UPTAKE ABILITIES AND HYDROLOGIC REGIMES OF SELECTED WETLAND AND AQUATIC PLANTS

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A NON-THESIS PROJECT PRESENTED TO THE GRADUATE SCHOOOL OF THE UNIVERSITY
OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

1998

Abstract

An extensive literature search was performed to collect data pertaining to uptake abilities and hydrologic regimes of selected wetland and aquatic plants. Uptake was determined by examining concentrations of metals (i.e., arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel and zinc) and nutrients (i.e, nitrogen and phosphorus) in aboveground tissue, roots and rhizomes of various wetland and aquatic plants identified from the literature. Areal concentrations and actual uptake rates of these metals and nutrients were also examined to determine uptake abilities. Data pertaining to the hydrologic requirements of the plants identified from the literature, specifically maximum water depths and duration of inundation were also collected and examined. Several submergent macrophytes had the highest concentrations of metals in aboveground tissue including *Myriophyllum spp.* (arsenic, cadmium, cobalt, copper, iron, lead, manganese and zinc), *Elodea canadensis* (arsenic, cobalt and iron), *Hydrilla verticillata* (cadmium and chromium), *Pistia stratiotes* (cadmium), *Ceratophyllum demersum* (chromium, iron and lead) and *Vallisneria spiralis* (chromium and lead). *Myriophyllum spp.*, *Elodea canadensis* and *Ceratophyllum demersum* can all withstand maximum water depths >5.0 m. Of these plants, *Elodea canadensis* tolerated the greatest duration of inundation of 88-95% of the growing season. Floating plants including *Azolla spp.* (cadmium, cobalt, copper, iron, lead, manganese and nickel), *Lemna minor* (copper, iron and zinc), *Spirodela polyrrhiza* (chromium, iron, lead) and *Salvinia natans* (manganese) also concentrated high levels of metals in their aboveground tissue. Floating vegetation has no limit on the depth of water they can tolerate and can all withstand long durations of inundation during the growing season (>85%). Of the data

reported for root concentrations, high levels of metals were observed for *Phragmites australis* (cadmium and zinc), *Bacopa spp.* (chromium and copper), *Typha spp.* (iron, manganese, nickel and zinc), *Scirpus lacustris* (chromium and copper), *Nymphoides spp.* (arsenic, lead and manganese) and *Potamogeton spp.* (lead, manganese and zinc). Elevated levels of metals were found in rhizome tissues of *Typha spp.* (copper, iron, manganese and zinc) and *Phragmites australis* (zinc). Aboveground areal uptake of nitrogen and phosphorus was greatest for floating-leaved emergents, specifically *Nuphar lutea*, *Nymphaea alba* and *Nymphoides peltata*. The highest uptake rates of nitrogen were reported for *Alternanthera philoxerides*, *Eichhornia crassipes* and *Pistia stratiotes*. *Hydrocotyle spp.* and *Pistia stratiotes* had the highest aboveground uptake rates of phosphorus.

Introduction

Constructed wetlands have received much attention due to their ability to reduce influent concentrations of nutrients and toxic metals. Several important processes occur in a wetland that contribute to reducing incoming pollutants and excessive concentrations of nutrients. These include nutrient cycling, absorption and assimilation by plants, filtration, and sedimentation (Hammer, 1997).

Reduction of these constituents is primarily due to microbial activity (Hammer, 1997). Bacteria and fungi are important in treatment wetlands, as they are responsible for assimilation, transformation, and recycling of chemical constituents present in various wastewaters (Kadlec and Knight, 1996). However, plants play an important role as they provide a substrate for microbes and attached algae, oxygenate both the surrounding soil and water, as well as absorb nutrients and toxic pollutants from the wastewater (Hammer, 1997). Numerous studies measuring wastewater treatment with and without plants have concluded that performance is higher when plants are present (Kadlec and Knight, 1996).

Hydrology is the most important component of a wetland as it defines both the structure and the function by: 1) controlling the composition of the plant community and thereby the animal community; and 2) directly influencing productivity in terms of controlling nutrient cycling and availability, import and export of nutrients, and fixed energy supplies in the form of organic particulates and decomposition rates (Hammer, 1997). Therefore, the hydrologic regime (i.e., water depth and duration of flooding) dictates the type of vegetation that can survive in a particular wetland. Plant physiology is strongly influenced by both duration and depth of flooding because of their effect on soil oxygen concentrations, soil pH, dissolved and chelated macro- and micronutrients, and toxic chemical concentrations (Kadlec and Knight, 1996). The effectiveness of a constructed wetland can be enhanced by examining both the hydrologic regime that a plant species can withstand as well as the uptake abilities of that species.

