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Testing the effectiveness of the SKIM foam fractionator to reduce nutrient levels in prawn farm effluent

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Abstract

To experimentally investigate the effect of the “SKIM” mechanical foam fractionator on suspended material and the nutrient levels in prawn farm effluent, a series of standardised short-term treatments were applied to various effluent types in a static 10,000-litre water body. Prawn pond effluents were characterised by watercolour and dominance of phytoplankton species. Three effluent types were tested, namely 1) particulate-rich effluent with little apparent phytoplankton, 2) green mircoalgal bloom predominately made up of single celled phytoplankton, and 3) brown microalgal bloom with higher prevalence of diatoms.

The effluent types were similar ($P>0.05$) in non-volatile particulate material, and nitrate/nitrite but varied from each other in the following ways:

1) The particulate-rich effluents were lower ($P<0.05$) in volatile solids (compared to brown blooms), total Kjeldahl nitrogen, dissolved organic nitrogen, dissolved organic phosphorus and chlorophyll *a* (compared to both green and brown blooms).
2) The brown blooms were higher ($P<0.05$) in ammonia (compared to green blooms), total nitrogen and total phosphorus (compared to both green and particulate-rich effluent), but were lower ($P<0.05$) in inorganic phosphorus (compared to both green and particulate-rich effluent).
3) The green blooms were higher ($P<0.05$) in dissolved (both organic and inorganic) phosphorus (compared to both brown and particulate-rich effluents).

Although the effluent types varied significantly in these aspects the effect of the Skim treatment was similar for all parameters measured except total phosphorus. Bloom type and Skim-treatment period significantly ($P<0.05$) affected total Kjeldahl phosphorus concentrations. For all effluent types there was a continuous significant reduction ($P<0.05$) in total Kjeldahl phosphorus during the initial 6-hour treatment period.

Levels of total suspended solids and volatile suspended solids in all effluent types were significantly ($P<0.05$) reduced in the first 2 hours but not thereafter. Non-volatile suspended solids were also significantly ($P<0.05$) reduced in the first 2 hours (30 to 40 % reduction) and a further 40% reduction occurred in the particulate-rich effluent over the next 2 hours. Mean values for total ammonia, dissolved organic nitrogen, total Kjeldahl nitrogen, total nitrogen, chlorophyll *a* and dissolved organic or inorganic phosphorus levels were not significantly ($P>0.05$) affected by the Skim unit in any bloom type during the initial 6 hours of testing. Nevertheless, non-significant nitrogen reductions did occur.

Foam production by the Skim unit varied with different blooms, resulting in different concentrate volumes and different end points for separate experiments. Concentrate volumes were generally high for the particulate-rich and green blooms (175 – 370 litres) and low for the brown blooms (25 – 80 litres). This was due to the low tendency of the brown bloom to produce foam. This generated higher nutrient concentrations in the associated condensed foam, but may have limited the treatment efficiency.

The results suggest that in this application, the Skim unit did not remove micro-algae as effectively as was anticipated. However, it was effective at removing other suspended solids. Considering these attributes and the other uses of this machinery documented by the manufactures, the unit’s oxygenation

and water mixing capacities coupled with inorganic solids removal may provide a suitable mechanism for construction of a continuously mixed bioreactor that utilises the filtration and profit making abilities of bivalves.

Introduction

High stocking densities of prawns are generally thought to prolong and stimulate microalgal blooms in farm grow-out ponds, and have been reported to increase suspended solids which can contribute to nutrients in discharge waters. Nutrients are mobilised by the prawns' feeding and swimming activities, and prawn metabolites may be one of the best sources of nutrients for algal bloom maintenance. Prawn farmers routinely use this process to maintain turbid conditions and shade-out problematic benthic macrophyte growth. Potentially, this bioturbation process may provide the means to collect waste nutrients from grow-out ponds, settlement ponds or discharge streams. Whilst these concepts are yet to be proven at an industrial scale, small-scale trials can provide a means of assessing potentials for future industrial uses. Development of intensive effluent remediation systems for prawn farms, will alleviate environmental concerns for industry expansion in Australia, and may allow settlement ponds now used to remediate effluent, to be used in the future to increase farm production capacities.

Foam fractionation is widely used to remove particulate matter in many industrial applications (eg: sewage treatment). Mechanical removal of suspended particles from prawn farm effluent, such as faeces and uneaten feeds, would provide for nutrient removal and a useful pre-treatment for in-line remediation systems (eg: sediment traps, evaporation ponds, digesters, detritivore and macrophyte systems, etc). Furthermore, direct removal and concentration of phytoplankton and other nutrient-rich materials, could provide profitable by-products (eg: plankton concentrates or raw ingredients for pharmaceuticals). The extent to which foam fractionation could be used to control or collect suspended material and different fractions of the effluent from prawn farming systems is generally unknown.

IFREMER has developed and patented a cyclonic foam fractionation unit called SKIM for various applications in the aquaculture industry. The documented uses include removal of contaminants from waters in closed and semi-closed systems, oyster purification plants and intensive fish farms. When deployed in a pond environment the manufacturers (AcquaEco, Italy) report removal of 3% total suspended solids (TSS), and 0.4% of dissolved organic carbon (DOC) in one pass. Specifications suggest that 13.8 kg TSS and 18 g DOC can be removed from intensive fish farm waters per day, and 180 g TSS and 21 g DOC per day can be removed from oyster stocking tanks. The unit is reported to be effective on particles down to a size of 5-10 μm, with a high capacity for bacteria and dissolved organic matter removal (promotional AcquaEco brochure).

Hussenot (2003) reported on a range of effluent management strategies (including SKIM) that may be suitable for fish farms of coastal Europe. Whilst SKIM was not recommended for flow-through aquaculture systems with large rates of water discharge, cyclonic foam fractionation is considered well suited to some partial recirculating systems, to reduce the need for water renewal and improve the quality of recycled waters. The effectiveness of SKIM to remove DOC and small particles is linked to the foaming capacity of water in the system. Foaming agents (like proteins) enhance removal of suspended solids, whilst antifoaming agents (like feeds high in lipids) hinder the process. Hussenot (2003) also draws attention to the potential use of foam fractionation in integrated biological treatment systems.

Clayton Engineering (a division of Clayton Investments Pty Ltd) are agents for SKIM in Australia. BIARC was approached in August 2002 by Clayton Engineering to assess the Skim unit commissioned in a pond at BIARC. Previous similar trials by Clayton Engineering at a private prawn farm had suggested this to be an effective micro-algal removal and control mechanism. This lead to a formal agreement for DPI&F to test the SKIM unit in a standardised way, whilst Clayton Engineering optimised its effective operation. Its nutrient-removal capabilities when applied to prawn farm effluent were of particular interest. The objectives of these trials were to construct and standardise a testing facility, provide assistance in the optimisation and evaluation of the SKIM system, and to test its effectiveness in microalgae and nutrient removal for a variety of typical prawn farm effluents generated at BIARC.

Materials and methods

Experimental system

A testing facility was constructed at the Bribie Island Aquaculture Research Centre consisting of a round 10,000-litre fibreglass tank (approx. 3.3 m diameter x 1.2 m high) with volume marks on the side and a bottom drain for water release and tank cleaning. This tank was positioned on a concrete slab and under a temporary tarpaulin to provide a stable platform and to prevent rain falling into the system during testing. An effluent supply system (40-50 mm diameter supply pipe) was also constructed so that the testing tank could be filled with effluent from a range of aquaculture ponds at the Centre. A flexible hose (30 mm diameter) was connected from the concentrate pump to a 300 litre plastic bag suspended inside the tank. This allowed the condensed foam concentrate to be removed from the system and collected/stored separately without affecting the height of water in the tank. Figure 1 provides diagrammatic representation of the testing system.

