Tertiary Treatment of Ayr Municipal Wastewater using Bioremediation: A Pilot Study. Report to the Burdekin Shire Council and the Burdekin Rangelands Reef Initiative. 2003

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Tertiary Treatment of Ayr Municipal Wastewater using Bioremediation: A Pilot-Scale Study

May 2003

A Report Prepared for the Burdekin Shire Council and the Burdekin Rangeland Reef Initiative

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Primary Industries

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Summary

This joint DPI/Burdekin Shire Council project assessed the efficacy of a pilot-scale biological remediation system to recover Nitrogen (N) and Phosphorous (P) nutrients from secondary treated municipal wastewater at the Ayr Sewage Treatment Plant. Additionally, this study considered potential commercial uses for by-products from the treatment system. Knowledge gained from this study can provide directions for implementing a larger-scale final effluent treatment protocol on site at the Ayr plant. Trials were conducted over 10 months and assessed nutrient removal from duckweed-based treatments and an algae/fish treatment – both as sequential and as stand-alone treatment systems.

A 42.3% reduction in Total N was found through the sequential treatment system (duckweed followed by algae/fish treatment) after 6.6 days Effluent Retention Time (E.R.T.). However, duckweed treatment was responsible for the majority of this nutrient recovery (7.8 times more effective than algae/fish treatment). Likewise, Total P reduction (15.75% reduction after 6.6 days E.R.T.) was twice as great in the duckweed treatment. A phytoplankton bloom, which developed in the algae/fish tanks, reduced nutrient recovery in this treatment.

A second trial tested whether the addition of fish enhanced duckweed treatment by evaluating systems with and without fish. After four weeks operation, low DO under the duckweed blanket caused fish mortalities. Decomposition of these fish led to an additional organic load and this was reflected in a breakdown of nitrogen species that showed an increase in organic nitrogen. However, the Dissolved Inorganic Nitrogen (DIN: ammonia, nitrite and nitrate) removal was similar between treatments with and without fish (57% and 59% DIN removal from incoming, respectively).

Overall, three effluent residence times were evaluated using duckweed-based treatments; i.e. 3.5 days, 5.5 days and 10.4 days. Total N removal was 37.5%, 55.7% and 70.3%, respectively. The 10.4-day E.R.T. trial, however, was evaluated by sequential nutrient removal through the duckweed-minus-fish treatment followed by the duckweed-plus-fish treatment. Therefore, the 70.3% Total N removal was lower than could have been achieved at this retention time due to the abovementioned fish mortalities. Phosphorous removal from duckweed treatments was greatest after 10.4-days E.R.T. (13.6%). Plant uptake was considered the most important mechanism for this P removal since there was no clay substrate in the plastic tanks that could have contributed to P absorption as part of the natural phosphorous cycle.

Duckweed inhibited phytoplankton production (therefore reducing T.S.S) and maintained pH close to neutral. DO beneath the duckweed blanket fell to below 1ppm; however, this did not limit plant production. If fish are to be used as part of the duckweed treatment, air-uplifts can be installed that maintain DO levels without disturbing surface waters. Duckweed grown in the treatments doubled its biomass on average every 5.7 days. On a per-surface area basis, 1.23kg/m^2 was harvested weekly. Moisture content of duckweed was 92%, equating to a total dry weight harvest of 0.098kg/m^2/week. Nutrient analysis of dried duckweed gave an N content of 6.67% and a P content of 1.27%. According to semi-quantitative analyses, harvested duckweed contained no residual elements from the effluent stream that were greater than ANZECC toxicant guidelines proposed for aquaculture. In addition, jade perch, a local aquaculture species, actively consumed and gained weight on harvested duckweed, suggesting potential for large-scale fish production using by-products from the effluent treatment process.

This suggests that a duckweed-based system may be one viable option for tertiary treatment of Ayr municipal wastewater. The tertiary detention lagoon proposed by the Burdekin Shire Council, consisting of six bays approximately 290 x 35 metres (x 1.5 metres deep), would be suitable for duckweed culture with minor modification to facilitate the efficient distribution of duckweed plants across the entire available growing surface (such as floating containment grids). The effluent residence time resulting from this proposed configuration (~30 days) should be adequate to recover most effluent nutrients (certainly N) based on the current trial. Duckweed harvest techniques on this scale, however, need to be further investigated. Based on duckweed production in the current trial (1.23kg/m^2/week), a weekly harvest of approximately 75 000kg (wet weight) could be expected from the proposed lagoon configuration under full duckweed production. A benefit of the proposed multi-bay lagoon is that full lagoon production of duckweed may not be needed to restore effluent to a desirable standard under the present nutrient load, and duckweed treatment may be restricted to certain bays. Restored effluent could be released without risk of contaminating the receiving waterway with duckweed by evacuating water through an internal standpipe located mid-way in the water column.

1. Introduction

Recent State and Federal reports into water quality impacts on the Great Barrier Reef (GBR) have stated that major land use practices in adjacent river catchments have led to an increased delivery of nutrients, and other pollutants, into the GBR lagoon (Productivity Commission 2003, Science Panel 2003). Community concerns are that this decline in water quality poses a significant threat to the ecological, social and economic values of the Reef.

There is some conjecture over the extent to which particular human activities contribute to nutrient enrichment of the GBR lagoon (Furnas 2002); however, both the Productivity Commission (2003) and the Science Panel (2003) have suggested that point sources of pollution, of which sewage discharge is the most important, can contribute to nutrient levels in the GBR lagoon. This is supported by studies throughout the world that have quantified the consequences of domestic wastewater discharge on receiving waters, ranging from human health concerns to environmental risks (see Chambers *et al.* 1997). The significance of these consequences is dependant on factors such as volume and treatment of effluent and the location of the effluent discharge point.