Many studies have been performed on the ability of individual plant species to uptake nutrients and toxic metals. Aquatic plants such as water hyacinth (*Eicchornia crassippes*) and duckweed (*Lemna minor*) have been especially noted for their effectiveness in treating polluted wastewater (Stewart et. al., 1986; Moorehead et.al., 1988; Chawla et. al., 1991; Kadlec and Knight, 1996; Wahaab et. al., 1996). However, there are few data that compare uptake abilities among plant species and growth habit (i.e., submergent, emergent, floating, etc.). The objective of this paper is to compare uptake abilities and hydrologic requirements of wetland plants through an extensive literature search. These comparisons can then provide some insight as to which macrophytes may be most suitable for wastewater treatment.

Materials and Methods

Scientific journal articles were the primary source for the data presented in this paper. The majority of articles were obtained from the database of the Center for Aquatic Weeds at the University of Florida. Literature searches were performed for wetland plant nutrient and metal uptake and also for wetland plant hydrologic requirements. Specific information pertaining to wetland plant uptake and hydroperiods was collected when researching each of the articles. The data collected were as follows:

- Constituent of interest (e.g., arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, zinc, nitrogen and phosphorus)
- Vegetation growth habit (e.g., emergent, submergent, etc.)
- Aboveground tissue, root, and rhizome concentration
- Sediment concentration
- Water concentration
- Aboveground tissue, root, and rhizome uptake rates
- Time of year and location of the study
- Water temperature and pH
- Maximum water depth where plant was found
- Duration of flooding during the growing season

Categories used for growth habits included emergent, floating-leaved emergents, floaters, sedges/grasses/rushes, and submergents. Although many grasses/sedges/rushes are considered emergents, there are morphological differences that distinguish between the two categories.

Once the information was collected, a database management system was used to store and retrieve the data. Data for both plant uptake and hydrologic regime were organized by plant genus or species, depending on which was identified in the journal article. Once all the data were entered, it was queried by each constituent (i.e., iron, lead, nitrogen, etc.) identified from the literature search. The data were then further separated and organized by aboveground tissue (AGT) concentration, root concentration, rhizome concentration, AGT uptake rates, root uptake rates, and rhizome uptake rates. Units reported for concentrations, uptake rates, and water depth were then converted to common units for each category. AGT, root, rhizome, and sediment concentrations were all converted to micrograms per gram (ug/g). Milligrams per liter (mg/l) were the units used for water concentration. In several articles, plant uptake rates were reported either with respect to area or time. For uptake reported with respect to area, grams per square meter (g/m^2) were used, while grams per square meter per day ($g/m^2/day$) were used for uptake rates with respect to time. Units used for water depth were meters (m).

Once the unit conversion was completed, a simple statistical analysis (i.e., mean, standard deviation, minimum and maximum values) was computed for AGT concentration, root concentration, rhizome concentration, AGT uptake rates, root uptake rates, and rhizome uptake rates. Only mean values were computed for sediment concentration, water concentration, maximum water depth, and percent inundation.

Results & Discussion

Tissue, sediment and root concentrations, as well as information pertaining to hydrologic regime for various wetland macrophytes identified from the literature are presented in the following sections. The uptake ability of each plant for a particular constituent is suggested by concentrations found in its aboveground, root, and rhizome tissue. Sediment and water concentrations are presented to see how tissue concentrations compare. Rooted and submerged vascular plants can take up substances via the water column, through submerged shoots, or through the roots from interstitial water of the sediment. However, the relative importance of these two pathways for metal and nutrient uptake is not clear, although it is accepted that both pathways may operate in the same plant (Coquery and Welbourn, 1994). It cannot be concluded from the comparisons presented in this paper whether the plant is using the substrate, water column, or both as a source. Since delineating the uptake mechanisms of each individual plant is beyond the scope of this paper, it is difficult to determine whether the substrate or water column is being utilized as a source based on the data. However, if a high sediment or water concentration correspond with a high tissue concentration, it is probable that the plant is utilizing one or both of these as a source.

Ranges of maximum water depths that wetland plant species can tolerate are presented along with AGT, sediment and water concentration data. Average flooding durations, represented as percent of the growing season are presented in Table 1. The values presented were obtained by averaging data found from the literature search.