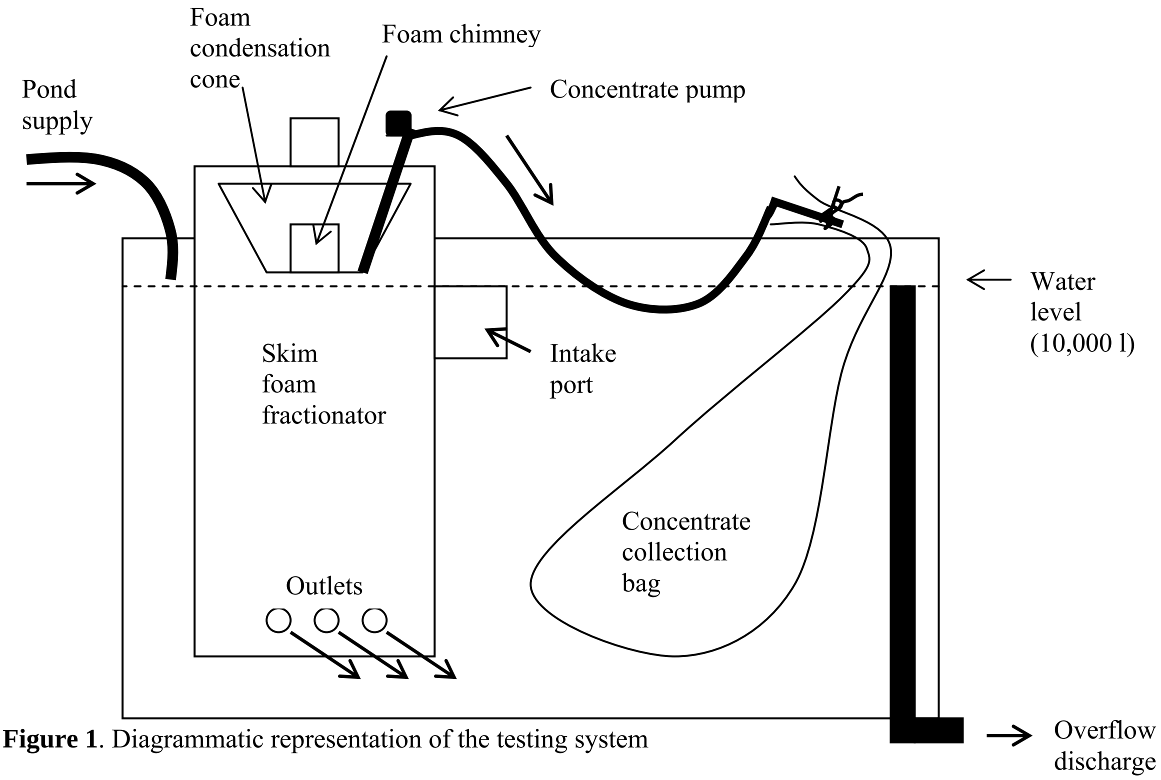


Figure 1. Diagrammatic representation of the testing system

The Skim unit was positioned within the tank so that the intake port was just submerged below the water level, giving a distance of 220 mm between the bottom of the unit and the tank bottom. The adjustable height of the condensation cone was standardised at the beginning of each trial so that the overflow point for foam (top of foam chimney) was 320 mm above the water level in the tank. The adjustable position at this point was “7 notches” showing above the top of the unit Adjustments were periodically made to this cone height during the operational testing, so that foam was continually flowing over the top of the chimney, in as concentrated a form as was possible. This generally entailed manually dropping the height by 1 (20 mm) or 2 notches after 2-3 hrs of operation. Given the configuration of this testing system, the minimum distance between the top of the chimney and the water level in the tank was 280 mm (5 notches showing). At lower heights, excessive water appeared to be carried through with foam to the collection cone, which eliminated the concentrating effect.

The Skim unit was equipped with a control box with timer for intermittent motor control and earth leakage protection for the three electric motors involved in its operation. These electric motors were:

1) 1.6 kilowatt motor driving Force 7 aerator-propeller hydro-injector
2) 0.36 kilowatt motor driving centrifuge to condense foam
3) 0.054 kilowatt motor driving the condensed-foam-concentrate evacuation pump.

Motors 1 and 2 ran continuously during operation. Motor 3 ran intermittently, where pump-out times for the condensed foam concentrate were gauged manually during the operational testing period, but generally, the pump-out timer remained set at 6-min-pumping every 60 min. Variations in the period between concentrate removal events from the collection cone did not appear to effect the foaming or particulate removal actions of the system.

Experimental design

Two small ponds in use at BIARC were used intermittently as effluent sources in the study. These ponds (N2 and N3) were aerated octagonal high-density-polyethylene lined ponds (200m^2; 0.4 ML) with a central discharge standpipe for water exchange and effluent supply. Pond N2 contained several hundred grey mullet *Mugil cephalus* and banana prawn *Penaeus merguiensis* broodstock during the study, and pond N3 contained approximately 500 kg of juvenile banana prawns.

The testing tank, foam fractionator (including cupel, hose and concentrate collection bag) and all other equipment in direct contact with effluent being treated and tested was cleaned thoroughly prior to each trial. Pond effluent was pumped into the testing system immediately prior to each trial (approx ½ hour pumping time to fill 10,000 litre tank). The effluent supply was turned off as soon as the tank was full, when the Skim unit was switched on and allowed to run continuously until the trial was terminated several hours later. Nine trials were undertaken using each of three broad effluent categories/types (3 replicates per category). All effluent types contained suspended organic matter from the pond water column. These categories were:

1) Particulate-rich effluent with little apparent phytoplankton.
2) Green microalgal bloom predominately made up of single celled phytoplankton.
3) Brown microalgal bloom predominately made up of diatoms.

The pond management variables that generated trial effluents are provided in Appendix 1, along with twice-daily water quality data, including water temperature, pH, dissolved oxygen, Secchi depth, and climatic variables.

Water sampling and nutrient analyses

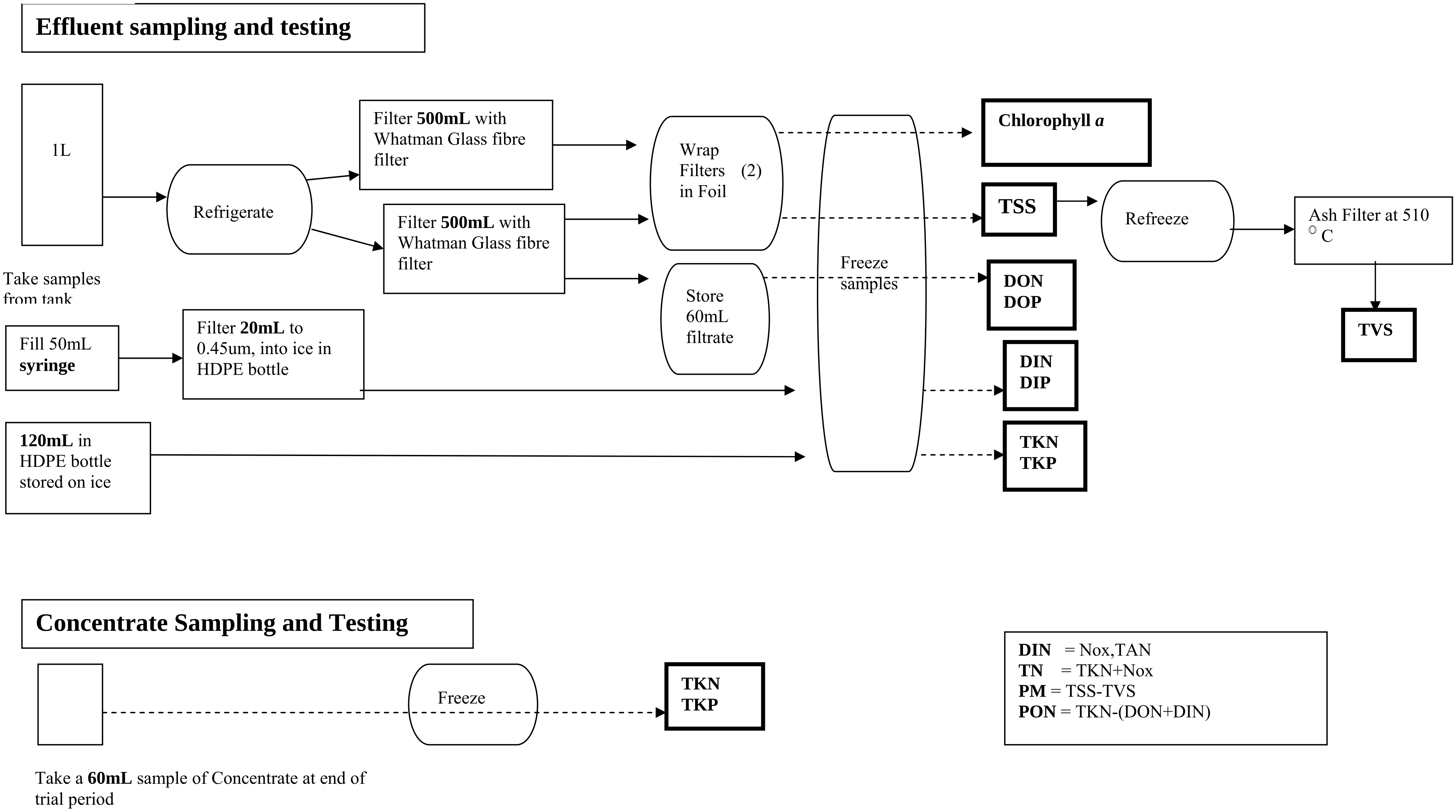
Initial samples of the effluent being treated in the testing tank were taken from the water column 1-2 min after turning the SKIM on, as soon as the mixing action of the unit appeared to create homogeneity of suspended solids. Subsequent samples were taken from the same position in the water column of the tank at 2-hourly intervals until the trial was terminated. The sampling and testing procedures are schematically described in Figure 2.

Nutrient parameters tested included total suspended solids (TSS), total volatile suspended solids (TVS) chlorophyll-*a* (Chl-*a*), dissolved organic nitrogen (DON), dissolved organic phosphorus (DOP), dissolved inorganic nitrogen (DIN) including oxides of nitrogen namely nitrite + nitrate (NOx) and total ammonia nitrogen (TAN), dissolved inorganic phosphorus (DIP), total Kjeldahl nitrogen (TKN), and total Kjeldahl phosphorus (TKP or TP). Measurement of these parameters allowed calculations for total nitrogen (TN), non-volatile particulate matter (PM) and particulate organic nitrogen (PON).

The condensed concentrate present in the collection bag at the end of each trial was also measured volumetrically, sampled after vigorous mixing and analysed for TKN and TKP to provide an estimate of the nitrogen and phosphorus removed during the treatment period, and for mass balance comparisons. Measurments of Chl-*a* and dissolved nutrients in the condensed foam concentrate were not possible using available methods, due to difficulties in filtering an adequate sample for testing.

