NUTRIENT REMOVAL FROM A STORMWATER DETENTION POND USING DUCKWEED

M. Perniel, R. Ruan, B. Martinez

ABSTRACT. *Different species of Lemnaceae (duckweed) were grown in pure and mixed cultures to examine nutrient absorption capacity in a stormwater detention pond. The duckweed was grown in 0.4 m^2 equilateral triangular floating Pens in a stormwater retention pond, which is part of a constructed wetland in Roseville, Minnesota. Both biomass productivity and nutrient (phosphorus and nitrogen) removal were measured for each species. It was concluded that: (1) monoculture Lemna minor consistently removed the largest amount of ammonia from stormwater and had the largest biomass density; and (2) a polyculture of Lemna minor and Spirodela polyrhiza was the most stable nutrient sink and removed the largest amount of phosphorus from stormwater in eight weeks.*
Keywords. *Stormwater management, Detention pond, Lemnaceae, Lemna, Spirodela, Duckweed, Phosphorus, Nutrient removal.*

In many urban areas the storm sewers are separated from the sanitary sewers to reduce CSO (Combined Sewer Overflow) violations and increase wastewater treatment plant capacity. Untreated storm sewers will discharge large quantities of urban runoff containing significant loads of phosphorus (P) and nitrogen (N) into local water bodies. Excessive N and P entering aquatic environments can lead to accelerated eutrophication. Limiting these nutrient inputs into urban aquatic ecosystems is the key to good management practices. Healthy lakes and streams support many human leisure activities, in addition to providing useful wildlife habitat.

Chemical treatment of stormwater such as injection of alum or ferric chloride into stormwater to precipitate phosphorus is an effective but very expensive process that offers no usable final product. These chemical/metal treatments may have unknown future detrimental ecological effects, but little research has been done studying the benthic impacts. One best management practice (BMP) to reduce stormwater nutrient loading to lakes and streams can be a series of constructed detention ponds and wetlands. Oberts and Osgood (1988) found detention ponds and wetlands can remove more than 50% of the nitrogen, and slightly less than 50% of the total dissolved. The majority of phosphorus in a wetland is removed from the stormwater by sedimentation followed by adsorption to iron and aluminum at the water sediment interface, with additional dissolved phosphorus removed by incorporation into the plant biomass. In the present managed wetland situation, cattails (*Typha sp*.), store most of the accumulated phosphorus in their surface rhizome and very little in the leaves and stems (Howard-Williams, 1985). Cattails are hardy but very difficult to harvest and currently offer no useful end product. A hardy, easily harvested plant which can exhibit a luxury consumption of phosphorus and may provide a useful end product could reduce the excess nutrient problem from stormwater.

Lemna (duckweed) has been useful in wastewater reclamation and has recently found commercial application in treating lagooned wastewater. Duckweed is a competitive, hardy plant that can grow at phosphorus levels as low as 0.031 mg/L (Fekete, 1973). However, little is known to date as to the effectiveness of using *Lemna* for the treatment of stormwater. The major body of applied field research encompassing duckweed is concerned with wastewater applications (Oron et al., 1988; Zirschky and Reed, 1988).

Sutton and Ornes (1975) using different species of Lemna achieved 90 and 97% reduction in orthophosphate levels in treated wastewater effluent in four and eight weeks, respectively. Tripathi et al. (1991) found *Lemna minor* L. the most efficient plant for removal of phosphorus from ponded wastewater during the winter months in tropical regions when compared with *Pistia*, *Salvinia*, and *Eichhornia*. When starting with concentrations of 3, 6, and 9 mg/L PO_4-P, *Lemna sp*. removed 50% of the total phosphate within 10 days.