Plant	Growth Habit	Minimun Flooding Duration (% of Growing Season)	Maximun Flooding Duration (% of Growing Season)
Alternanthera spp.	emergent	85	NA
Eichornia spp.	emergent	90	NA
Glyceria spp.	emergent	50	NA
Hydrocotyle spp.	emergent	62.5	63
Panicum spp.	emergent	25	NA
Pontederia spp.	emergent	63	85
Typha spp.	emergent	52.5	85
Azolla sp.	floating	85	NA
Lemna spp.	floating	88	95
Salvinia spp.	floating	85	NA
Spirodela spp.	floating	88	95
Nuphar spp.	floating-leaved	75	95
Nymphaea spp.	floating-leaved	88	95
Nymphoides spp.	floating-leaved	90	NA
Carex spp.	sedge/grass/rush	56.5	75
Juncus spp.	sedge/grass/rush	63	75
Phragmites spp.	sedge/grass/rush	57	85
Scirpus spp.	sedge/grass/rush	87.5	NA
Ceratophyllum demersum	submergent	51	NA
Egeria spp.	submergent	95	NA
Elodea spp.	submergent	88	95
Fontinalis spp.	submergent	90	NA
Hydrilla spp.	submergent	95	NA
Pistia stratiotes	submergent	85	NA
Potamogeton spp.	submergent	63	95
Vallisneria spp.	submergent	88	95

NA – Not Available
*Flooding durations reported are average values

Table 1. Average flooding duration values for the growing season.

Arsenic

Elodea canadensis and *Myriophyullum verticillatum*, both submergents, concentrated the highest average levels of arsenic (228 and 340 ug/g, respectively) in their aboveground tissue which corresponded closely with sediment concentrations (Figure 1), but did not appear to have a positive relationship with water concentrations (Figure 2).

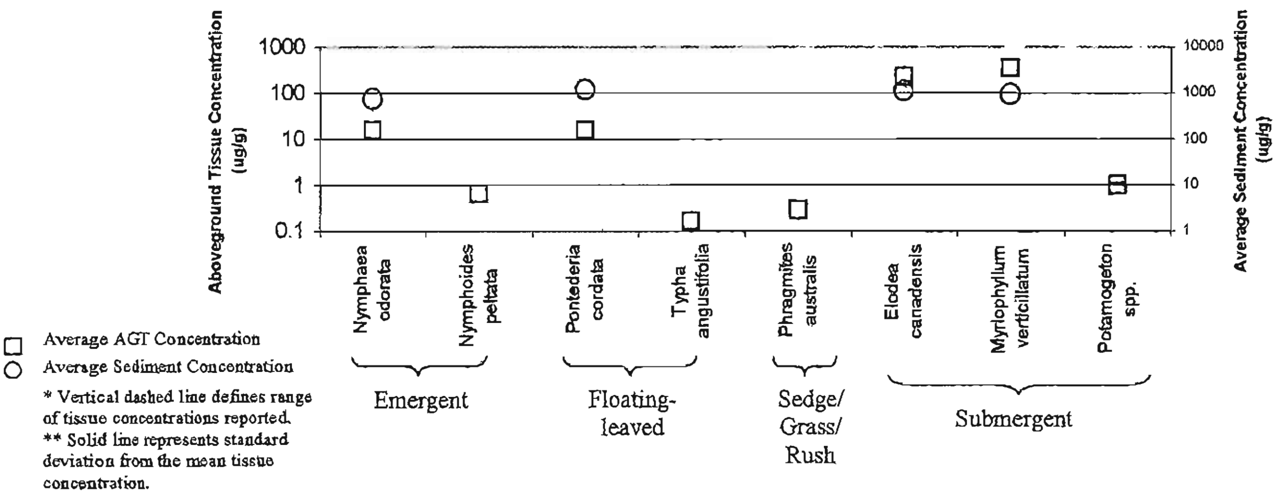


Figure 1. Arsenic concentrations in aboveground tissue and sediment.

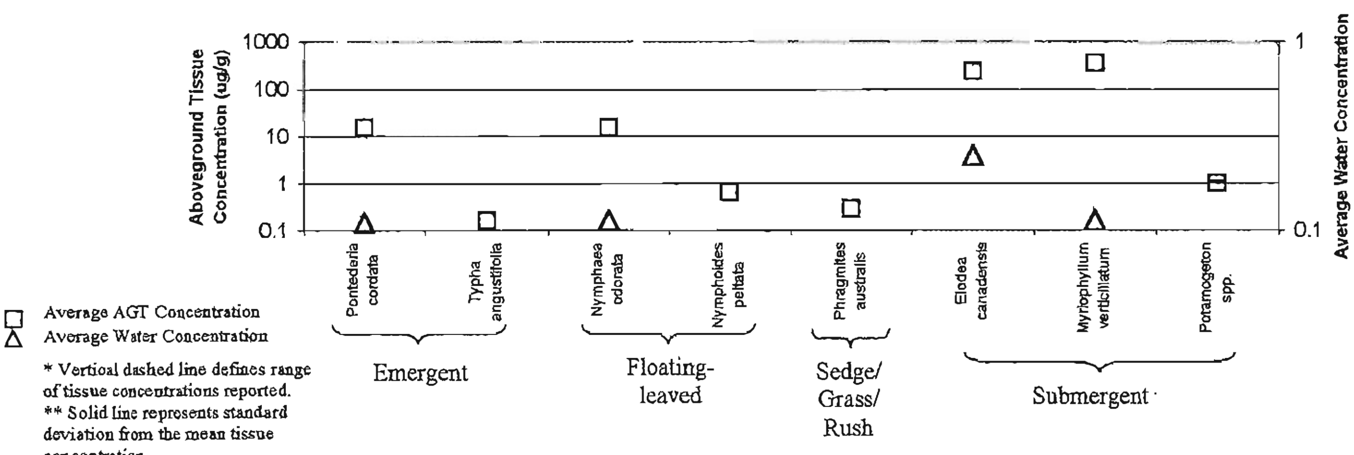


Figure 2. Arsenic concentrations in aboveground tissue and water.