Seawater analyses were performed using standard methods described by Parsons, Maita and Lalli (1984) and nutrient analyses utilised a Lachat QC8000 Flow Injection Analyser using methods described in the instrument manufacturers methods (QuickChem Methods, Zellweger Analytics Inc. Milwaukee WI 53218). The dominant algal species present in the effluent were photographed and identified, and algal cell density counts were performed on the effluent at the beginning and end of testing periods. Chl-*a* was studied using GF/C filters (47mm) and spectrophotometric determination using the trichromatic method.

Figure 2


Effluent sampling and testing
1L
Take samples from tank
Refrigerate
Filter 500mL with Whatman Glass fibre filter
Filter 500mL with Whatman Glass fibre filter
Wrap Filters (2) in Foil
Store 60mL filtrate
Freeze samples
Chlorophyll a
TSS
Refreeze
Ash Filter at 510 ° C
TVS
DON
DOP
DIN
DIP
TKN
TKP
Fill 50mL syringe
Filter 20mL to 0.45um, into ice in HDPE bottle
120mL in HDPE bottle stored on ice
Concentrate Sampling and Testing
Freeze
TKN
TKP
Take a 60mL sample of Concentrate at end of trial period
DIN = Nox,TAN
TN = TKN+Nox
PM = TSS-TVS
PON = TKN-(DON+DIN)

Statistical analyses

Nutrient, Chl-*a*, and TSS data for the first 6 hours of testing, were analysed by repeated-measures analyses of variance with effluent type and time as factors. This was performed using GenStat® for Windows (6th Edition) (GenStat, 2000). Comparisons of means were performed with protected least significant difference (LSD) testing using a 5% level of significance.

Results

The water quality and management details for aquaculture ponds supplying effluent for this study are presented in Appendix 1. Salinities remained high (33-35 ppt.) for all effluent types studied. The dates of testing and summarised pond effluent sources are provided in Table 1 below. Figures thereafter provide parameter means (± SE) for different effluent types as treatment with the Skim unit proceeded. Tables 2 and 3 provide descriptions of the effluent types in terms of species of microalgae that could be identified using light microscopy, and starting and finishing cell densities during the study. Table 4 provides a summary of the mean nutrient removal efficiencies over time as a percentage of the starting concentration. Tables 5, 6 and 7 provide a description of the nutrient concentrations in the condensed foam concentrates and volumes collected, and provide mass balance estimates based on TKN and TKP.

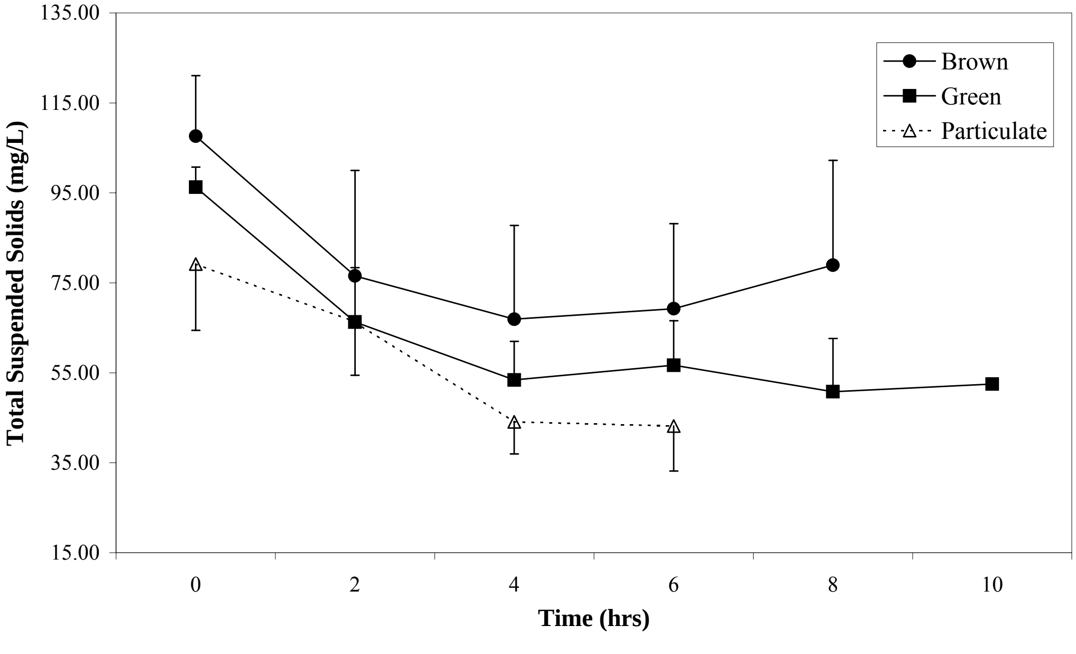
Table 1. Effluent sources utilised during the study

Date	Source pond	Bloom type	Pond management / culture stock
19-03-03	Nursery pond N3	Particulate – 65 cm Secchi depth	Super-intensive banana prawns
24-03-03	Nursery pond N3	Particulate – 80 cm Secchi depth	Super-intensive banana prawns
26-03-03	Nursery pond N3	Particulate – 70 cm Secchi depth	Super-intensive banana prawns
31-03-03	Nursery pond N2	Green – 35 cm Secchi depth	Semi-intensive mullet + banana prawns
2-04-03	Nursery pond N2	Green – 35 cm Secchi depth	Semi-intensive mullet + banana prawns
7-04-03	Nursery pond N2	Green – 35 cm Secchi depth	Semi-intensive mullet + banana prawns
14-04-03	Nursery pond N3	Brown – 55 cm Secchi depth	Super-intensive banana prawns
30–04-03	Nursery pond N3	Brown – 50 cm Secchi depth	Super-intensive banana prawns
2-05-03	Nursery pond N3	Brown – 50 cm Secchi depth	Super-intensive banana prawns

Suspended solids analyses

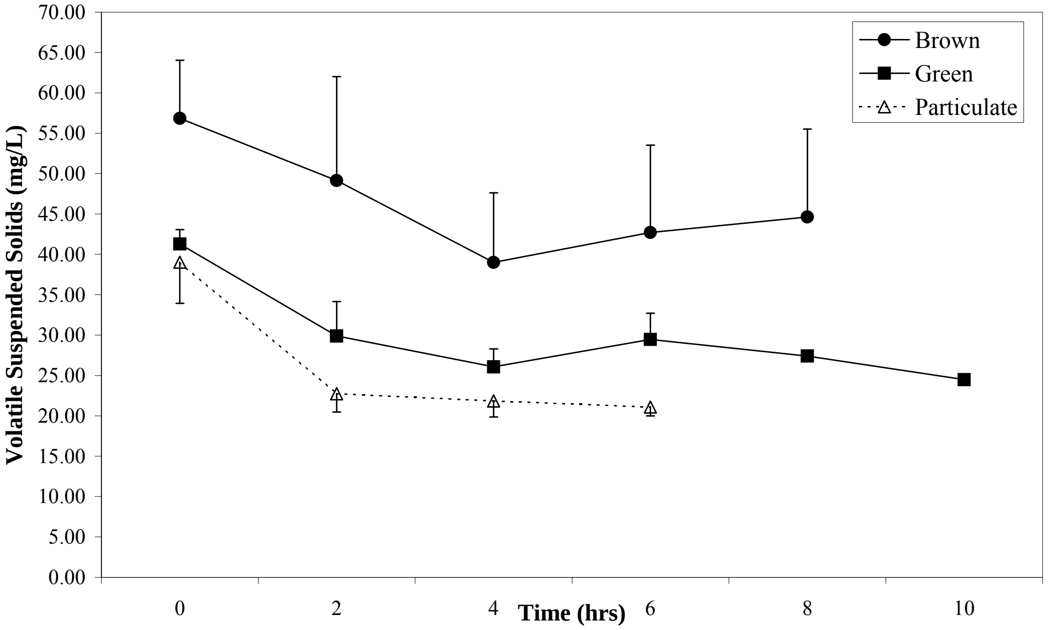
Total suspended solids (TSS)

Levels of TSS were significantly ($P<0.05$) reduced in the first 2 hours, and further non-significant reductions occurred between the 2- and 4-hour samples. There was a similar effect on TSS for all effluent types. (Note that for consistency and valid statistical comparisons, only the first 6 hours of data were used in the analyses).