The Burdekin Shire forms part of the GBR catchment and the Shire’s two Sewage Treatment Plants (STP’s) at the townships of Ayr and Home Hill operate as conventional trickling filter processors that currently discharge secondary treated effluent to local drainages. Wastewater managers in the region are now taking a pro-active approach to further reducing nutrients by investigating options for tertiary treatment of sewage effluent.

The use of relatively inexpensive aerobic lagoons is now an integral part of final stage wastewater treatment in many communities. These lagoon systems rely on the removal of nitrogen and phosphorous in effluent through the processes of biological nitrification/denitrification, uptake by algae, volatilisation or settlement. A number of authors have shown, however, that these lagoons can be inefficient since dissolved nutrients are readily mineralised from settled organic matter and diffuse into the water column – at times causing an increase in discharged nutrients (Preston et al. 2000, Erler 2003, and others). In addition, phytoplankton (planktonic algae) blooms are inevitable in these lagoons, and nutrients contained in the phytoplankton are subsequently lost in discharged water (Iqbal 1999). Both of these facts indicate that aerobic lagoons systems require modification to be truly beneficial for effluent remediation.

Recent work conducted in the Burdekin Region has demonstrated that aerobic lagoon concepts for removing nutrients can be enhanced through the addition of artificial substrate and fish (Willett *et al.* 2002). Placement of artificial substrate promotes settlement of particulate matter and can help shift the site of primary production from planktonic algae to attached algae that assimilate and store nutrients within its biomass (Erler 2003). The additional surface area provided by substrate can also stimulate additional bacterial communities, which in turn process organic matter or effectively convert inorganic nutrients through nitrification/ denitrification (Azim *et al.* 2001).

Left unchecked, however, excess aquatic weed growth can cause self-shading, algal death and subsequent release of nutrients. Efficient functioning of this system can be achieved through the addition of fish species capable of grazing the algae so that it remains in active growth phase. Fish also aid nutrient cycling by converting some effluent nutrients into biomass whilst excreting waste nutrients in a form readily assimilated by algae. Our previous study (Willett *et al.* 2002) in the Burdekin demonstrated that greater than 50% of incoming Nitrogen and Phosphorous was removed by a self-regulating algae/mullet system after a 14-day retention time.

Other studies using biological approaches to treat municipal wastewater have used lagoon systems that work to prevent rather than encourage algal growth – thereby eliminating the risk of producing planktonic algae that contribute to suspended solids counts. These involve deliberately stocking floating macrophytes, which out-shade planktonic algae while concurrently acting as the nutrient sink (Skillicorn *et al.* 1993). These systems, however, are not self-regulating and rely on frequent harvesting of the plants to remove nutrients and prevent over-growth. Water hyacinth and duckweed especially have been used for this purpose due to their ability to efficiently accumulate nutrients and for their ease in harvesting.

The advantages of duckweed-based treatment systems include:

- Duckweed has one of the fastest growth rates of all plants and is capable of nutrient uptake under a wider range of environmental conditions than hyacinth (Zirschky & Reed 1998).
- The floating duckweed mat has been reported to control disease vectors (mosquito larvae) and odour in wastewater bodies (Iqbal 1999).
- The harvested duckweed can be a valuable by-product. Duckweed plants contain up to 45% crude protein by dry weight with higher concentrations of essential amino acids than most plant proteins. Duckweed meal also has a low fibre content but high levels of vitamin A and pigment making it an especially valuable and proven food source for cultured animals such as fish, ducks, chickens, pigs horses and ruminants (Skillicorn *et al.* 1993; Bio-Tech Waste Management 1998; Iqbal 1999; Landesman *et al*. 2002).

The current project assesses the efficacy of a pilot-scale biological remediation system to recover nutrients from secondary treated municipal wastewater at the Ayr Sewage Treatment Plant. An additional facet of this trial is to investigate potential local uses for by-products from the treatment system. Knowledge gained from this trial can provide directions for implementing a larger-scale final effluent treatment protocol on site at the Ayr plant.

Expected outcomes:
1. Increased knowledge of the nutrient dynamics in final stage municipal effluent treatments.
2. Cleaner water available for discharge into the environment or for use in commercial ventures. Options for commercial use of treatment system by-products.
3. Knowledge of management implications for the large-scale bioremediation of Ayr municipal wastewater.

2. Methods

2.1 Experimental System:

In May 2002, an experimental system was constructed at the Ayr STP to represent a series of flow-through treatment lagoons for processing secondary treated effluent. The treatment “lagoons” were 10 000 litre (rotational mounded) plastic tanks. Secondary treated effluent was gravity-fed to the tanks via a 20 000 litre storage header tank. The header tank allowed regulated control over effluent delivery rates to the treatment tanks, and flow rates were adjusted during the course of the study to assess nutrient removal at different retention times.

The treatment lagoons were labelled *Primary* and *Secondary* to accommodate sequential treatment of the effluent and the whole configuration was replicated for scientific validation. Volumes in the Primary and Secondary Lagoons were approximately 8 000l and 7 000l, respectively. Water flowing out of the treatment “lagoons” was drawn from mid-water column via internal standpipes. Towards the end of the trial, jade perch (*Scortum barcoo*) were stocked into an additional downstream tank to demonstrate the use of effluent-grown duckweed as stock feed. The configuration was designed to allow water to be sampled leaving the header tank and each treatment lagoon for nutrient analyses (Figure 1).