The high sediment and AGT concentrations suggest that *E. canadensis* and *M. verticillata* may be taking up arsenic from the substrate. A similar trend was also observed between average AGT and sediment concentrations for *Nymphaea odorata*, a floating-leaved emergent, and *Pontederia cordata*, an emergent, but at lower concentrations. Overall, it appears that both emergents and submergents have the greater ability to uptake arsenic. *Nymphoides peltata* had the highest reported root tissue concentration (20 ug/g), however, there were no data available for substrate concentrations for this species (Figure 3).

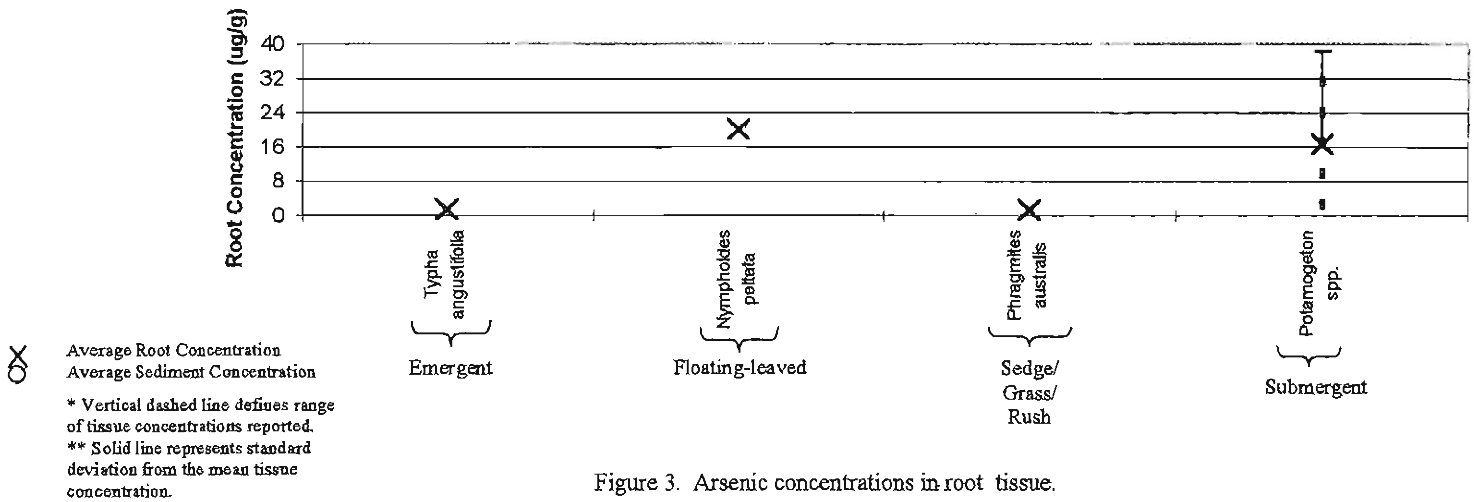


Figure 3. Arsenic concentrations in root tissue.

Ratios of AGT concentration to sediment concentration for both *E. canadensis* and *M. verticillata* were <1.0, whereas ratios of AGT concentration to water concentration were greatest for these species. This suggests that sediment concentrations and AGT concentrations are fairly close and that both species may rely on the substrate as a source for arsenic (Figure 4). *E. canadensis* and *M. verticillata* can also withstand the greatest maximum water depths reported of 6.5 and 5.0 m, respectively. AGT concentrations were at least two orders of magnitude greater than water concentration for all plants, suggesting that these plants are most likely not taking up arsenic from the water column (Figure 5).