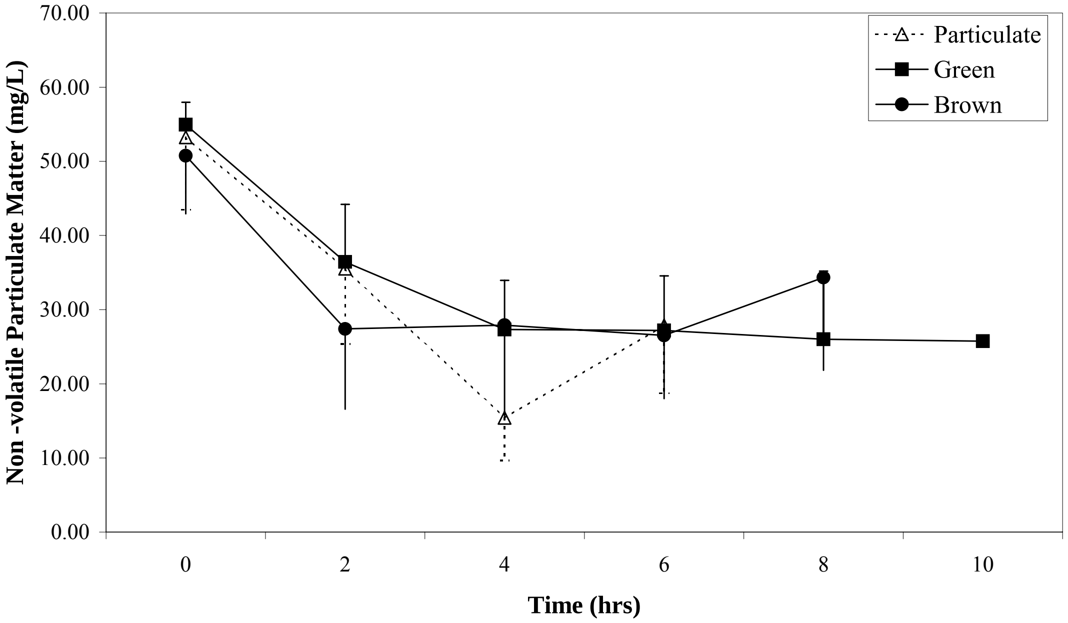
Total volatile solids (TVS)

For all effluent types, the level of TVS was significantly lower ($P<0.05$) at the 2 hr sampling compared to initial samples. The particulate-rich effluent contained significantly less ($P<0.05$) TVS than the brown bloom. No other significant differences in TVS were detected.



Non-volatile particulate matter (PM)

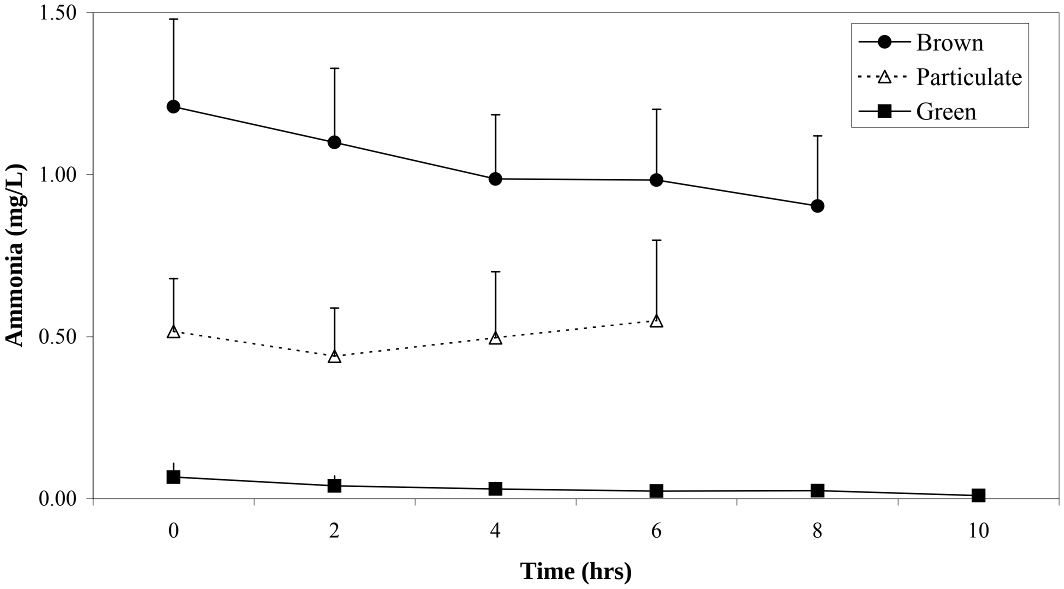
The levels of PM were similar ($P>0.05$) for all effluent types. Samples taken after 2 hours of treatment were significantly lower ($P<0.05$) than initial samples. Between 30 and 40 % reduction occurred in the first two hours and a further 40% occurred in the particulate-rich effluent in the next 2 hours.



Nutrient analyses

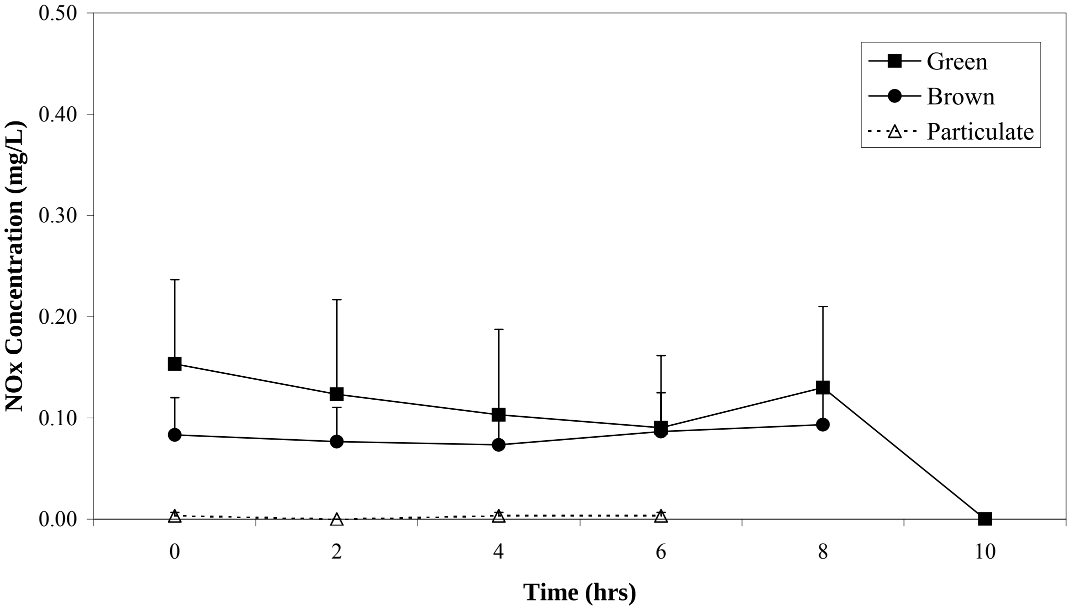
Total ammonia nitrogen (TAN)

The concentration of TAN in the brown bloom was significantly higher ($P<0.05$) than that in the green bloom. No significant differences ($P>0.05$) in TAN levels, were detected over the first six hours of the experiments for any of these effluent types. However there was evidence of a decline of TAN in the brown bloom.



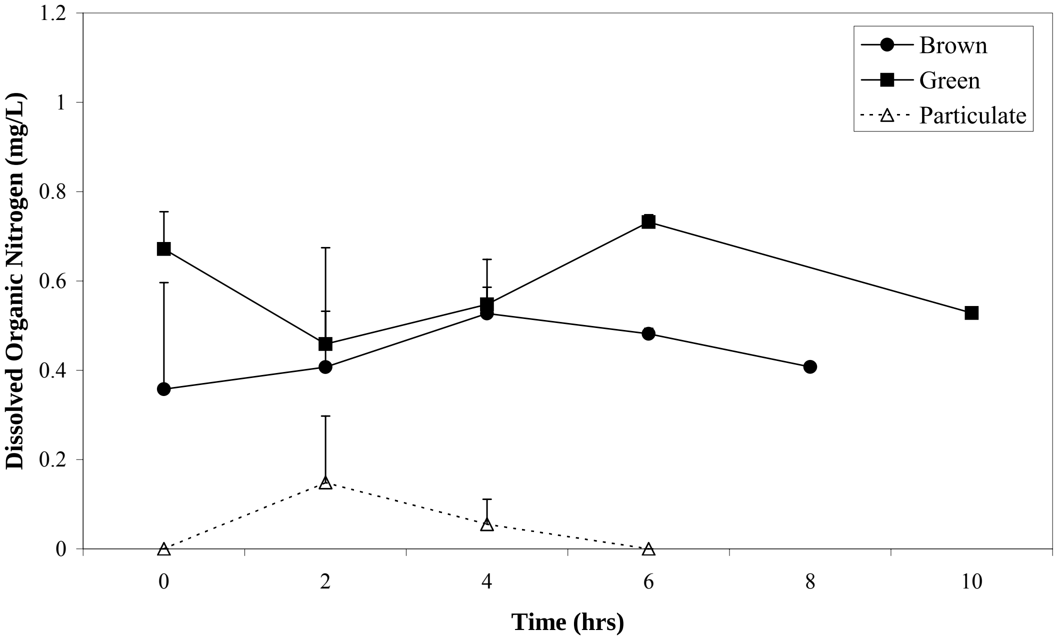
Oxides of ammonia (NOx)

Whilst the analyses suggest that there was a significant ($P<0.05$) interaction between effluent type and NOx removal over time, the concentrations were very low and were close to our testing capabilities, thus, generalisations about NOx removal in this study should be treated with caution.