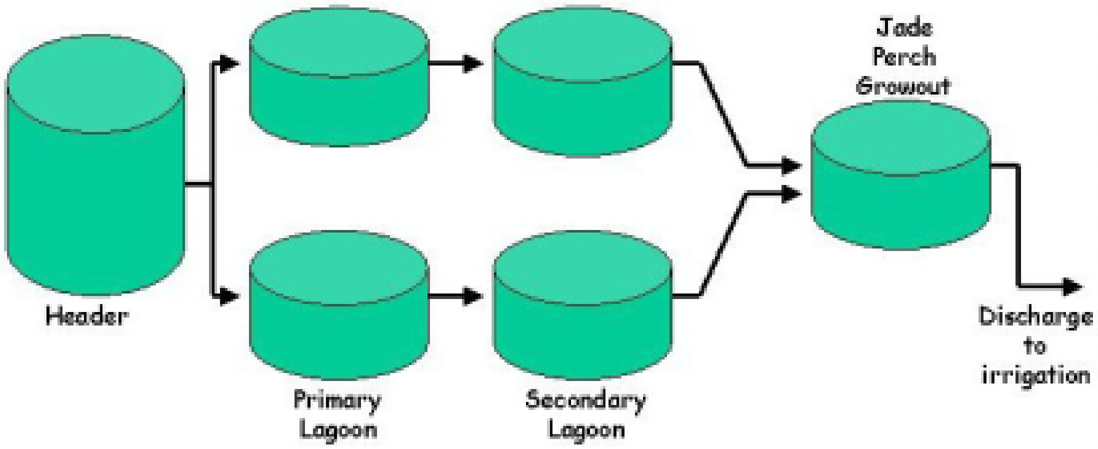

Figure 1. Configuration of the pilot-scale tertiary effluent treatment system at the Ayr Sewage Treatment Plant.

2.2 Treatments:

Trial A – Duckweed and Algae/fish Systems:

An early goal of the study was to reproduce the algae/mullet system used previously (Willett *et al*. 2002) to assimilate dissolved nutrients into filamentous algae and fish biomass. The ammonia and chlorine residual levels in incoming sewage effluent in the current trial, however, were too high for fish to tolerate. Therefore, duckweed was grown in the Primary Lagoons to eliminate chlorine and reduce ammonia levels so that fish could survive in the subsequent Secondary Lagoons. The duckweed was sourced locally and was a species of the *Spirodela* genera. An initial density of approximately 0.5kg/m^2 wet-weight was stocked. A 15 cm thick layer of gravel was placed in the Primary Lagoons to provide surface area for bacterial biofilms to aid in nutrient processing.

The Secondary Lagoons were equipped with artifical substrate (12 m^2 x 2mm oyster mesh hung vertically in the water column). After a four-week period to establish a biotic community on the substrate, mullet (*Mugil cephalus*) were introduced into the Secondary Lagoons at a density of 15 fish/tank (Mean individual weight: 12.2g). Aeration was provided to oxygenate water in the Secondary Lagoons.

Flow rate from the header tank was adjusted to give an effluent retention time of 6.6 days through the treatment system (i.e 3.5 days in the Primary Lagoon; 3.1 days in the Secondary Lagoon according to lagoon volumes). While nutrient recovery by the system as a whole was assessed, this trial provided opportunity to compare the efficiency of the duckweed (Primary Lagoons) with the algae/mullet system (Secondary Lagoons). This trial continued for 20 weeks.

Trial B – Duckweed Efficiency:

A second trial tested whether the addition of fish enhanced duckweed treatment by evaluating systems with and without the inclusion of mullet. In this trial, flow rate was reduced to achieve an extended residence time of 5.5 days in the Primary Lagoons (minus mullet) and 4.9 days in the Secondary Lagoons (plus mullet) according to lagoon volumes (i.e. total of 10.4 days E.R.T. through the treatment system). Aeration was not provided for fish in the Secondary Lagoons since aeration agitates the surface water and therefore inhibits duckweed growth. This trial continued for 14 weeks

Following these experiments and when fish mortalities from the low dissolved oxygen became obvious, air-uplifts were installed in the Secondary Lagoon to test whether it was possible to maintain high DO levels beneath the duckweed blanket without disturbing the water surface. The air-uplifts, powered by a 14-watt linear air compressor, were designed to vent through pipes without disturbing the water surface (Figure 2). Five air-uplifts were installed into each replicate in the Secondary Lagoons.

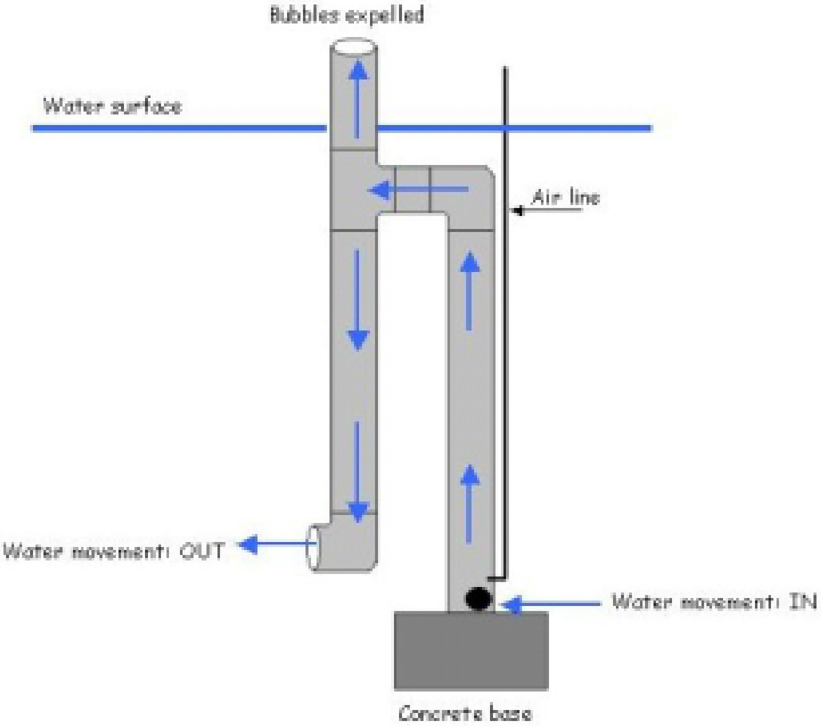

Figure 2. Air up-lift as installed under the duckweed blanket to provide oxygenation without disturbing surface waters.

