride. As the salinity rises, salts precipitate: $CaCO_3$ at around 70°/₀₀ and $CaSO_4$ (gypsum) at 140°/₀₀. NaCl begins to precipitate at 300°/₀₀.

The process of salt mining by removal from seawater takes place in four stages [2]. Saline water is pumped into concentrating ponds that are typically 300 to 500 ha in size with a salinity ranging from 35°/₀₀ (salinity of seawater) to 100°/₀₀. These ponds generally contain most of the biota of the system. The second stage consists of the ponds where gypsum precipitates. They are typically 40 to 200 ha in size with a salinity ranging from 100°/₀₀ to 200°/₀₀. The biotic diversity gradually decreases along the flow path of these ponds. This brine flowing out of the final concentration pond is pumped into crystallisation ponds that are about 15 to 20 ha in size. The biotic diversity of the crystalliser ponds is low with the benthic community ideally absent. The fourth stage is the harvesting stage.

The biota of solar saltworks contributes to the efficiently functioning and harvesting of salt [1,3]. Biota seals the ponds, contributes to evaporation (by colour) and purifies the brine to reduce organic contamination of the salt. Overproduction of organic matter loads the salt with carbon resulting in production of "dirty" salt, increased expense due to ashing or increased contaminants on and inside the crystals. Mucilage excreted by algae may interfere with efficient harvesting and floating algae reduce evaporation.

A benefit of biota may be their use as indicators of time-integrated water quality in the ponds. Dominant benthic diatoms, in particular, have been shown to be useful bioindicators [4]. This is in contrast to the instantaneous pond condition determined by direct water quality measurement.

The aim of this study was to determine whether diatoms could be used as bioindicators in solar saltworks. While benthic diatoms are commonly used as indicators [4], it is possible that planktonic diatoms may also be used indicators in solar saltworks because of the controlled nature of water flow and the compartmentalisation caused by the pond system.

2. MATERIALS AND METHODS

2.1. Study area

The saltworks sampled for this study were located approximately 40 km east of the city of Port Elizabeth, South Africa. The area is semi-arid, with a temperate, oceanic climate. The average maximum air temperature is 26°C, and the average minimum is 7°C, with extremes of 0°C to 34°C [5]. The 30-year average annual rainfall for the area is 614 mm [5]. The system consists of a series of four large concentration ponds (30 to 45 ha each) followed by another four small concentration ponds (up to 15 ha). These ponds have been numbered sequentially from 1 to 8. Two of the crystallisers were sampled but these were not found to contain live diatom cells and are excluded from this study.

2.2. Pond condition

Water salinity was measured using an Atago hand-held refractometer. Brine samples over 100°/₀₀ were diluted with distilled water to bring them onto scale. Samples were stabilised at 20°C before salinity determinations. Water temperature was measured using a mercury thermometer. Light penetration was measured using a Secchi disk. The ammonium concentration in filtered (GF/C filters) brine was determined using the method of Solórzano [6]. The method described by Bate and Heelas [7] was used determine the nitrate concentration and the method of Strickland and Parsons [8] was used to determine soluble reactive phosphorus in the same samples. Three replicates of each analysis were done for each sample.

2.3. Diatoms

Water samples were preserved using a 10% solution of Lugol's iodine [9]. Diatom frustules were cleaned by boiling samples with concentrated HCl (50%) for 15 minutes whereafter they were identified from scanning electron micrographs. Diatoms were enumerated into three abundance categories 1 to 3 where 1 was assigned to the dominant species in the sample; 2 was assigned when the species was highly dominant (only a few other dominant species) and 3 assigned when the species was the only dominant and highly abundant. Uncommon species were assigned a value of 0.

Multivariate analysis of diatom communities was done using CANOCO [10]. Detrended correspondence analysis (DCA) was used for combined ordination. Detrended canonical correspondence analysis (DCCA) was used to analyse the planktonic and benthic diatom communities separately.