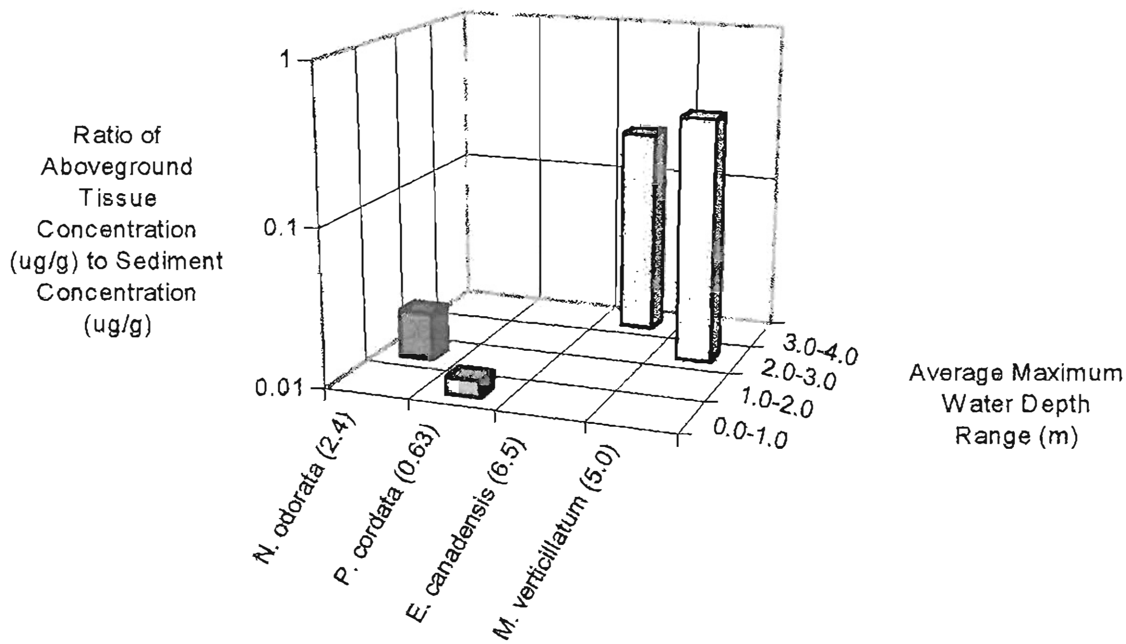


Figure 4. Ratio of AGT concentration to sediment concentration for arsenic and ranges of average maximum water depths.

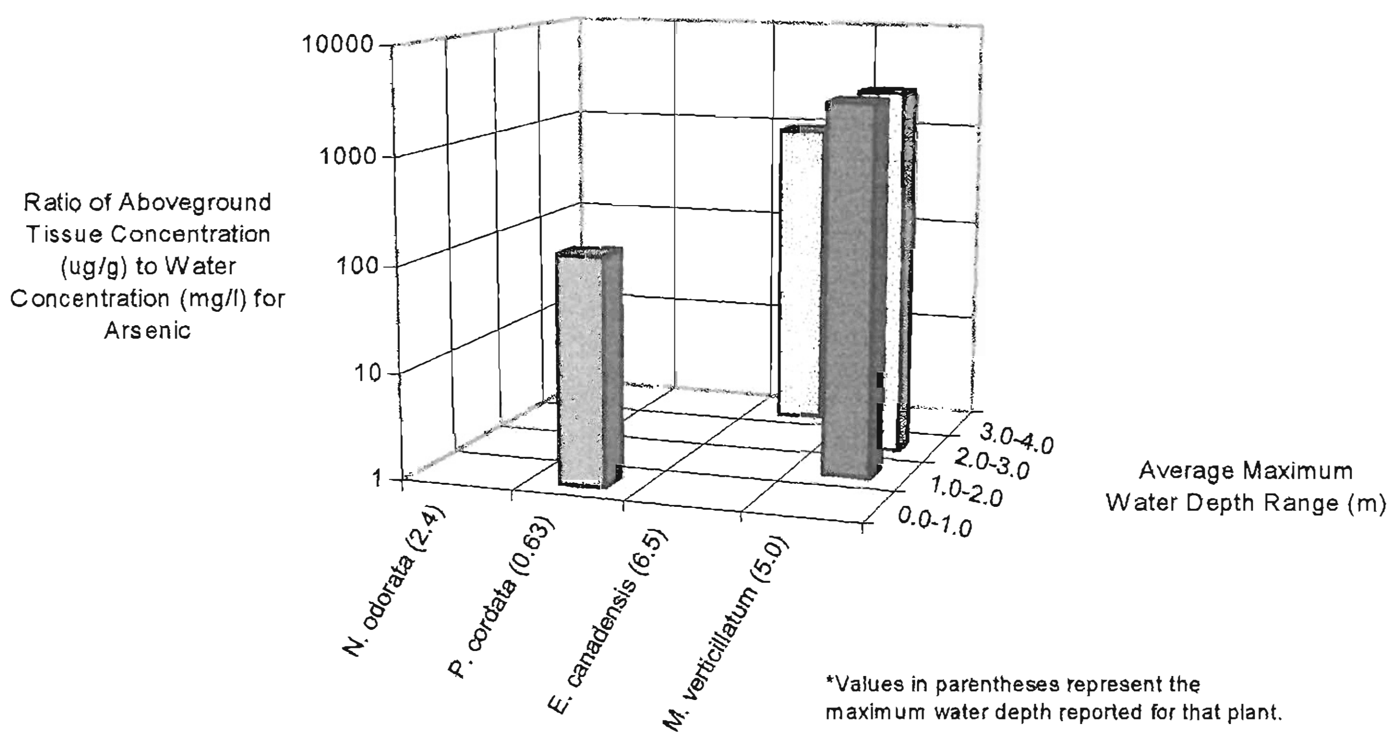


Figure 5. Ratio of AGT concentration to water concentration for arsenic and ranges of average maximum water depths.