2.3 Duckweed Harvesting:

Due to practical considerations (such as labour constraints) harvesting in the current trial was scheduled weekly to return the crop to a standing density of approximately 1kg/m^2 (wet weight). This equated visually to a complete coverage of the surface by a single layer of duckweed fronds. Harvesting was done manually with a dip net. Standardised wet weights of harvested duckweed were measured by hand-squeezing out excess water from the biomass and weighing to the nearest 100 grams.

2.4 Water Quality Analyses:

Effluent was sampled weekly according to standard methods (APHA, 1989) for dissolved and total nitrogen and phosphorous content. Samples were taken from incoming effluent, and from effluent discharged from each of the Primary and Secondary lagoons. Samples were stored at –18°C until collected and analysed. Samples of duckweed were dried to determine moisture content and analysed for dry-weight nutrient content (Total N and P). All nutrient analyses were conducted on a Lachat QC8000 flow injection analyser according to standard methods (QuikChem methods, 1996).

Other water quality variables such as water temperature, pH and dissolved oxygen (DO) were recorded periodically from the treatment system.

2.5 Duckweed as a Food Source:

Native jade perch (*Scortum barcoo*) are an omnivorous species that currently has wide market acceptance as a local aquaculture product. While it was beyond the scope of the current trial to establish a replicated feeding trial using wastewater grown duckweed, we aimed to ascertain whether jade perch showed inclination for eating fresh harvested duckweed.

Ten jade perch (mean individual weight: 345g) were sourced from a local aquaculture farm and released into the final tank. Harvested duckweed was added to the tank as required to maintain an over-supply and feeding responses of the fish were observed for 102 days. At this point fish were weighed and growth rates were assessed.

As an adjunct to this demonstration, samples of fresh harvested duckweed were frozen prior to semi-quantitative analysis for inorganic contamination by sewage effluent. This was to determine whether the wastewater grown duckweed contained any contaminants to render it unsuitable to feed to fish. (Note: Semi-quantitative analyses provided approximate concentrations of the full range of trace elements. For absolute concentration of individual standout elements, quantitative analysis is required. Analyses were conducted by Australian Government Analytical Laboratories.)

3. Results and Discussion

3.1 Trial A:

All mullet survived in the algae/mullet treatment. Average growth increase was 0.8g/week/fish. According to Erler (2003) and others, the role of fish as a nitrogen sink is minor compared with plants and N removal by denitrification. Nevertheless, fish play an important role in facilitating N removal by foraging settled organic matter and processing it into forms that are more readily taken up by plants or nitrified by bacteria, hence their value in the treatment system. The current trial demonstrated that mullet would survive in the effluent stream.

Total incoming Nitrogen (N) included organic and dissolved inorganic forms derived directly from the sewage treatment plant's secondary treatment process. Over the duration of *Trial A*, incoming Total N ranged between 10.63mg/L and 21.73mg/L (average: 15.55mg/L). Average Total N discharge from the experimental treatment system was 8.97mg/L over this period, which represents a 42.31% reduction in Total N after 6.6 days

Analysis of Total N discharged from the two treatment lagoons, however, showed that the duckweed-based treatment (Primary Lagoons) was responsible for the majority of the nutrient removal (average discharge from duckweed treatment: 9.72mg/L) (Figure 3). The duckweed treatment removed 37.5% of incoming N after 3.5 days, while the algae/fish system only further reduced N levels by 4.8% after an additional 3.1 days E.R.T. As a standardised comparison based on reduction of incoming Total N/L/day, the duckweed treatment was 7.8 times more effective than the algae/fish treatment (duckweed average daily N removal: 13 325.7mg; algae/fish average daily N removal: 1693.5mg).