3. RESULTS AND DISCUSSION

3.1. Pond conditions

Salinity fluctuated along the flow path but showed no temporal variation. The salinity gradient ranged from $42 \pm 3°/_{oo}$ in pond 1 to $213 \pm 18°/_{oo}$ in pond 8 just before to delivery of brine to the crystallisers (Fig. 1). There was no significant seasonal fluctuation in salinity (e.g. pond 1: F = 1.08; p = 0.3751; d.f. = 28 and pond 8: F = 2.21; p = 0.112; d.f. = 28) and between-sample variation was low (small error bars, Fig. 1). Salinity is considered to be a temporally stable factor.

Water temperature in the ponds had a seasonal fluctuation from 15.4 ± 0.3°C in winter to 26.8 ± 0.4°C in summer. Concentration ponds 7 and 8 as well as the crystallisers had a significantly higher temperature (t = 2.762, p = 0.006, d.f. = 360) due to the increased solute potential of the water (Fig. 1). Temperature is considered to be spatially stable but a factor that shows long-term variation (seasonal).

Light penetration showed no seasonality (e.g. the autumn average was 164 ± 23 cm as opposed to spring when light penetrated 158 $\pm$ 20 cm) and can be considered to vary over the short term (monthly).

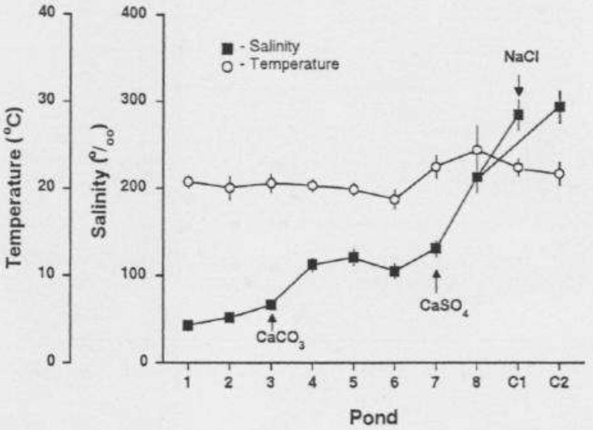

Figure 1. The average salinity and temperature of pond water at the Tankatara solar saltworks. Vertical bars represent + 1 standard error.

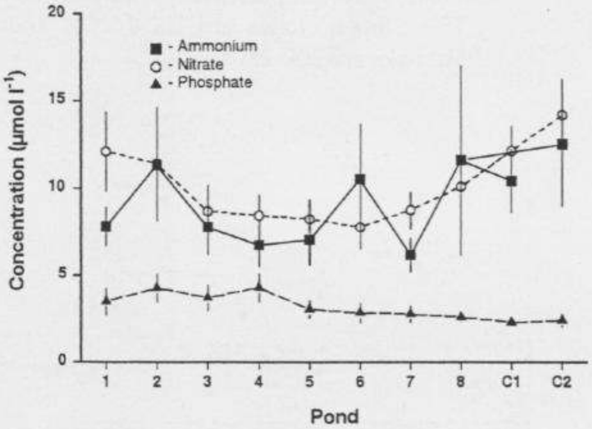

Figure 2. The average ammonium, nitrate and phosphate concentrations of pond water at the Tankatara solar saltworks.

Ammonium concentrations averaged 8.8 $\pm$ 0.8 µmol l^{-1} (Fig. 2). Concentrations varied between sampling sessions resulting in large error bars (Fig. 2). There was more than twice the amount of ammonium in the ponds in autumn and winter compared to spring and summer (e.g. the autumn average was 12.2 $\pm$ 1.2 µmol l^{-1} as opposed to spring when the concentration was 6.3 $\pm$ 1.2). Ammonium can be considered to vary temporally both on short (monthly) and long (seasonally) scales.

Nitrate values were slightly higher (not significant; $t = 2.637$, $p = 0.0092$, d.f. = 158) in the first two ponds and the crystallisers compared to ponds 3 to 8 (Fig. 2; an average for all ponds and crystallisers was 10.1 $\pm$ 0.5 µmol l^{-1}). Nitrate concentrations also showed seasonal fluctuations (e.g. the autumn average was 11.7 $\pm$ 1.0 µmol l^{-1} as opposed to spring when the concentration was 5.4 $\pm$ 0.3). Nitrate can be considered to vary temporally over a long term (seasonally).