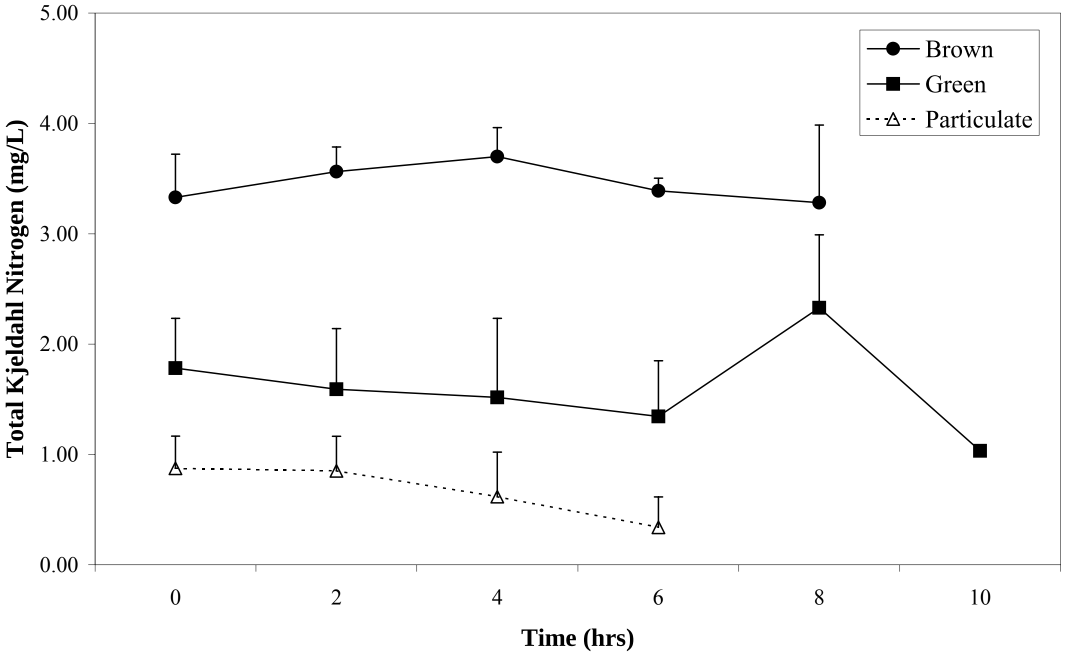
Dissolved organic nitrogen (DON)

The particulate-rich effluent had significantly lower ($P<0.05$) concentrations of DON than the other effluent types. There were no significant changes ($P>0.05$) in DON levels over time in any effluent type.



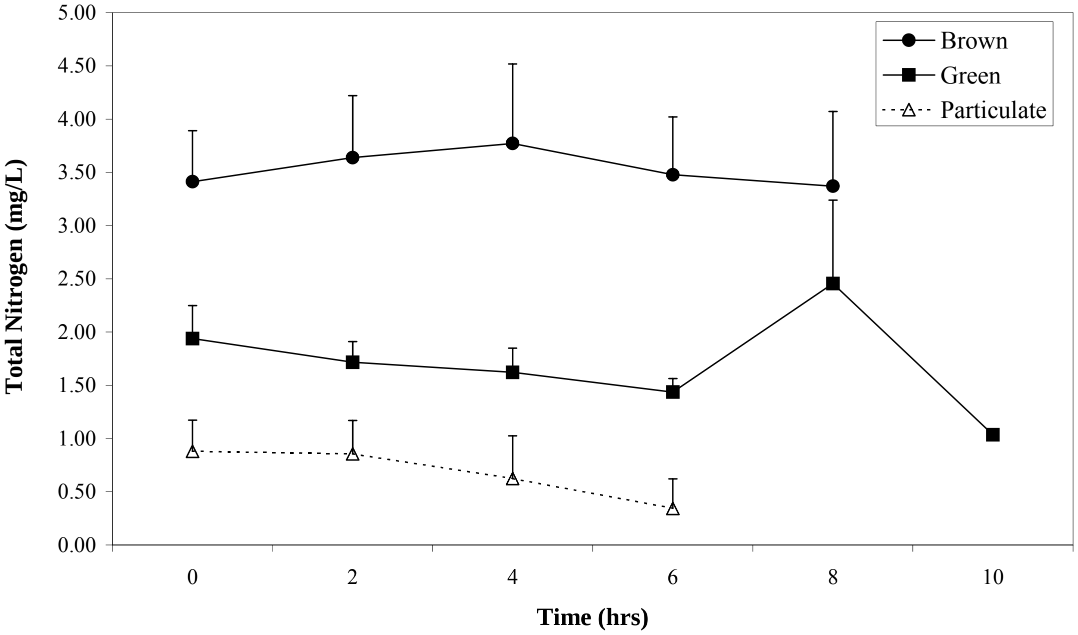
Total Kjeldahl nitrogen (TKN)

All effluent types had significantly different ($P<0.05$) concentrations of TKN. Over the initial 6 hours of the experiments, no significant differences ($P>0.05$) in TKN levels were detected.



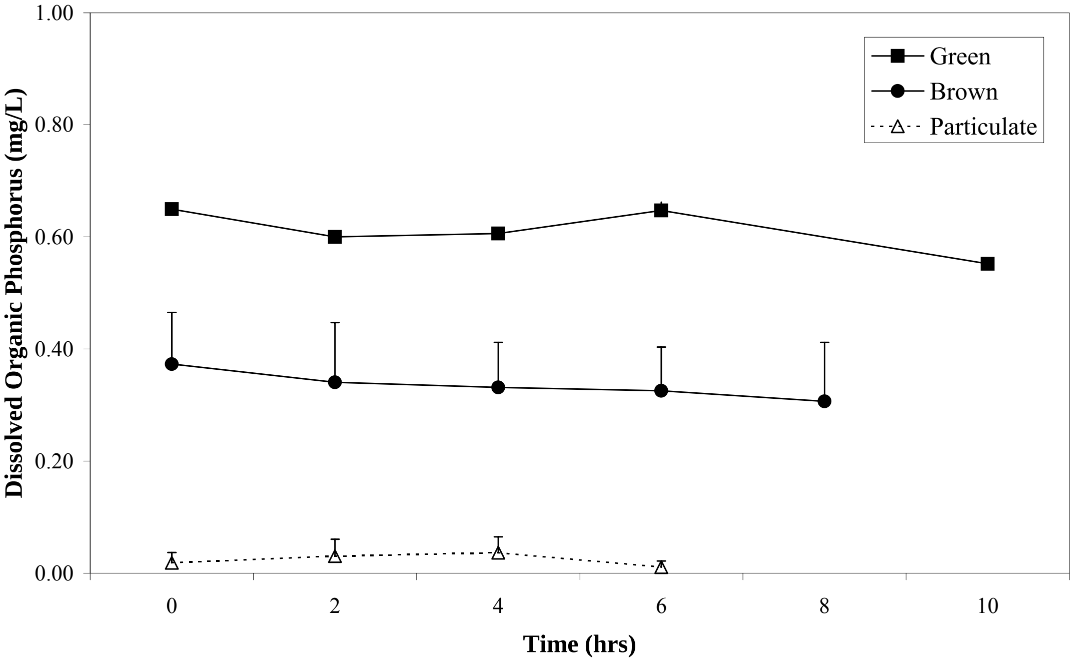
Total nitrogen (TN)

The TN concentration was significantly higher ($P<0.05$) in the brown bloom than in the other effluents. There were no significant changes ($P>0.05$) in TN over time for any effluent type.



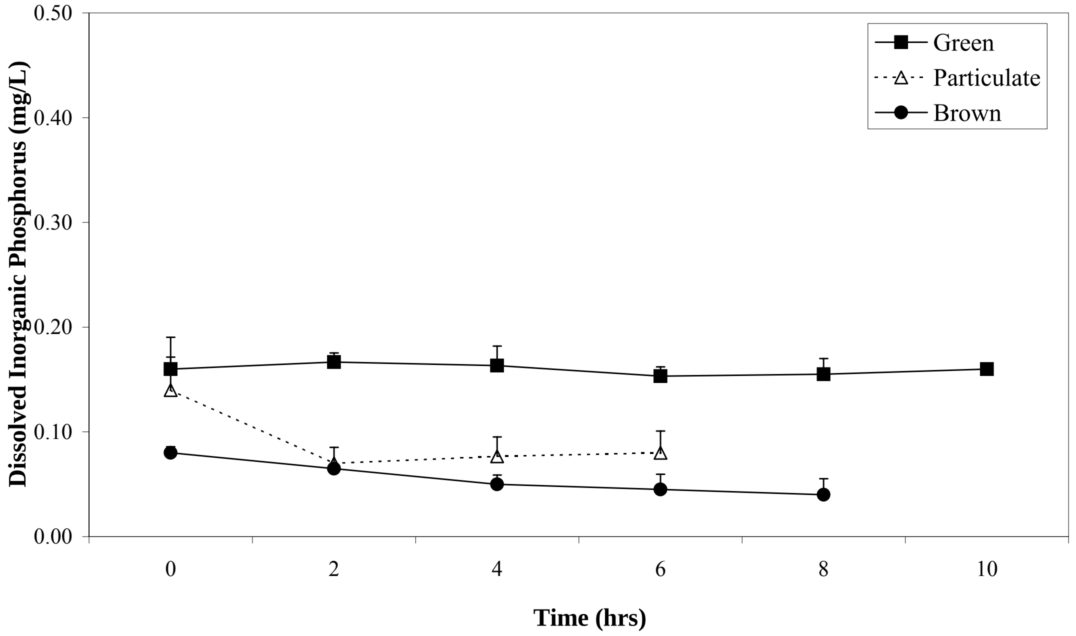
Dissolved organic phosphorus (DOP)

All effluent types had significantly different ($P<0.05$) levels of DOP. No significant differences ($P>0.05$) were detected in DOP levels over the six-hour period for any effluent type. (Note: standard errors associated with mean values for the green bloom were small - error bars are obscured from view by symbols).