Cadmium

The highest average AGT concentrations of cadmium were found in *Myriophyllum spp.* (625 ug/g), *Hydrilla verticillata* (350 ug/g), *Pistia stratiotes* (125 ug/g), all submergents, and *Azolla pinnata* (259 ug/g), a floater (Figure 6). AGT concentrations were greater than sediment concentrations in all cases, implying that these plants may only be absorbing small amounts of cadmium from the substrate.

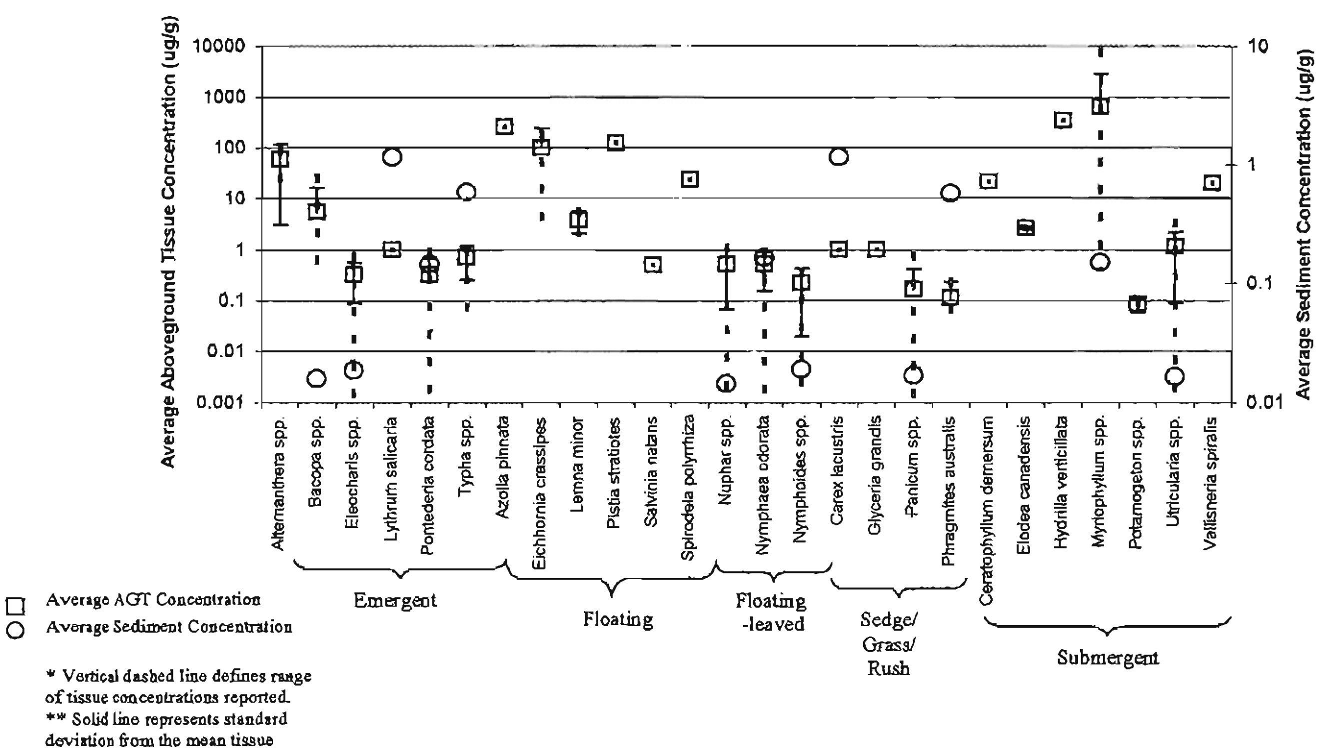


Figure 6. Cadmium concentrations in aboveground tissue and sediment.

Other plants that appear to have an affinity for cadmium include *Alternanthera spp., Eichhornia crassipes, and Spirodela polyrrhiza.* AGT concentrations were also several orders of magnitude greater than water concentrations for all plants (Figure 7), suggesting that these plants may be taking up only small amounts of cadmium, if any, from the water column.