Hillman and Culley (1978) outlined the unique characteristics and remediation potential duckweed offers to wastewater treatment. They suggested that the rapid growth, potential nutritional value (high protein) and high biomass productivity of duckweed plants could be very useful for water treatment. Duckweed (*Lemna* minor) has a very high crude protein concentration, 20 to 40% dry weight (Skillicorn et al., 1993), comparable to alfalfa. It is one of the few freshwater aquatic plants that many animals (fish, chickens) find palatable (Culley and Epps, 1973). As many aquatic plants do, duckweed also accumulates heavy metals which are of concern when treating stormwater

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runoff. According to Skillicorn et al. (1993), "Testing over the years of many duckweed samples harvested from nutrient rich urban wastewater has consistently failed to find any heavy metals or known toxins in concentrations approaching U.S. FDA food standards prohibiting human consumption." If metal accumulation is of concern, it is recommended that duckweed be disposed of by landspreading or composting. Duckweed may well be an effective aquatic nutrient sink. As a small floating aquatic plant, it is an easily harvestable plant with a usable end product. It can be harvested using floating mechanical harvesters or hand raked.

Stormwater by its nature is sporadic in volume and nutrient loading. The best aquatic plant candidate for stormwater treatment should exhibit variable uptake rates with a high capacity for nutrient utilization. As McPharlin and Bieleski (1987) suggested, *Spirodela sp*. and *Lemna sp*. may be a good phosphorus sink. Their laboratory research indicates that over a 12-h period, phosphorus deficient *Lemna sp*. and *Spirodela sp*. have enhanced the phosphorus uptake rates of 60 to 120% and 30 to 60%, respectively, compared with controls were phosphorus was adequate. Phosphorus deficient *Lemna* may absorb significant quantities of phosphate from stormwater and exhibit luxury consumption. Virtually all stormwater contains phosphorus above duckweeds critical phosphorus concentration of 0.031 mg/L (Fekete, 1973; Nation Wide Urban Runoff Program, 1983). Nitrogen appears to be the more likely limiting nutrient in stormwater for duckweed.

Immature, uncrowded, actively growing *Lemnaceae* appears to consume larger amounts of phosphorus than mature, or overcrowded older populations. Furthermore, density and senescence seem to play a major role in alkaline phosphatase activity where duckweed cleave bound particulate phosphorus and then absorb it as dissolved phosphorus. Strother (1984) found that the highest alkaline pyrophosphatase occurred in cells associated with active biosynthesis or young actively growing plants.

One limitation of many of the previous experiments using duckweed for nutrient removal was that they were conducted in laboratory microcosms. Laboratory findings may not transfer well into field applications. The overall objectives of this study were to: (1) find if duckweed in an *in situ* mesocosm (floating pen) could be a useful bioremediation tool for stormwater treatment; (2) assess the effectiveness of using *Lemnaceae* (duckweed) as a potential sink to absorb and remove phosphorus and nitrogen from urban stormwater; and (3) evaluate the biomass density using different mixtures of native and non-native duckweed species.

Materials and Experimental Design

Five, 1-m (inner dimension) equilateral triangle pens were set up, loosely tethered together, and staked to 2.4-m metal posts anchored into the sediment. The water was approximately 1 m deep, and fluctuated to approximately 1.5 m deep during large storms. The pens resembled triangular enclosed silt curtains. Each pen was constructed of heavy-duty interlocking woven landscape fabric (Stock No. PR4100, Teknor Apex, Pawtucket, RI 02861) supported with floats. The floats were high-density extruded Styrofoam, the dimensions of which were 10 cm × 10 cm × 1 m (H × W × L). The styrofoam floats were reinforced with wooden lath for additional strength. The completed triangular pen (fig. 1) has approximately 0.4 m^2 of surface area. The landscape fabric was drawn together and weighted at the bottom (1 m below surface) to prevent loss of the duckweed due to sinking. Each pen was planted with approximately 20 g (wet weight) of plant material. Pen 1 contained *L. minor* and *Wolffia columbiana Karsten*; Pen 2 contained *L. minor*; Pen 3 contained *L. minor*, *W. columbiana Karsten* and *Spirodela polyrhiza*; Pen 4 contained *L. minuta*; and Pen 5 contained *L. trisulca*. The non-native species in Pens 4 and 5 were provided by Lemna Corporation in Mendota Heights, Minnesota. They were from Lemna Corporation's extensive specimen library and chosen as the expected best candidates for phosphorus removal.