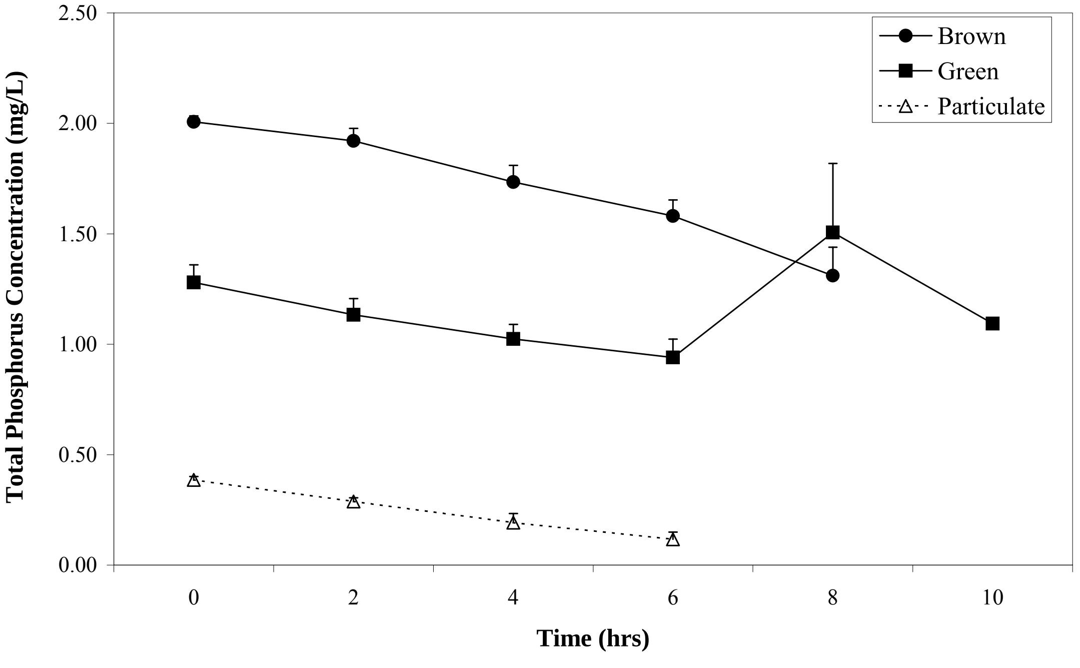


Dissolved inorganic phosphorus (DIP)

All effluent types had significantly different (P<0.05) levels of DIP. No significant differences (P>0.05) were detected in DIP levels over the six-hour period for any effluent type.



Total phosphorus (TKP)



Effluent type and treatment period significantly (P<0.05) affected TKP concentrations. For all effluent types there was a continuous significant reduction (P<0.05) in TKP over time during the initial 6-hour period. Note that the later 'spike' in the green bloom (evident in the graph), may be due to high variability in the 2 replicates at the 8-hour sampling period, and only one replicate at the 10-hour period.

Algal types and densities

Dominant microalgal species

Table 2. Microalgal species noted during the study

Effluent type^{date}	**Dominant species**	**Other species present**
Particulate$^{19-03-03}$	Small (<1µm) unicellular green algae	*Cosciniodiscus* sp.
Particulate$^{24-03-03}$	Small (<1µm) unicellular green algae	*Cosciniodiscus* sp., *Skeletonema* sp., *Navicula* sp.
Particulate$^{26-03-03}$	Small (<1µm) unicellular green algae	NA
Green$^{31-03-03}$	Small (<1µm) unicellular green algae	NA
Green$^{2-04-03}$	Small (<1µm) unicellular green algae	NA
Green$^{7-04-03}$	Small (<1µm) unicellular green algae	*Nitzschia* sp., *Chaetoceros* sp., *Cosciniodiscus* sp., *Guinardia* sp., *Navicula* sp.
Brown$^{14-04-03}$	Mixed diatoms without particular dominance	*Nitzschia* sp., *Chaetoceros* sp., *Leptocylindricus* sp., *Guinardia striata*, *Hemiaulus* sp., unicellular green algae
Brown$^{30-04-03}$	Mixed diatoms without particular dominance	*Nitzschia* sp., *Leptocylindricus* sp., *Navicula* sp.
Brown$^{2-05-03}$	Mixed diatoms without particular dominance	NA

NA=not available

Microalgal cell densities

Data available on microalgal removal during the study suggests high variability but better utility in diatom blooms. Cell densities in the green bloom were reduced by 1.6 – 35.1% over 8-10 hours of Skim treatment, but in the brown bloom cell densities were reduced by 40.5 – 43.7% with 8 hours of treatment.

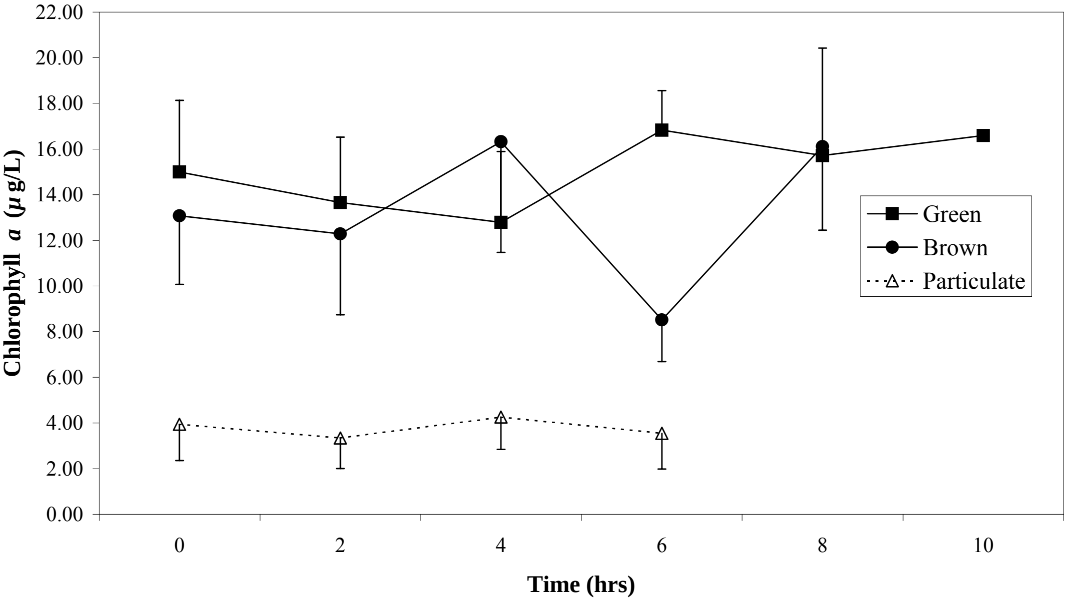
Table 3. Starting and finishing microalgal cell densities

Effluent type^{date}	**Starting cell density (cells/ml)**	**Finishing cell density (cells/ml)**	**Treatment period**
Particulate$^{19-03-03}$	510,000	NA	6
Particulate$^{24-03-03}$	440,160	NA	6
Particulate$^{26-03-03}$	620,200	NA	6
Green$^{31-03-03}$	440,000	432,800	10
Green$^{2-04-03}$	558,833	362,500	8
Green$^{7-04-03}$	320,000	300,000	8
Brown$^{14-04-03}$	NA	14,000	8
Brown$^{30-04-03}$	8,400	5,000	8
Brown$^{2-05-03}$	5,333	3,000	8

*Note: using light microscopy, some difficulties were experienced in distinguishing between small algal cells and particulates, which is likely to have inflated cell counts.
NA=not available

Chlorophyll-a

Chlorophyll *a* levels in the green and brown blooms were significantly higher ($P<0.05$) than in the particulate-rich effluent. No significant effects ($P>0.05$) on chlorophyll *a* were found over time.



Summary of nutrient removal data

Table 4. Summary of mean removal efficiencies over time as a percentage of starting concentration*

Para-meter	0 hr starting conc. (mg/L)**			2 hr % removed			4 hr % removed			6 hr % removed		
	P	**G**	**B**	**P**	**G**	**B**	**P**	**G**	**B**	**P**	**G**	**B**
TSS	79.2	96.3	107.6	16.3	31.1	28.9	44.3	44.5	37.8	45.5	41.1	35.6
TVS	39.0	41.3	56.8	41.7	27.6	13.5	44.1	36.8	31.4	46.0	28.6	24.8
PM	53.2	55.0	50.8	33.3	33.7	46.0	71.1	50.3	45.0	47.6	50.5	47.8
TAN	0.52	0.07	1.21	15.4	42.9	9.1	3.8	57.1	18.2	-5.8	71.4	19.0
NOx	0.0	0.15	0.08	0	20.0	0	0	33.3	12.5	0	40.0	-12.5
DON	0.00	0.67	0.36	0	31.3	-13.9	0	17.9	-47.2	0	-9.0	-33.3
TKN	0.87	1.78	3.33	2.3	10.7	-6.9	28.7	14.6	-11.1	60.9	24.2	-1.8
TN	0.88	1.94	3.41	2.3	11.3	-6.7	29.5	16.5	-10.6	61.4	25.8	-2.1
DOP	0.02	0.65	0.37	-50.0	7.7	8.1	-100	6.2	10.8	50.0	0	10.8
DIP	0.14	0.16	0.08	50.0	-6.3	12.5	42.9	0	37.5	42.9	6.3	37.5
TKP	0.39	1.28	2.01	25.6	11.7	4.5	51.3	20.3	13.9	69.2	26.6	21.4
Chl-*a*	3.95	14.99	13.08	15.2	8.9	6.0	-7.8	14.7	-24.8	10.1	-12.3	34.9

* Negative values indicate percentage increases.