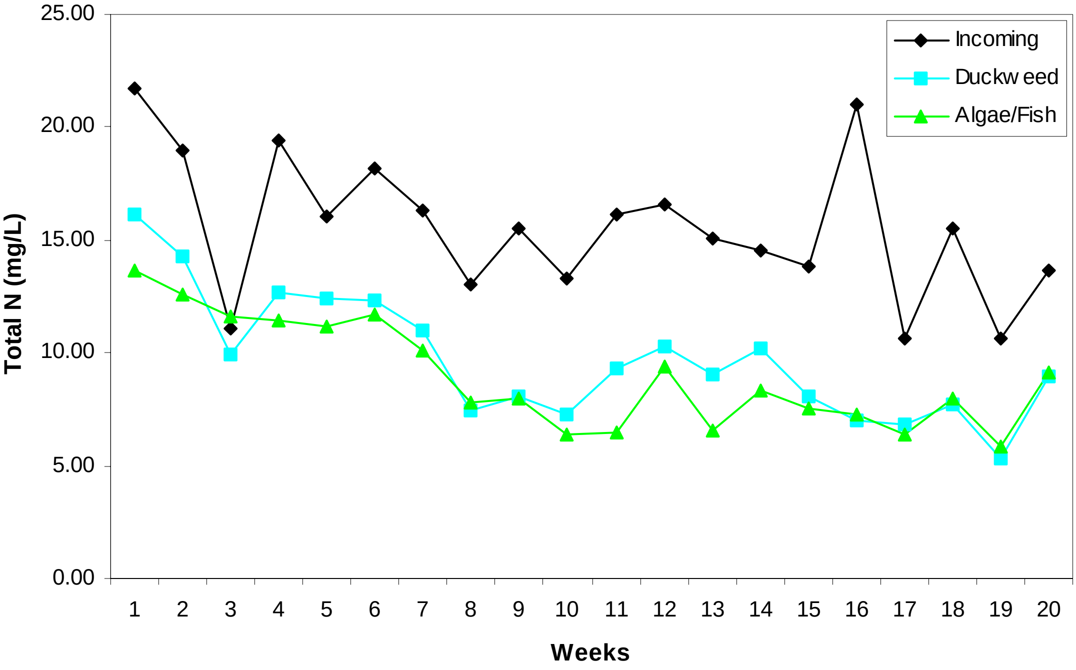

Figure 3. Total Nitrogen profiles over the experimental period for Trial A. Data are mean values (*n*=2).

A breakdown of the Nitrogen species into Organic N, Total Ammonia Nitrogen (TAN), and NO_x (combined Nitrite/Nitrate) indicated that the duckweed treatment was able to process all forms (Figure 4). The algae/fish treatment showed a marked reduction in TAN but an increase in NO_x – indicative of effective nitrification. Overall in this algal-fish treatment, however, there was a reduction in combined dissolved inorganic N (TAN + NO_x) suggesting that this treatment was also promoting denitrification as well as uptake of inorganic N by algae (Figure 4). An increase in organic N leaving the fish/algae treatment was most probably the result of a phytoplankton bloom that persisted for most of the trial. While some filamentous algae grew on the vertical substrate to sequester nutrients, this wasn't able to prevent the phytoplankton bloom.

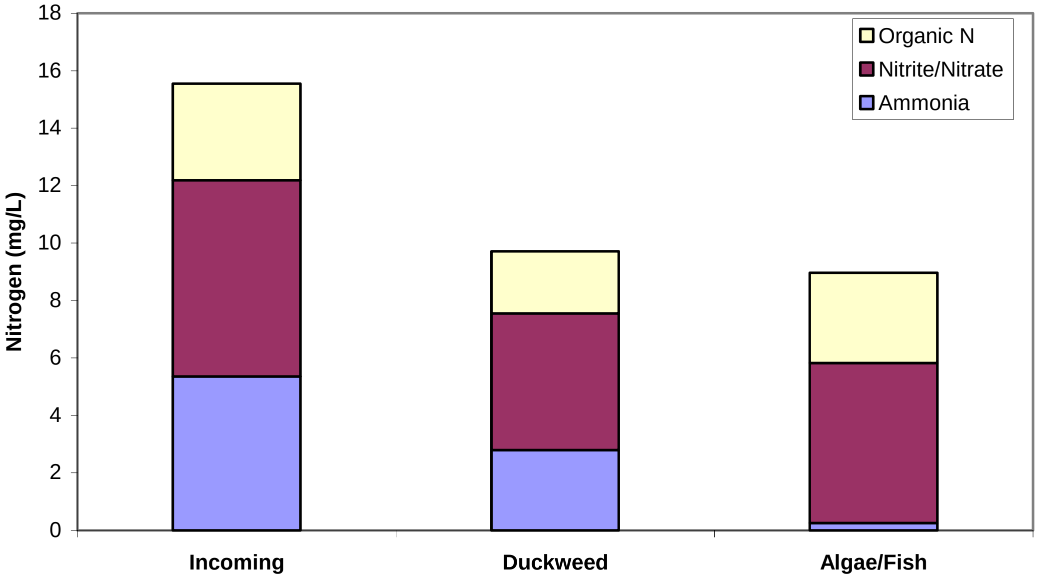

Figure 4. Breakdown of Nitrogen species in incoming effluent and effluent discharged from the duckweed and algae/fish treatments, averaged over the duration of Trial A.

Total Phosphorous (P) entering the treatment system ranged between 6.8mg/L and 16.9mg/L over the duration of the trial (average: 9.97mg/L). Average Total P discharge from the experimental treatment system was 8.40mg/L over this period, which represents a 15.75% reduction in Total P after 6.6 days E.R.T. Again, the duckweed treatment (Primary Lagoons) was responsible for the majority of P nutrient removal (average discharge from duckweed treatment: 8.92mg/L). The duckweed treatment recovered 10.5% of incoming P after 3.5 days, while the algae/fish system only further reduced P levels by 5.25% after an additional 3.1 days E.R.T. (Figure 5). As a standardised comparison based on reduction of incoming Total P/L/day, the duckweed treatment was approximately twice as effective as the algae/fish treatment (duckweed average daily P removal: 2400mg; algae/fish average daily P removal: 1174.2mg).