There was little variation in soluble reactive phosphorus concentrations (Fig. 2) and can be considered to be spatially and temporally stable.

3.2. Planktonic diatoms

Diatoms were the dominant algal group at mid salinities (pond 5) ranging from 100 to 130°/₀₀ but diatoms were recorded from all the concentration ponds. Very few diatoms were recorded from the crystallisers with a few frustules carried into these ponds with the water flow.

Thirty diatom species were recorded as dominants in this study (Table 1). A DCA ordination of all the samples shows that benthic and planktonic diatoms did not form separate communities (Fig. 3).

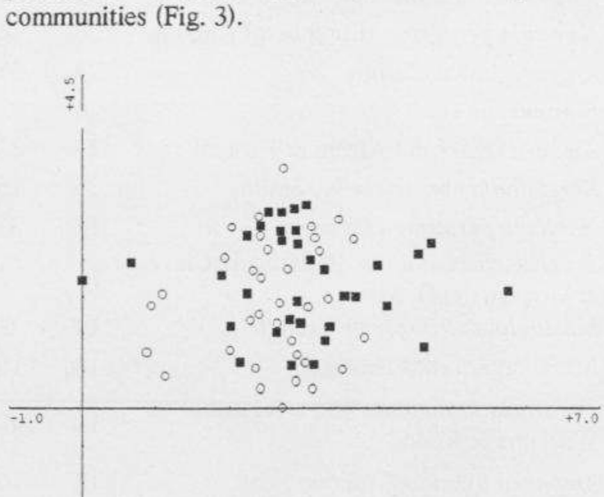

Figure 3. Detrended correspondence analysis of all diatom samples from Tankatara solar saltworks. Solid squares are benthic samples and open circles are planktonic.

All of the diatoms most often dominant were common to both the plankton and benthos (Table 1).

Amphora hyalina was recorded in nine (out of 48) benthic samples but never from the plankton. *Mastogloia* sp. and *Nitzschia fasciculata* were recorded in five plankton samples (out of 40) but never in benthic samples. Other species that dominated the benthos on occasion (less than 10% of the samples) but were never recorded from the plankton are *Biremis ambigua* (A.S.) D.G. Mann & Cox, *Navicula gracilis* Ehrenberg, *Navicula gregaria* Donkin, *Nitzschia bacilliformis* Hustedt, *Nitzschia compressa* Hustedt, *Nitzschia punctata* (W. Smith) Grunow, and *Psammodicyton panduriforme* (Gregory) D.G. Mann. *Brachysira aponina* Kützing, *Cylindrotheca gracilis* (Brébisson) Grunow and *Stauroneis* sp. each dominated the plankton once but was never recorded from the benthos.

Table 1. The frequency (%) of common planktonic and benthic diatom species of the Tankatara solar saltworks. P = plankton; B = benthos.

Species	Frequency	
	P	B
Nitzschia angustata (W.Smith) Grunow	*58*	*54*
Navicula peregrina (Ehrenberg) Kützing	30	46
Ampora costata Smith	28	38
Entomoneis sp.	26	6
Ampora tenerrima Aleem & Hustedt	23	23
Rhopalodia constricta W. Smith	23	15
Navicula perminuta Grunow	19	33
Tryblionella balatonis (Grunow in Cleve & Grunow) D.G. Mann	16	13
Mastogloia sirbonensis Ehrlich	14	6
Nitzschia baccata Hustedt	14	15
Tabularia fasciculata (C.A. Agardh) Williams & Round	14	6
Amphora hybrida Grunow	12	10
Entomoneis alata (Ehrenberg) Ehrenberg	12	6
Cocconeis placentula Ehrenberg	9	8
Ampora castellata Giffen	7	15
Amphora hyalina Donkin	0	19

DCCA of the diatoms in the plankton only (Fig. 4) shows that the first three ponds formed a community separate from the rest.