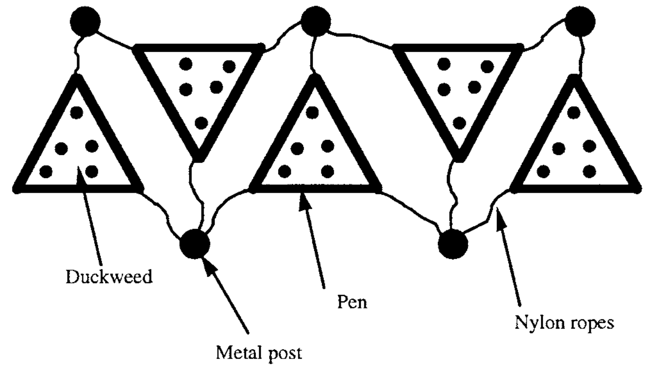

Figure 1–A top view diagram of the floating pens. The pens rise and fall freely during storm events, but are rafted together and tethered to metal stakes anchored into the sediment.

Experiment

The experiment was undertaken at Villa Park Wetland, a re-constructed wetland built in 1985 to receive and treat stormwater for the City of Roseville, Minnesota. This wetland is the main collection point and surface tributary to McCarrons Lake. The pen locations were on the southwest side of the upper retention pond (approx. 1.1 ha).

Pens 1-3 were planted on 7/3/95 with indigenous mixed and pure species of *Lemnaceae* (*W. columbiana, L. minor,* and *S. polyrhiza)* collected from nearby wetlands (Eggers and Reed, 1987). Pen 4 contained *L. minuta,* a non-native species. *L. minuta* were grown to a large biomass in the laboratory and subsequently planted in the field.

The monitoring schedule consisted of a minimum of two site visits per week by the same individual for observation and measurement of air temperature, water temperature, clarity and color of water, color of duckweed, visually estimating the percent algal material in the duckweed mat, and relative percent "live" *Lemna* coverage. Biomass density was determined upon harvest. Harvesting was performed every two weeks, after an initial three-week acclimation and growth period. This intensive harvesting schedule required some modification as to extend the time between harvest later in the growing season as the plant biomass growth slowed. The harvest procedure consisted of (1) obtaining a sub-surface water sample outside the pen for pH analysis (within 30-60 min) and then freezing the remaining water for later total Kjeldahl nitrogen (TKN), nitrogen ammonia (NH_3), and total phosphorus analysis; and (2) bisecting the triangular pens with a piece of styrofoam and completely removing the floating duckweed from one side of the bisected pen.

Chemical and Biological Analysis

The harvested duckweed was dried by spreading it evenly in approximately 1-cm-thick layers between industrial paper towels and the excess of water was carefully removed from the duckweed. Care was taken to remove any foreign objects, e.g., wood, snails. Laboratory analysis for total solids, total volatile solids, TKN, NH_3, and total phosphorus were done according to *Standard Methods for the Examination of Water and Wastewater*, (APHA, 1992). The TKN and NH_3 analyses were carried out using the MacroKjeldahl method and distillation and titration methods respectively and run in triplicate with the average and standard deviations reported. Density was determined by taking the weight of the duckweed harvested and dividing it by half of the pen's surface area (0.2 m^2).

Results and Discussion

It was assumed in this experiment that target nutrients (nitrogen and phosphorus) incorporated into the plant tissue were removed from the surrounding water column. Shortly after planting, *W. columbiana* appeared stressed and disappeared from Pens 1 and 3. The exact reason for *W. columbiana Karsten* disappearance is unknown, but it is believed that turbulence may have played a large role. The non-native *L. minuta* (Pen 4) grew at an accelerated rate in the laboratory, but was unable to thrive in the field. It is not know why this non-native species was unable to survive.

From the analysis of the water samples, phosphorus concentrations in the pond appear to remain relatively constant, while both the TKN and NH_3 concentrations decreased during late July (week 5) and August (week 8) (fig. 2). Ammonia concentrations in the water during the whole study were low (0.16 to 0.93 mg/L, fig. 3) and this may explain a general decrease in the ammonia values of