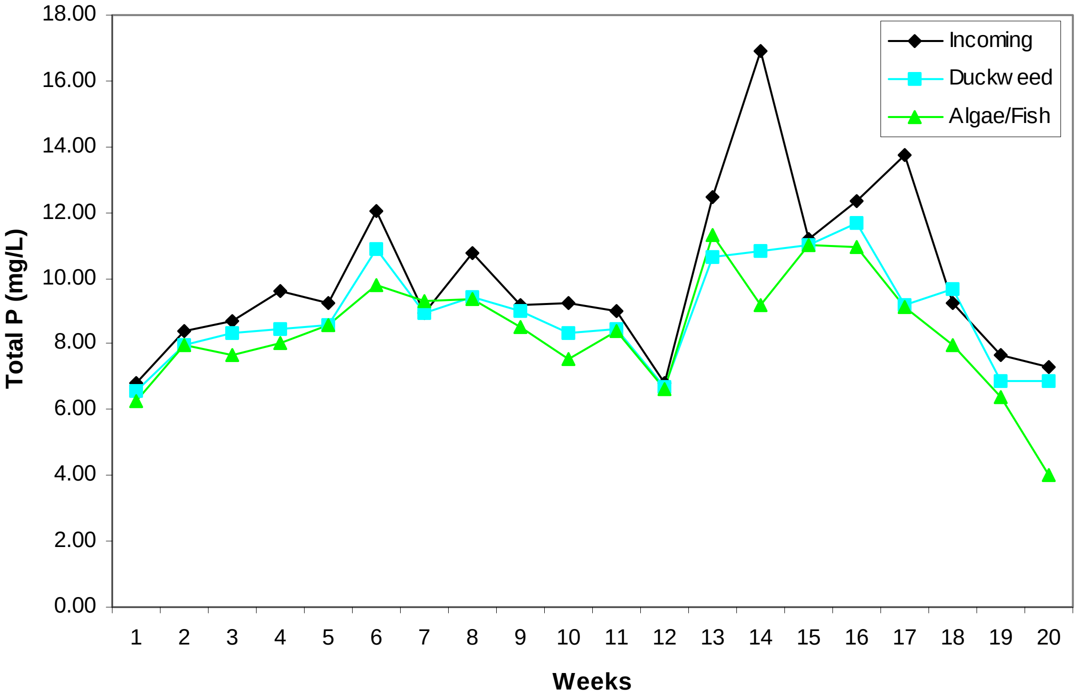

Figure 5. Total Phosphorous profiles over the experimental period for Trial A. Data are mean values (*n*=2).

3.2 Trial B:

Analysis of Total N discharged from the treatment lagoons containing duckweed showed that the Primary Lagoons (minus fish) were responsible for greater overall nutrient removal than the Secondary Lagoons (plus fish) (Figure 6). A standardised comparison based on average reduction of incoming Total N/L/day, showed that the Primary Lagoon treatment removed 9269.6mg N daily while the Secondary Lagoon treatment removed 2401.2mg N daily. The likely reason for this was that the mullet did not survive in the Secondary Lagoon treatment after dissolved oxygen dropped to below 1ppm in the fourth week of the trial. The mortalities could not be recovered from the treatment and therefore contributed an organic load to the system. This is reflected in the breakdown of the Nitrogen species into Organic N and Dissolved Inorganic N (DIN) that showed an increased input of organic N in the Secondary Lagoon treatment. Organic N contributed to only 16% of N remaining in the Primary Lagoon treatment, whereas organic nitrogen contributed to 45% of N remaining in the Secondary Lagoon treatment (Figure 7). However, the Dissolved Inorganic Nitrogen (DIN: ammonia, nitrite and nitrate) removal was similar between treatments with and without fish (57% and 59% DIN removal, respectively).

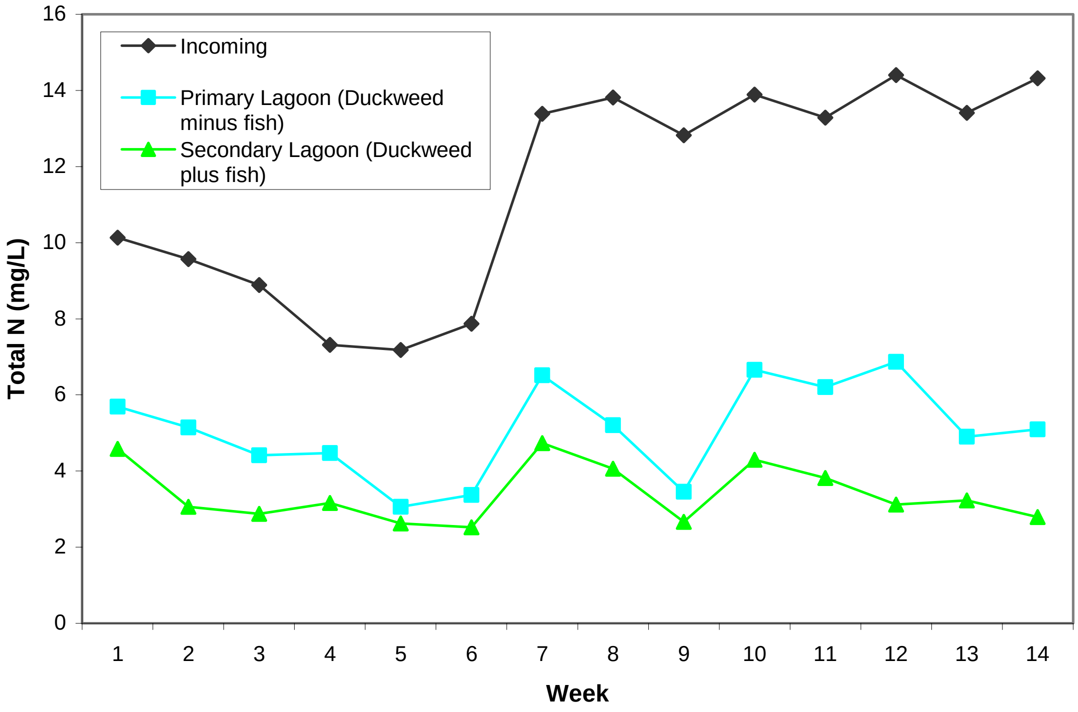

Figure 6. Total Nitrogen profiles from two duckweed treatments over the experimental period for Trial B. Data are mean values (*n*=2).