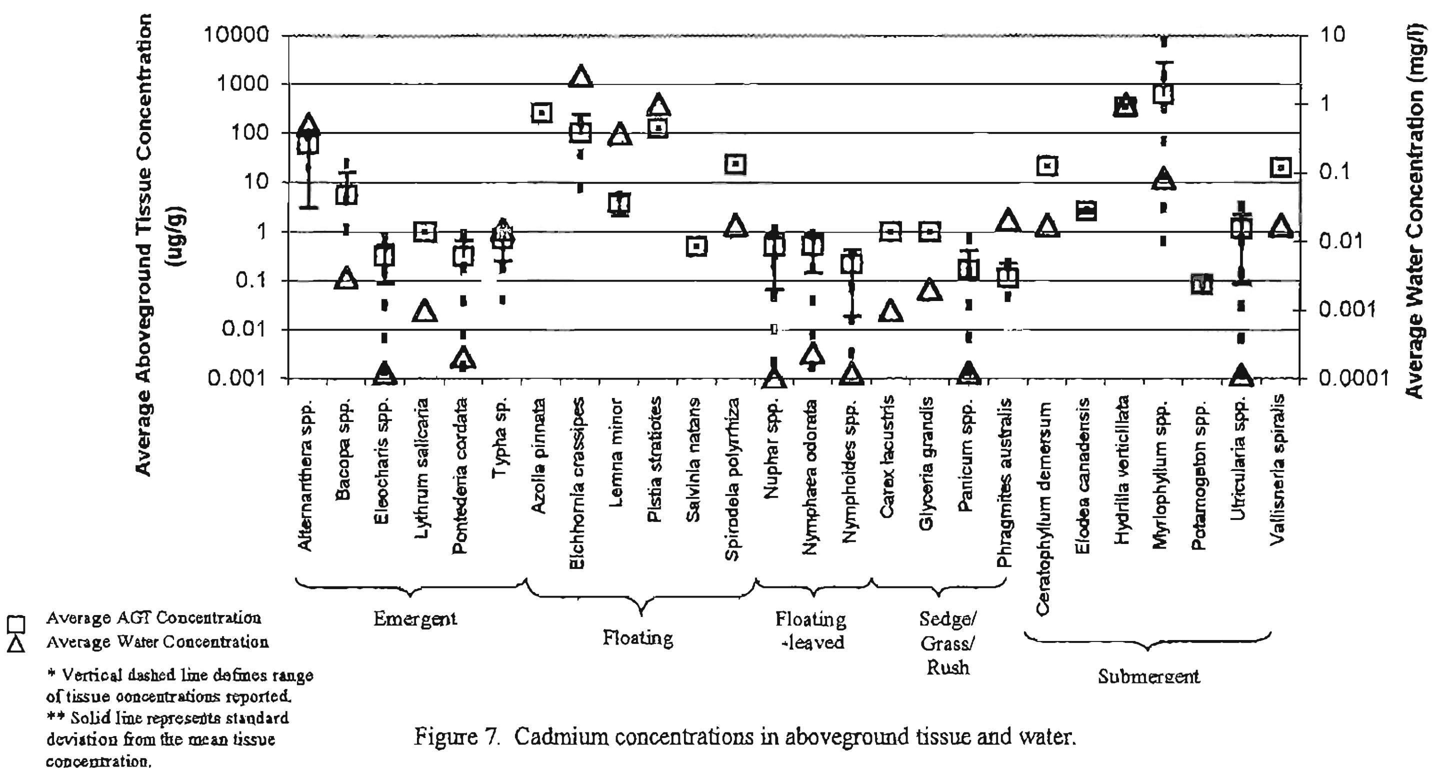


Figure 7. Cadmium concentrations in aboveground tissue and water.

Phragmites australis had the highest average root tissue concentration (0.61 ug/g) which showed a close relationship to sediment concentration and was also greater than AGT concentration (0.112 ug/g) (Figure 8).