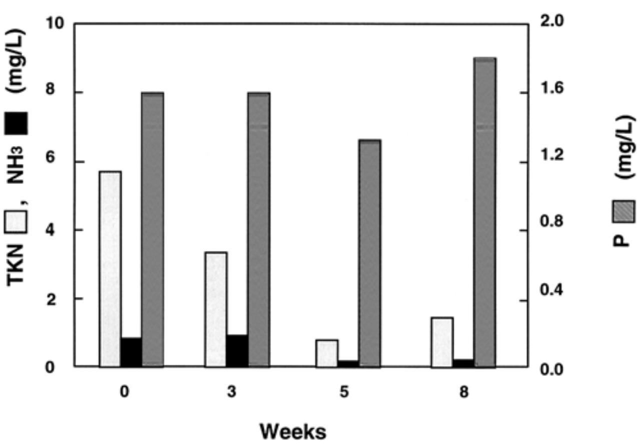

Figure 2–Nutrient composition of detention pond water surrounding the duckweed floating pens. Ammonia fall sharply after week 3 and nitrogen may become the limiting nutrient for duckweed. Phosphorus levels remain relatively constant.

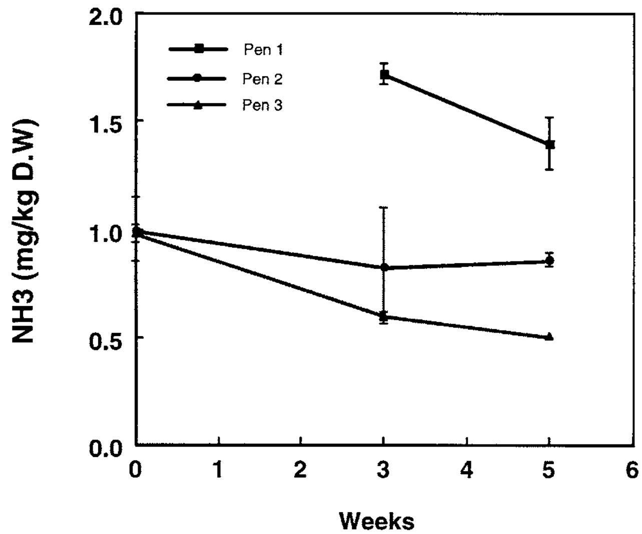

Figure 3–Ammonia level measured in duckweed tissue. Pen 1 = *L. minor, W. columbiana*; Pen 2 = *L. minor*; Pen 3 = *L. minor, W. columbiana, S. polyrhiza*.

the dry duckweed in weeks 1-3 and then a leveling out in Pens 2 and 3 in weeks 3-5 (fig. 3).

The biomass density expanded four or fivefold within the first three weeks in all pens. The initial density in all pens was 54 g/m^2. After three weeks the density in all pens increased fivefold to 310 ± 19 g/m^2. During weeks 5-8 the density increased in all pens to 348 ± 16g/m^2 and fell to 90 ± 75 g/m^2, respectively. The arrested growth phase after five weeks may have been affected by low nitrogen availability in the water column, increased water temperatures, and competition with algae surrounding the pens became noticeable around this time. No visual evidence of fungal infestation was present within the duckweed mat.

The nitrogen threshold requirement for duckweed growth is unknown at this time. Available nitrogen (NH_3) in stormwater appears more sporadic than available phosphorus. The ammonia uptake by the duckweed fell at each successive harvest, which is further evidence it may have become a limiting nutrient (fig. 3). Nitrate and nitrite were not measured in the water column, so a nitrogen deficiency of the duckweed cannot be fully discussed. Field observations in late summer of a yellowish duckweed mat indicated a nitrogen deficiency (Denver Regional Council of Governments, 1994).

Field measurements indicated the average water temperatures increased from 23.4°C (8/1-14/95) to 27.9°C (8/17-25/95). The upper temperature growth tolerance of duckweed is above 35°C (Denver Regional Council of Governments, 1994). Thus, high water temperatures in the latter part of August were undoubtedly an additional stress to the duckweed.