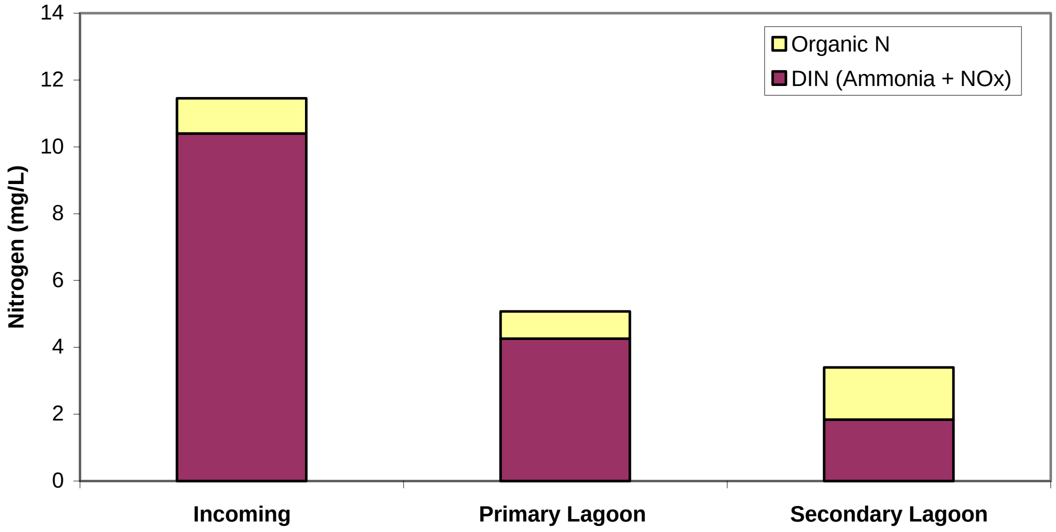

Figure 7. Organic and Dissolved Inorganic N in incoming effluent and effluent discharged from the Primary Lagoon (minus fish) and Secondary Lagoon (plus fish), averaged over the duration of Trial B.

Overall, three effluent residence times were evaluated using duckweed-based treatments; i.e. 3.5 days (from Trial A), 5.5 days and 10.4 days (from Trial B). Total N removal was 37.5%, 55.7% and 70.3%, respectively. The 10.4-day E.R.T. trial, however, was evaluated by sequential nutrient removal through the duckweed-minus-fish treatment followed by the duckweed-plus-fish treatment. Therefore, the 70.3% Total N removal was lower than could have been achieved at this retention time due to the abovementioned fish mortalities. Nevertheless, Total N removal was positively correlated with effluent retention time. A summary of this data is presented in Table 1.

Table 1. Average nutrient removal from duckweed treatment at three Effluent Residence Times (E.R.T.) expressed as percentage of total incoming nutrient.

Nutrient Type	**3.5-days E.R.T.**	**5.5-days E.R.T.**	**10.4-days E.R.T.**
DIN (Ammonia + NO_x)	38.07	59.04	82.31
Organic N	35.7	22.7	*47.8% increase
Total Nitrogen	37.55	55.67	70.35
Total Phosphorous	10.5	5.64	13.62

* Fish mortalities in the Secondary Lagoons inputted additional organic load into treatment system at 10.4 days E.R.T.

Total phosphorous removal varied throughout the trials with the greatest P removal evident at 10.4 days E.R.T. (Table 1). Phosphorous recovery throughout the trials, generally, was lower than expected based on the scientific literature. For instance, P removal efficiencies between 14-99% from duckweed systems were reported by Oron *et al*. (1986), Alaerts *et al*. (1996) and Korner & Vermaat (1998). Korner & Vermaat (1998) actually measured a release of P from some low nutrient treatments in their study. However, direct comparison of these studies is difficult due to different treatment systems, retention times, water depths, initial nutrient concentrations, duckweed densities and harvesting regimes. Reed *et al*. (1987) state that phosphorous removal from aquatic plant systems is not very effective where there are limited contact opportunities between the wastewater and soil. This is because the principal mechanism for phosphorous removal, in addition to plant uptake, is absorption/chemical precipitation in clay soils (Iqbal 1999). Lower than expected P recovery in the current study may be due, in part, to the plastic tanks used in the pilot-system containing no clay substrate, impeding this precipitation and maintaining P in suspension. Plant uptake, therefore, was the most important mechanism for P removal in the current study.

3.3 Duckweed – water quality, harvest and nutrient content:

Duckweed was cultured for a total of ten months over the duration of both trials, with plants showing good growth rate over all seasons. In addition, clear water was maintained beneath the duckweed blanket compared to the algae/fish replicates, which were subjected to persistent green phytoplankton blooms that increased suspended solids, raised pH and contributed to nutrient loss from the treatment. By contrast, the pH of water beneath the duckweed mat was maintained between 6.8 and 7.5, while in the algae/fish treatment, pH peaked at over 9.3 on occasions. Dissolved oxygen dropped below 1ppm in the duckweed tanks after four weeks, but this does not reportedly limit duckweed production (Oron *et al*. 1986). At the conclusion of nutrient sampling, the air-uplifts installed in the Secondary Lagoon showed that DO levels beneath the duckweed blanket could be maintained above 6ppm without disturbing the duckweed floating on the surface. Further testing of duckweed efficiency to recover nutrients under conditions with and without fish/aeration is warranted to test whether the addition of fish to the treatment system would improve efficiency through foraging settled organic matter and processing it into biomass or forms that are more readily uptaken by the duckweed.

Duckweed harvests ranged from 2.5 to 15kg/tank/week and were therefore quite variable. Difficulties were experienced in calculating nutrient recovery of duckweed, as a function of effluent retention time or incoming nutrient load since labour constraints prevented strict harvesting schedules. Duckweed was harvested once or twice weekly throughout the trial by several operators, and quantities harvested varied considerably on a weekly basis in order to return the crop to approximate standing density of 1kg/m^2. Growth rates, presumably, would also have varied depending on localised climatic conditions.