** Chl-*a* in µg/L.

P = particulate-rich effluent; G = green bloom; B = brown bloom.

Condensed foam concentrate analyses

Table 5. Nutrient concentrations in condensed foam concentrates and volumes collected

Effluent type^{date}	**Treatment period (hr)**	**Total volumes collected (l)**	**Volumes collected (l/hr)**	**TKN (mg/l)**	**TKP (mg/l)**
Particulate$^{19-03-03}$	6	330	55	9.66	3.81
Particulate$^{24-03-03}$	6	205	34.2	31.75	9.99
Particulate$^{26-03-03}$	6	250	41.7	27.77	10.10
Green$^{31-03-03}$	10	175	17.5	37.79	26.7
Green$^{2-04-03}$	8	175	21.9	45.61	21.43
Green$^{7-04-03}$	8	370	46.3	26.18	13.37
Brown$^{14-04-03}$	8	80	10	169.70	33.96
Brown$^{30–04-03}$	8	25	3.1	231.85	68.76
Brown$^{2-05-03}$	8	48	6	141.80	43.84

Mass nutrient balance estimates

Nutrients removed from the water column were assessed in two ways: 1) by comparing nutrient levels in the tank before and after the Skim treatment period (6 - 10 hrs); and, 2) by comparing the nutrients present in the tank at the start of the trial with the nutrients in the concentrate bag at the end of the trial. Gross amounts of nutrients removed from the water column were calculated for both of these methods, whereby actual removal efficiencies are likely to be between these two calculations (2 right-hand columns in Tables 6 and 7).

Table 6. Mass balance estimates for TKN*

Effluent type^{date}	**Starting TKN in tank (mg)**	**Finishing TKN in tank (mg)**	**Finishing TKN in foam concentrate (mg)**	**TKN removed from tank as a % of starting TKN in tank**	**TKN removed in foam concentrate as a % of starting TKN in tank**
Particulate$^{19-03-03}$	3200	1257	3300**	60.7	103.1**
Particulate$^{24-03-03}$	13000	8718	6560	32.9	50.5
Particulate$^{26-03-03}$	10000	0	7000	100	70.0
Green$^{31-03-03}$	19600	10120	6650	48.4	33.9
Green$^{2-04-03}$	23600	16015	8050	32.1	34.1
Green$^{7-04-03}$	10300	29179**	9620	-183.3**	93.4
Brown$^{14-04-03}$	26400	19443	13600	26.4	51.5
Brown$^{30–04-03}$	41800	39501	5800	5.5	13.9
Brown$^{2-05-03}$	31700	39111**	6816	-23.4**	21.5

*Approximate calculations due to the estimation of volumes and associated gross nutrient present.
**Exceeds starting nutrient level

Table 7. Mass balance estimates for TKP*

Effluent type^{date}	**Starting TKP in tank (mg)**	**Finishing TKP in tank (mg)**	**Finishing TKP in foam concentrate (mg)**	**TKP removed from tank as a % of starting TKP in tank**	**TKP removed in foam concentrate as a % of starting TKP in tank**
Particulate$^{19-03-03}$	3300	1257	1320	61.9	40.0
Particulate$^{24-03-03}$	4000	2155	2050	46.1	51.3
Particulate$^{26-03-03}$	4300	0	2500	100	58.1
Green$^{31-03-03}$	16200	11790	4725	27.2	29.2
Green$^{2-04-03}$	10200	6386	3675	37.4	36.0
Green$^{7-04-03}$	11900	22727**	4810	-91.0**	40.4
Brown$^{14-04-03}$	18900	7539	2720	60.1	14.4
Brown$^{30–04-03}$	20500	14564	1725	29.0	8.4
Brown$^{2-05-03}$	20800	17117	2112	17.7	10.2

*Approximate calculations due to the estimation of volumes and associated gross nutrient present.
**Exceeds starting nutrient level

Discussion

Categorising the effluent and measuring nutrient removal

Our analysis, of the suitability of the SKIM foam fractionator to remove nutrients from prawn farm effluent, involved two operational considerations. Firstly, broad groupings were created which categorised mariculture effluents available for the study into some typical types (eg: particulate-rich, green and brown), with replicate (3) tests for each conducted during relatively stable pond bloom periods. Secondly, the testing facility and procedure measured nutrient removal over time in a contained and standardised manner.

Periodic measurements were made in the static 10,000-litre system as the Skim unit repeatedly treated the effluent. This generally led to a gradual exhaustion of the effluent's capacity to foam, and hence to lower effectiveness as the testing procedure proceeded. SKIM could therefore be expected to be more effective in effluent treatment systems that promote consistently high foaming capacities, such as in larger ponds or flow-through systems.

The parameters tested and levels measured were consistent with components previously identified in prawn farm effluent in Australia (eg: Preston *et al.* 2000; Jackson *et al.*, 2003). They included moderate levels of particulate matter, dissolved nutrients and micro-algae. Particulate matter was measured in a number of ways including TSS, TVS, TN and TP. Total suspended solids is a measure of all particulate matter above the pore size of the filter. Total volatile solids measures the organic material in the suspended solids. Total nitrogen and TP measure the nutrients bound in organic material plus that in the water column as dissolved nutrients.

A wide variety of microalgae are also known to occur in mariculture ponds, according to different successional stages during the crop, and due to differences between farms (eg: climate, stocking densities, management practices) and the prevalence of seed organisms in their water sources. Particulate-rich effluent with low levels of phytoplankton can occur under certain conditions at some farms, for example, between successional algal blooms or as a result of intense grazing pressures by planktonic animals (eg: copepods, rotifers). To provide an indication of the phytoplankton composition in this study, we briefly surveyed the phytoplankton present in each of the effluents and conducted direct counts to determine cell densities.

Suspended solids removal

SKIM effectively reduced the TSS in the effluent by approximately 30% in the first 2 hours. Further reduction to approximately 50% of the original concentration was achieved within 4 hours, however this later reduction was not statistically significant. It's effectiveness on TSS concentrations was comparable for each of the effluent types tested, and much higher than results reported in literature relating to foam fractionation using micro-bubbles generated by ceramic diffusers connected to a blower (eg: Hussenot *et al.* 1998).

Total volatile solids data suggests that between 30 and 80% of the solids (w/w) present in the water column were organic. Volatile solids were effectively removed by SKIM from all effluent types during the first 2 hours. This initial reduction of approximately 30% is similar to the TSS results.

The non-organic particulate matter data was calculated from the TSS and TVS results. It confirms the effectiveness of foam fractionation to also remove inorganic suspended solids. Again, the data suggests a 30% reduction in the first 2 hours, with no apparent preferential removal of inorganic or organic particulate matter.

This process of TSS reduction could be a valuable treatment of prawn farm effluents, because regulations on farm discharge levels are restrictive, and because prawn farmers would generally prefer to utilise alternative facilities (extensive settlement ponds) to grow more prawns. Obviously, the industrial volumes that must be handled would necessitate an upscale from the system trialled in the present work, but intensive in-line reduction of TSS could also facilitate other effluent treatments that require low suspended solids, and possibly provide more consistent water quality for controllable biosystems. For example, Jones and Preston (1999) found the TSS levels in prawn effluent (which can consist of 60-90% inorganic particles: Preston *et al.* 2000) hindered the growth of oysters, which are recognised as a potential remediation species for microalgal-rich effluents. Pre-treatment of prawn farm effluents to reduce suspended solids, particularly inorganic silts, may facilitate further development of bivalve remediation systems. The mixing and oxygenation created by the Skim unit could further provide the mechanical means to create a continuously mixed reactor for bivalve filtration (eg: after Shpigel *et al*., 1997). This approach could be particularly effective if the Skim process can effectively remove bivalve faeces and pseudofaeces from the reactor, as it does in shellfish depuration systems. Issues such as bivalve stocking densities and their tolerance of conditions in close proximity to the Skim unit (eg: gas bubble disease) would need further investigation.

Nutrient removal

Total phosphorus levels in the 10,000-litre tank were effectively reduced by a 6-hr foam fractionator treatment to 21-69 % of the original concentration. This TP reduction was relatively consistent between replicates as is shown by the small standard error bars in the figures, and was statistically significant ($P<0.05$) for each of the effluent types. In contrast, TN levels were not reduced by the Skim process to a statistically significant level. However, consideration of the summary data in Table 4 suggests that nitrogen reductions did occur, and the mass balance calculations presented in Table 6 shows that unexplained increases in nitrogen during some trials would have influenced these statistical analyses.

The significant reductions in TSS are probably the contributing factor in the reduction of TP, because phosphorus is well recognised for its association with sediment particles (Preston *et al*., 2000). As stated previously, effluents from prawn ponds can vary as different stages in the maturity of the pond ecosystem develop (eg: different micro-algal blooms with different particle sizes and settling rates). Particulate nitrogen can include non-phytoplankton protein sources such as bacteria, detritus, uneaten feed, faecal fragments and zooplankton (Preston *et al*., 2000). Although a variety of differences in the make up of pond effluents were demonstrated in the present study, no major differences in the effect of SKIM on different pond blooms were detected.