Under natural conditions duckweed can usually compete effectively with algae by blocking the light penetration in the water with a thick duckweed mat (Skillicorn et al., 1993). In this study, duckweed coverage was small and confined by the pen 0.4 m^2 so algae outside of the pens likely competed with the duckweed for nutrients and light. However, the pH values (9.05, 8.01, and 8.74) of water samples, at weeks 3, 5, and 8, respectively, did not strongly

Table 1. *Lemnacea* field performance summary

Pen No.	Collection No. 1	Collection No. 2	Collection No. 3
	% Algal Material		
1	0	> 5	10
2	0	> 5	5
3	0	> 5	5
4	0	> 5	na*
5	0	> 5	na
	% Live Coverage		
1	100	95	20
2	100	100	75
3	100	100	75
4	0	10	15
5	0	0	0
	Wet Biomass (g/m^2)		
1	275	345	10
2	295	315	155
3	305	310	95
4	0	0	0
5	0	0	0

* na = not available.
Pen 1. *L. minor, L. Wolffia columbiana Karsten*.
Pen 2. *L. minor*.
Pen 3. *L. minor, L. Wolffia columbiana Karsten, Spirodella polyrhiza*.
Pen 4. *L. minuta* (non-native).
Pen 5. *L Trisulca* (non-native).

support an algal inhibition. Table 1 shows that algal competition within the mat only became an issue in latter August. Algae can increase the pH of the surrounding water inhibiting the growth of other competing plants. (Denver Regional Council of Government, 1994; W. Pool, Personal communication).

Figure 4 shows a general upward trend of TKN concentrations in duckweed tissue, except for week 5 which might be due to the low TKN and NH_3 values in the surrounding water (fig. 2). For week 3, the average TKN in Pen 1 was approximately 1/3 higher than the other pens. In week 5, TKN values fell to their lowest levels in all the pens. In week 8, TKN values were close together in all the Pens, and Pens 2 and 3 had risen to the highest recorded levels in the experiment. The TKN values in Pen 1 were erratic. Pen 2 and 3 tracked very well together, with Pen 2 always having a slightly higher average TKN value.

The phosphorus concentrations in different duckweed species were similar at each harvest, with the exception of week 3 (fig. 5). At week 3, Pen 1 had roughly two times as much phosphorus as Pens 2 and 3, but then it quickly fell. The conclusion week (8) ended with the phosphorus levels being fairly evenly distributed the duckweed in Pen 1 contained the least phosphorus. The duckweed in Pen 2 contained the greatest amount of phosphorus (approximately 1/3 higher than Pen 1). The phosphorus concentration in the duckweed tissue increased from levels of approximately 4 g/kg dry weight at preplanting time to levels of 14 to 20 g/kg dry weight after eight weeks, even though the phosphorus content of the surrounding water column seemed to be constant (fig. 2) indicating a possible luxury consumption. One would not expect the "small" amount of duckweed growing in the Pens to have a large effect on the surrounding water column. *Lemna minor* and *S. polyrhiza* located in Pen 3 show the most consistent and stable phosphorus removal rate as compared to Pens 1 and 2, throughout the eight-week study (fig. 5).

Future studies should include larger mesocosms, nitrate/nitrite analysis of both the water and duckweed, and possible additions of nitrogen if it becomes limiting to see if growth of the biomass could continue.

Summary and Conclusions

This research suggests that duckweed mixtures can be grown in stormwater detention ponds. Among the species tested, the *L. minor* monoculture (in Pen 2) seemed to have endurance by producing the largest steady biomass density. The polyculture planted in Pen 1 (*L. minor* and *W. columbiana*) removed almost twice as much ammonia and grew most quickly to the single largest biomass density

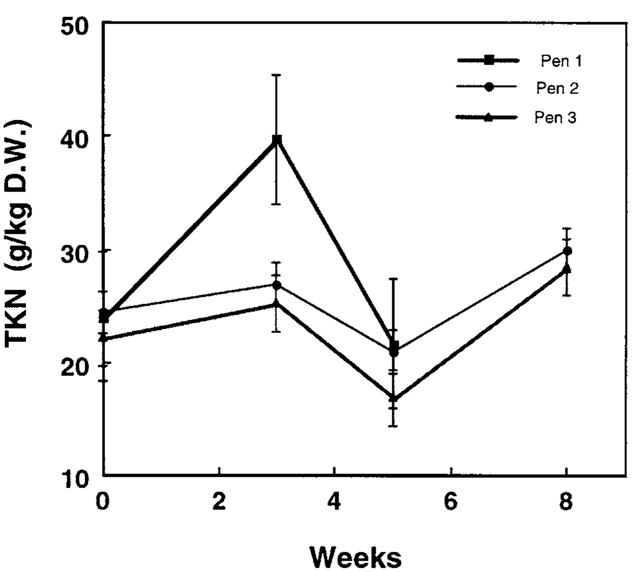

Figure 4–Total Kjeldahl nitrogen level measured in duckweed tissue. Pen 1 = *L. minor, W. columbiana*; Pen 2 = *L. minor*; Pen 3 = *L. minor, W. columbiana, S. polyrhiza*.