Nevertheless, as an indication of duckweed productivity, mean duckweed harvest from all duckweed treatment tanks over the duration of both trials was 8.6kg/week/tank or 1.23kg/day/tank (wet weight). With a standing density of approximately 7.0kg/tank, duckweed doubled its biomass on average every 5.7 days. On a per-surface area basis, 1.23kg/m^2 of duckweed was harvested weekly.

Oven drying of the duckweed showed that moisture content was 92%, equating to a total dry weight harvest of 0.098kg/tank/day. Nutrient analysis of dried duckweed gave an N content of 6.67% and a P content of 1.27%. Therefore, approximately 6.53g of N and 1.24g of P were removed daily from each tank in the effluent stream as duckweed. However, nutrient recovery by duckweed treatment systems is realised by other processes in addition to direct uptake by the plants. Korner & Vermaat (1998) have shown in laboratory trials that indirect contribution of duckweed to nutrient removal was considerable and included uptake and removal of N and P by microalgae and bacteria in biofilms attached to the duckweed.

3.4 Duckweed as a Food Source:

The value of duckweed as a commercial food source for Australian cultured fish has not been realised despite ample overseas experience in feeding duckweed to cultured fish, as a low-cost supplement in commercial diets for both tilapias (Hasen & Edwards 1992; Skillicorn *et al*. 1993; Fasakin *et al*. 1999) and channel catfish (Robinson *et al*. 1980). It is also a sole source of feed for carp polyculture (Skillicorn *et al*. 1993). The challenge for the current project was to identify a local species with aquaculture potential that may be reared on duckweed-supplemented diets. This may eventually contribute to cost recovery of the wastewater treatment process or help glean environmental benefits using aquaculture.

The jade perch used in the current trial actively consumed and gained weight (average weight gain: 0.7g/day/fish over 102 days) on harvested duckweed. Survival was 100%. These results are supported by a local aquaculturist who now claims to rear jade perch on feed supplemented by 70% homegrown duckweed with no reduction in growth rate (G. Pollard, pers comm). This significantly reduces grow-out costs. These findings suggest a more formal feeding trial is warranted to quantify the value of duckweed as a food source for jade perch. In addition, Fletcher & Warburton (1997) have found that decomposed *Spirodela* duckweed is as effective as commercial pellets as feed for cultured red claw crayfish, *Cerax quadricarinatus*. This has positive implications for the local red claw industry.

There are, however, public health considerations when using effluent-grown duckweed as a feed for aquacultured crops. Assured safety of duckweed to feed to cultured stock destined for human consumption is critical, especially regarding contamination from heavy metals and other toxins in the effluent. Skillicorn *et al.* (1993) state that while growth nutrients (nitrogen and phosphorous) remain, duckweed plants are predisposed to absorb them to the exclusion of other elements present in the wastewater column. This predilection for exclusive uptake of nutrients is important in enabling the safe utilization of plants harvested from urban wastewater. Haustein *et al.* (1987) have shown that repeated testing of duckweed samples harvested from nutrient rich urban wastewater has consistently failed to find any heavy metals or known toxins in concentrations approaching USFDA (United States Food and Drug Agency) food standards prohibiting human consumption.

In the current study, semi-quantitative analyses of our harvested duckweed showed no residual elements from the effluent stream that were greater than ANZECC (2000) toxicant guidelines proposed for aquaculture. We concluded therefore that further quantitative analysis was not warranted at this stage. While this demonstrates potential for large-scale fish production using effluent-grown duckweed, public assurance is paramount for wide acceptance of food cultured using by-products from the effluent treatment process.

4. Implications for Large-Scale Final Effluent Treatment at the Ayr STP

Results from the current trial suggest that a duckweed-based system may be one viable option for tertiary treatment of Ayr municipal wastewater. The tertiary detention lagoon proposed by the Burdekin Shire Council, consisting of Six bays approximately: 290 x 35 metres (x 1.5 metres deep) in sequence, would be suitable for duckweed culture with minor modification to facilitate the efficient distribution of duckweed plants across the entire available growing surface (such as floating containment grids). The effluent retention time resulting from this proposed configuration (~30-days) should be adequate to recover most effluent nutrients (certainly N) based on the current results.

Duckweed harvesting on this scale would present management problems and cost-effective techniques need to be further investigated. Based on duckweed production in the current trial (1.23kg/m^2/week), a weekly harvest of approximately 75 000kg (wet weight) could be expected from the proposed lagoon configuration under full duckweed production. There are commercial duckweed harvesters available in Australia (Bio-Tech Waste Management, Armidale, NSW) and contamination issues aside, harvested duckweed could be used as a stock feed supplement. Developing an industrial drying facility on site to convert the duckweed into a saleable stock feed product could be commercially viable (Robert Bell, Bio-Tech Waste Management, pers comm.) At worse, harvested product could be used as a valuable agricultural soil conditioner/mulch.

A benefit of the multi-bay lagoon proposed by the Burdekin Shire Council is that full lagoon production of duckweed may not be needed to restore effluent to a desirable standard under the present nutrient load, and duckweed treatment could be restricted to certain bays. Ideally, duckweed would be cultured in at least the final bay in order to remove and prevent planktonic algae suspended solids (phytoplankton), which are the bane of standard lagoon treatment systems. In this way, planktonic algae are out-shaded, unable to photosynthesise, and simply die and precipitate to the bottom where their released nutrients are utilized by the duckweed. While duckweed exists naturally in Burdekin waterways, restored effluent could be released without further risk of contaminating the receiving waterway with duckweed by evacuating water through an internal standpipe located mid-way in the water column.

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