Ammonia in these experiments was measured by TAN analysis, which measures both ionised and un-ionised forms of ammonia. Volatisation of un-ionised ammonia is a potentially important process in the reduction of nitrogen levels in effluent and can be enhanced by high pH, aeration and wind (Preston *et al*., 2000). The Skim unit did not appear to significantly affect ammonia levels, which suggests the aeration/mixing of the system did not enhance the volatisation of the un-ionised NH_3. Alternatively, the ammonia present may have been in the ionised form, or the process was restricted by other factors. In practice, these factors will change for different effluent sources, for example, due to the increase in pH caused by increased micro-algal cell densities and variable buffering capacities.

Despite the majority of the N in prawn farm discharge waters being in a particulate form, Jackson *et al*. (2003) describes DON as a significant component of dissolved N in prawn farm effluent, and suggests that further research to reduce DON is necessary. It is only slowly utilized by bacteria in shrimp pond water, and tends to accumulate over the crop cycle. Hussenot *et al*. (1998) has reportedly used a foam fractionation process to remove dissolved organic material before bacterial processes degraded these proteins to ammonia. They reported that the foam fractionation process was very efficient at removing dissolved organic material. In our study, the particulate bloom demonstrated significantly lower levels of DON than the other blooms, but SKIM did not significantly effect DON in any of the effluents tested.

Mass balance data

The concentrate separated by the foam fractionation process was somewhat variable in the volumes and concentrations obtained. Generally, the volumes were high for the particulate and green blooms (175 – 370 litres) and low for the brown blooms (25 – 80 litres). This generated higher nutrient concentrations in the condensed foam from the brown bloom, but in practical terms, less liquid waste for subsequent disposal or treatment. Previous data for the SKIM model presented by Hussenot (2003), suggests that it functions more efficiently when large volumes of clearer foam are produced, rather than small volumes of dark foam. An extraction volume of 20-40 $l\ h^{-1}$ is recommended in that paper, which is similar in this study to the volumes produced in the particulate and green blooms (17.5-55 $l\ h^{-1}$), but higher than volumes produced in the brown blooms (3.1-10 $l\ h^{-1}$). Although this generated higher TKN and TKP levels in the foam from the brown bloom, it may have limited the treatment efficiency in this bloom type.

Mass balance estimates that compared nutrient reductions in the water column during the Skim-treatment period and nutrient measurements of the condensed concentrate proved difficult to equate.

This is thought to be due to the combined imprecision of sampling, nutrient analyses, volume estimations, and the multiplying effect of extrapolating sample results to total volumes.

Algal types and densities

Chlorophyll *a* is commonly used as a measure of phytoplankton (algae) density. Our Chl-*a* measurements suggest that there was no significant effect on phytoplankton density by the SKIM foam fractionator, regardless of bloom type. The direct cell density counts however, showed that there were in fact, small reductions of miro-algal densities, and suggest that the larger diatom cells may be more readily removed with the Skim process. Since the testing system was at times in direct sunlight, primary productivity during the testing period may have masked a proportion of the phytoplankton removal capacity. Better micro-algae removal may also occur with heavier cell densities, or during night-time when the foaming properties of pond water could be higher (pers. com. J.M.E. Hussenot). It is well recognised that the process of foam fractionation is affected by numerous parameters including surface tension, pH, organic materials, temperature and viscosity (Lawson and Wheton, 1980). So although the results were somewhat consistent for different bloom types in these experiments, application to different situations are likely to produce differing results.

Economic and operation considerations

For comparison, sedimentation in settlement ponds has also been reported to reduce TSS and TP in prawn farm effluent to a greater degree than TN (Preston *et al.*, 2000). This stimulates discussions of the benefits, capital outlays and running costs of utilising mechanical systems such as a scaled up version of SKIM, compared with sedimentation ponds. Both options have presently unevaluated potential to produce bioremediation species to offset the costs of operation. Both also have significant capital outlay and operational or opportunity costs.

Whilst the virtues of each of these two approaches to nutrient removal from effluent (ie: hydraulic settlement vs mechanical filtration) need to be evaluated, they also should be compared within the context of their different applications, and should not be viewed as being mutually exclusive. For example, settlement ponds receive and control the large water flows that routinely emanate from a prawn farm, and therefore, could provide flow mitigation for systems that are engineered to handle set continuous flows. Furthermore, foam fractionation can concentrate the suspended particles and associated nutrients, and this partitioning of wastes into separate more consistent types for specialised treatment, could provide a stabilising effect on integrated biological and mechanical systems.

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Appendix 1. Water quality and management details for the prawn culture ponds used as an effluent source for the "SKIM" foam fractionation trials in 2003.

Pond	Date	Time	pH	Temp (ºC)	Dissolved oxygen (mg/l)	Secchi depth (cm)	Feed added (kg/d)	Comments (eg: bloom colour; weather; pond-water exchange rate)
N3	17 / 3	0830	8.20	28.4	5.4	80	10.2	Indistinct colour; partially overcast; 343 l/min=124 %/d
		1530	8.23	26.5	6.7	75		
	18 / 3	0830	7.87	25.0	5.0	80	11.4	Indistinct colour; overcast; 343 l/min=124 %/d
		1530	8.21	26.0	6.4	70		
	19 / 3	0830	7.97	25.0	4.9	65	11.4	Indistinct colour; fine; 343 l/min=124 %/d
		1530	8.19	26.0	6.0	65		
Start	*trial at*	*1035*						
N3	22 / 3	0800	7.98	25.9	5.0	70	11.4	Indistinct colour; overcast; 343 l/min=124 %/d
		1530	8.22	27.0	6.6	70		
	23 / 3	0800	7.86	26.0	4.9	70	11.4	Indistinct colour; partially overcast; 343 l/min=124 %/d
		1530	8.10	27.0	5.8	70		
	24 / 3	0830	7.83	26.2	4.8	80	11.4	Indistinct colour; fine; 343 l/min=124 %/d
		1530	8.27	27.3	6.5	70		
Start	*trial at*	*1100*						
N3	25 / 3	0830	7.86	26.3	4.9	80	11.4	Indistinct colour; fine; 343 l/min=124 %/d
		1500	8.32	27.5	7.2	70		
	26 / 3	0830	7.85	26.4	5.0	70	11.4	Indistinct colour; am fine, pm overcast; 343 l/min=124 %/d
		1600	8.31	27.5	7.6	70		
Start	*trial at*	*1000*						
N2	29 / 3	0700	8.02	28.6	5.1	40	2.0	Green bloom; partially overcast; 40 l/min=14.4 %/d
		1400	8.21	29.3	5.5	40		
	30 / 3	0800	8.06	28.5	5.0	40	2.0	Green bloom; fine; 40 l/min=14.4 %/d
		1500	8.25	29.5	5.6	40		
	31 / 3	0830	8.17	28.9	4.8	40	2.0	Green bloom; partially overcast; 40 l/min=14.4 %/d
		1500	8.36	30.5	5.4	25		
Start	*trial at*	*1015*						
N2	1 / 4	0830	8.07	29.1	4.9	35	2.0	Green bloom; fine; 40 l/min=14.4 %/d
		1530	8.37	30.2	5.0	30		
	2 / 4	0830	8.10	28.9	4.7	45	2.0	Green bloom; fine; 40 l/min=14.4 %/d
Start	*trial at*	*0855*						
								Continued over page

Appendix 1 (continued).

Pond	Date	Time	pH	Temp (ºC)	Dissolved oxygen (mg/l)	Secchi depth (cm)	Feed added (kg/d)	Comments (eg: bloom colour; weather; pond-water exchange rate)
N2	5 / 4	0800	7.86	28.3	5.0	60	2.0	Green bloom; partially overcast; 40 l/min=14.4 %/d
		1400	8.05	29.0	5.4	50		
	6 / 4	0800	8.00	27.8	4.7	50	2.0	Green bloom; fine; 40 l/min=14.4 %/d
		1400	8.13	28.6	5.6	50		
	7 / 4	0930	7.98	24.9	5.2	35	2.0	Green bloom; fine; 40 l/min=14.4 %/d
Start	*trial at*	*0930*						
N3	12 / 4	0830	7.77	25.1	5.1	80	12.6	Brown bloom; overcast; 150 l/min=54 %/d
		1530	8.02	25.6	7.1	70		
	13 / 4	0800	7.25	25.0	4.9	80	12.6	Brown bloom; fine; 150 l/min=54 %/d
		1530	7.37	25.9	8.7	70		
	14 / 4	0900	7.6	25.4	5.1	55	12.6	Brown bloom; fine; 150 l/min=54 %/d
		1600	7.9	25.9	5.9	55		
Start	*trial at*	*0900*						
N3	28 / 4	1000	7.72	22.7	5.2	80	12.9	Brown bloom; overcast; 150 l/min=54 %/d
		1500	8.06	23.7	5.5	75		
	29 / 4	0900	7.55	23.2	4.9	70	12.9	Brown bloom; fine; No exchange
		1530	8.00	24.3	6.5	65		
	30 / 4	0900	7.33	24.0	4.5	50	12.9	Brown bloom; fine; No exchange
		1500	7.54	25.1	6.7	50		
Start	*trial at*	*0830*						
N3	1 / 5	0900	7.58	23.9	4.4	55	12.9	Brown bloom; fine; 150 l/min=54 %/d
		1530	8.08	25.0	6.6	60		
	2 / 5	0930	7.40	24.6	3.8	50	12.9	Brown bloom; overcast; 150 l/min=54 %/d
		1500	7.38	24.4	2.6	60		
Start	*trial at*	*0850*						