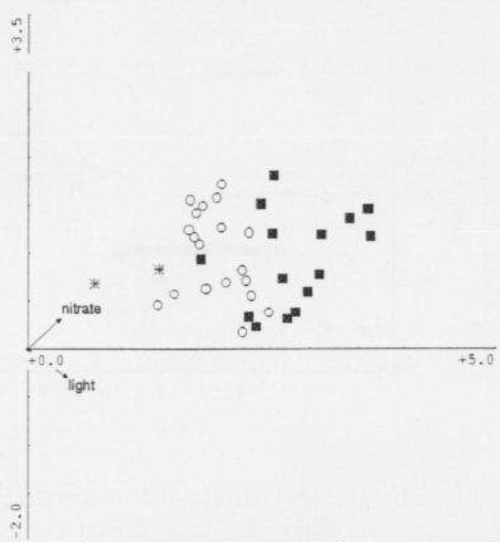

Figure 4. Detrended canonical correspondence analysis of planktonic diatom samples from Tankatara solar saltworks. Solid squares are samples with salinity of 35-75°/₀₀, open circles are 100-160°/₀₀ and asterisks are 200-280°/₀₀.

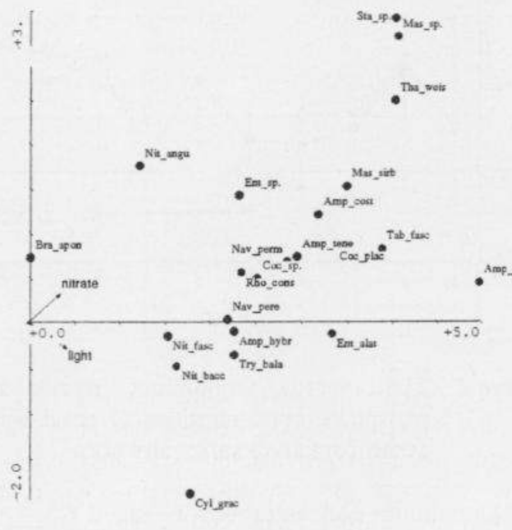

Figure 5. Detrended canonical correspondence analysis of planktonic diatom species from Tankatara solar saltworks. Solid squares are samples with salinity of 35-75°/₀₀, open circles are 100-160°/₀₀ and asterisks are 200-280°/₀₀.

The gradient that forms the horizontal axis in Figures 4 and 5 is controlled by salinity. Planktonic diatoms adapted to salinity below 75‰ can be inferred from this analysis (Fig. 5): *Mastogloia* sp., *Stauroneis* sp. and *Thalassiosira weisflogii* Grunow. The rest can be considered to be tolerant of salinity above 100‰.

The secondary gradient was controlled by nitrate and light penetration as shown by the arrows in Figures 4 and 5. This indicates that planktonic diatoms may be used as indicators of short (month to month) and long-term pond condition.

3.3. Benthic diatoms

Diatoms were part of the benthic mat of ponds 1 to 7. Benthic diatoms were recorded in the mat between 35 and 230‰.

DCCA of the benthic diatom samples showed that the first three ponds had a community different from the rest (Fig. 6 & 7).

Benthic diatoms adapted to salinity below 75‰ were *Amphora hyalina*, *Amphora tenerrima*, *Cocconeis placentula*, *Cocconeis* sp., *Mastogloia sirbonensis*, *Nitzschia bacilliformis*, *Nitzschia baccata*, *Nitzschia compressa*, *Tabularia fasciculata* and *Thalassiosira weisflogii*. The rest can be considered to be halotolerant.

In the case of benthic diatoms, however, salinity acted together with temperature, turbidity and nitrate concentration as environmental controllers acting on the diatom community (Fig. 6). In this ordination the vectors indicate the direction and magnitude of variation of environmental control.

The longest vector (greatest influence) operates in a nearly horizontal direction with species and samples on the left of Figures 6 and 7 being low salinity species and samples. The high salinity samples, and hence the halotolerant species are on the right of each of the figures.