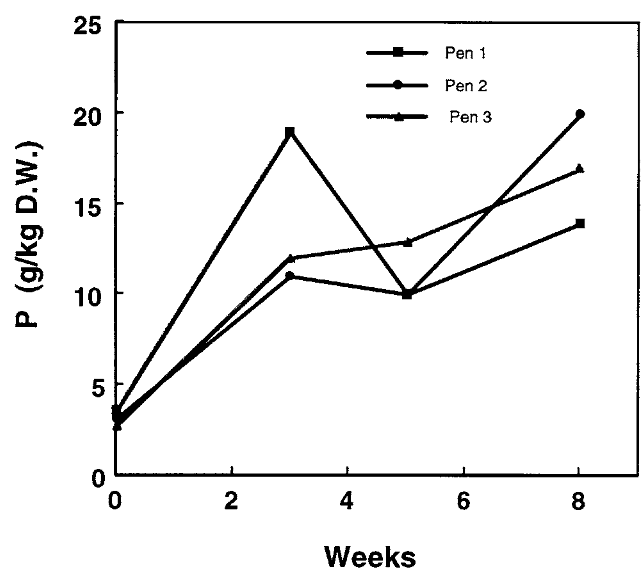

Figure 5–Phosphorus level measured in duckweed tissue. Pen 1 = *L. minor, W. columbiana*; Pen 2 = *L. minor*; Pen 3 = *L. minor, W. columbiana, S. polyrhiza*.

before a significant decrease in production following the second harvest (week 5).

The level of phosphorus incorporated into duckweed varied. Overall, *L. minor* in Pen 1 extracted the greatest amount of phosphorus: at week 3, the phosphorus tissue levels were twice as high as the other two pens, with the exception of week 5 where it fell significantly (fig. 5). Pen 3, *L. minor*, (*W. columbiana* — which died later), and *S. polyrhiza* did not have the erratic phosphorus levels from harvest to harvest as did Pen 1 and increasing at each successive harvest. It is believed that nitrogen became the limiting factor in late summer, following week 5, and caused the biomass collapse. Thus, it should be possible to continue expanding biomass production and remove phosphorus by adding nitrogen sources for duckweed growth in the late summer months. When done appropriately, the nitrogen would be thinly applied to the surface and incorporated into the duckweed mat quickly.

Manipulation of the duckweed species complement may target a nutrient for removal. Depending on the target nutrient to be removed from stormwater, either nitrogen or phosphorus, a culture of *L. minor* or *L. minor* and *S. polyrhiza*, respectively, should be planted. Polycropping provides the most ecologically stable niche for nutrient removal. A polyculture of *L. minor* and *Spirodela* is the most desirable because of its stability (table 1, fig. 5). The non-native species *L. minuta* was able to thrive in the field but *L. trisulca* was unable to thrive even under laboratory conditions. In future experiments it will be necessary to better acclimate laboratory grown duckweed. Future experiments should incorporate multiple replicates into the experimental protocol.

The advantage of duckweed systems is that they remove nitrogen and phosphorus, provide an easily harvestable and useful end product and can be grown in most stormwater ponds. Since very small amount of phosphorus is required to sustain duckweed growth nitrogen will likely be the limiting nutrient. Optimal harvesting should occur when the duckweed density reaches from 400 to 800 g/m^2 (Skillicorn et al., 1993). A full-scale duckweed stormwater treatment system has been attempted with mixed success near Denver, Colorado (Denver Regional Council of Government, 1994). The major hurdle appears to be active versus passive oversight of the systems. For example, when an arrested growth phase occurs due to a limiting nutrient, most likely nitrogen, it must be added to the duckweed mat to continue growth. Active oversight is more expensive and requires additional training for oversight personnel.

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