Nutrients and turbidity (light) act in the vertical direction (Fig. 6 & 7). Ammonium and soluble reactive phosphorus vectors are very short implying little influence on diatom dominance. Species dominating in low nitrate conditions are near the bottom of the graph (Fig. 7) while those that dominate when nitrate concentrations were high are near the top of the same graph.

The combination of nitrate and salinity gradients from Figures 6 and 7 yields the indicators as given in Table 2.

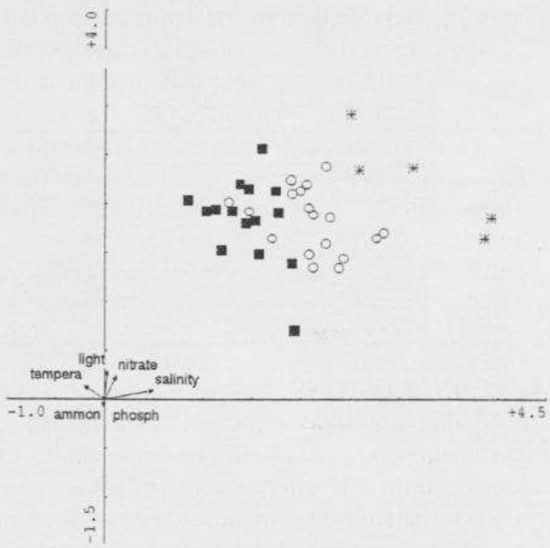

Figure 6. Detrended canonical correspondence analysis of benthic diatom samples from Tankatara solar saltworks. Solid squares are samples with salinity of 35-75‰, open circles are 76-160‰ and asterisks are 180-320‰.

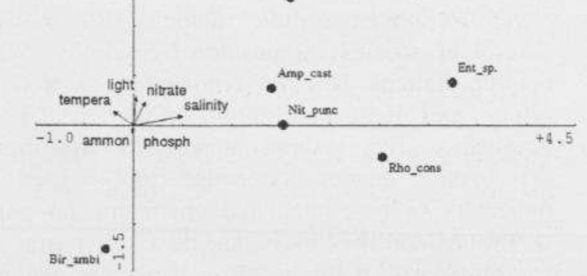

Figure 7. Detrended canonical correspondence analysis of benthic diatom samples from Tankatara solar saltworks. Solid squares are samples with salinity of 35-75‰, open circles are 76-160‰ and asterisks are 180-320‰.

Table 2. Benthic diatom indicators as implied by detrended canonical correspondence analysis of benthic diatom samples from Tankatara solar saltworks.

	ow salinity	High salinity
High nitrate	*itzschia compressa* *sammodictyon panduriforme* *halassiosira weisflogii* *itzschia bacilliformis*	*Navicula gracilis* *Navicula gregaria*
Low nutrient	*irimis ambigua* *itzschia punctata* *mphora castellata*	*Rhopalodia constricta* *Entomoneis sp.*

4. CONCLUSIONS

It is important to the successful maintenance of biota that pond conditions remain within their tolerance limits. If tolerance limits are exceeded, even for a short period of time the organisms may die and be washed downstream or decompose. Direct measurement of environmental variables gives an instantaneous measure of pond condition.

It is not possible to measure these variables continually and so a time-integrated measure would be useful for the managers of saltworks.

Ordination of dominant planktonic diatom species showed that there are two communities were controlled by salinity, light penetration and nitrate concentration. Indicators of salinity are not useful to managers as salinity is a temporally stable variable. However, nitrate varies over long time scales and light penetration over short time scales. This analysis supports the hypothesis that planktonic diatoms can be used as indicators of time-integrated environmental pond condition in solar saltworks.

Ordination of benthic diatoms also showed control of species composition by salinity. With benthic diatoms, however temperature as well as nitrate and light penetration influenced diatom dominance. This analysis supports the hypothesis that benthic diatom dominance can be used as indicators of time-integrated environmental pond conditions, but they may indicate a larger suite of environmental conditions than planktonic diatoms do.

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