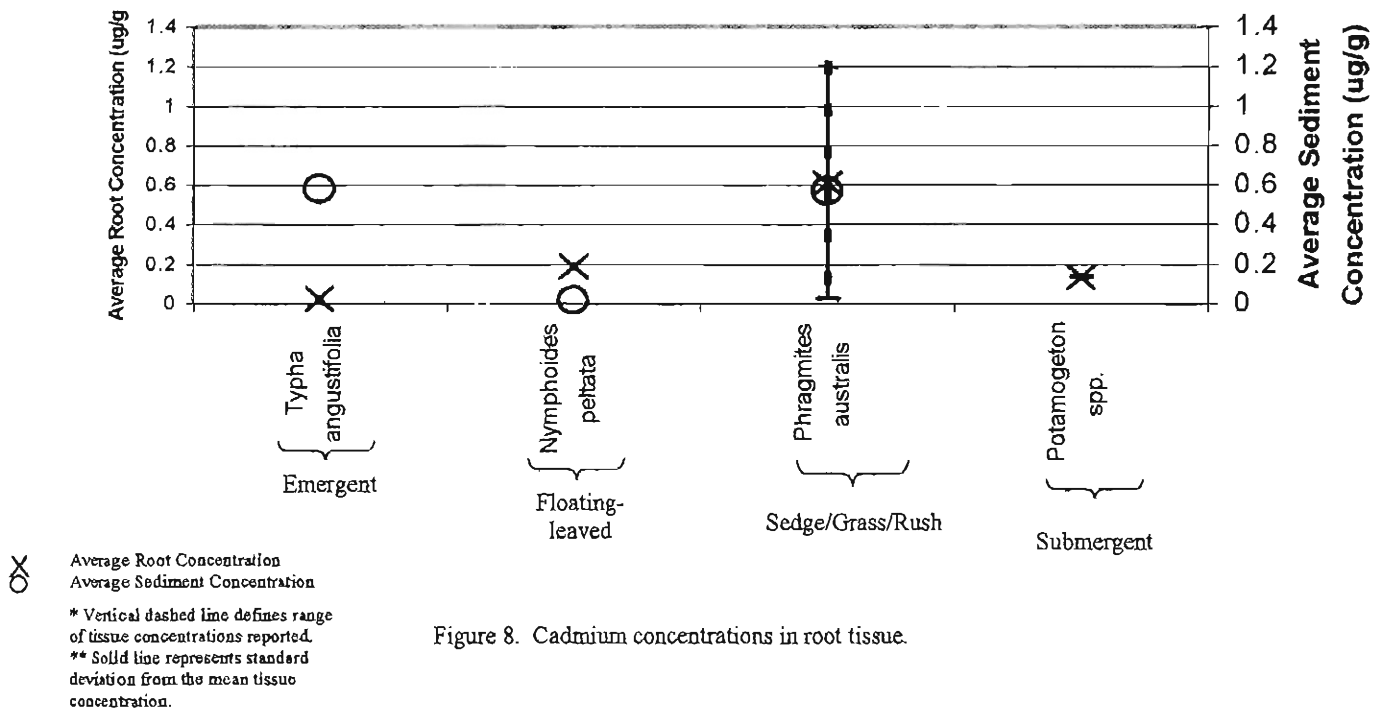


Figure 8. Cadmium concentrations in root tissue.

Average rhizome concentrations (0.16 ug/g) of *P. australis* were fairly close to AGT concentration but less than root concentration (Figure 9).

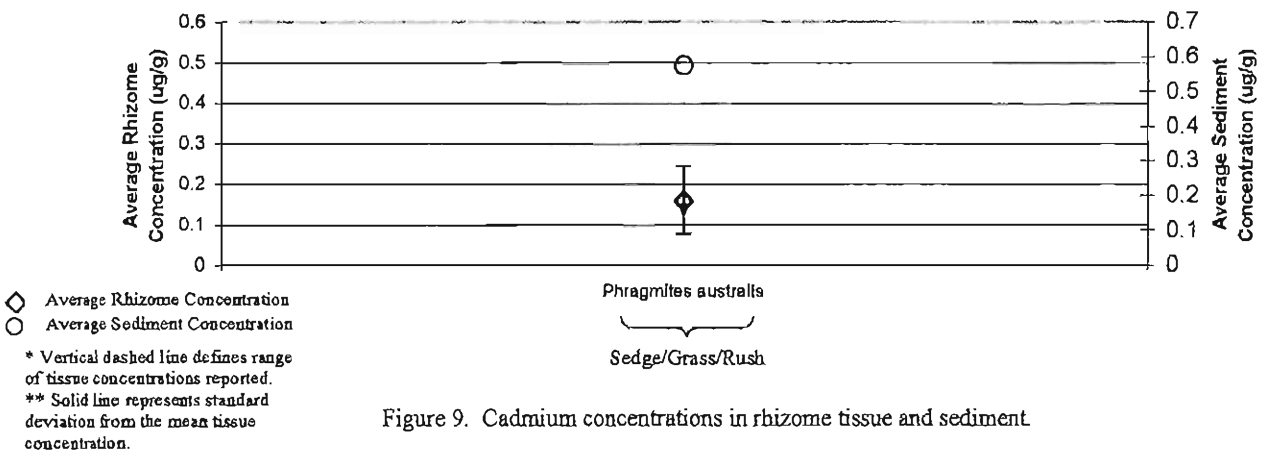


Figure 9. Cadmium concentrations in rhizome tissue and sediment.

In all cases, the ratio of AGT to sediment concentration displayed a closer relationship than AGT to water concentration (Figures 10 & 11). This provides more evidence that

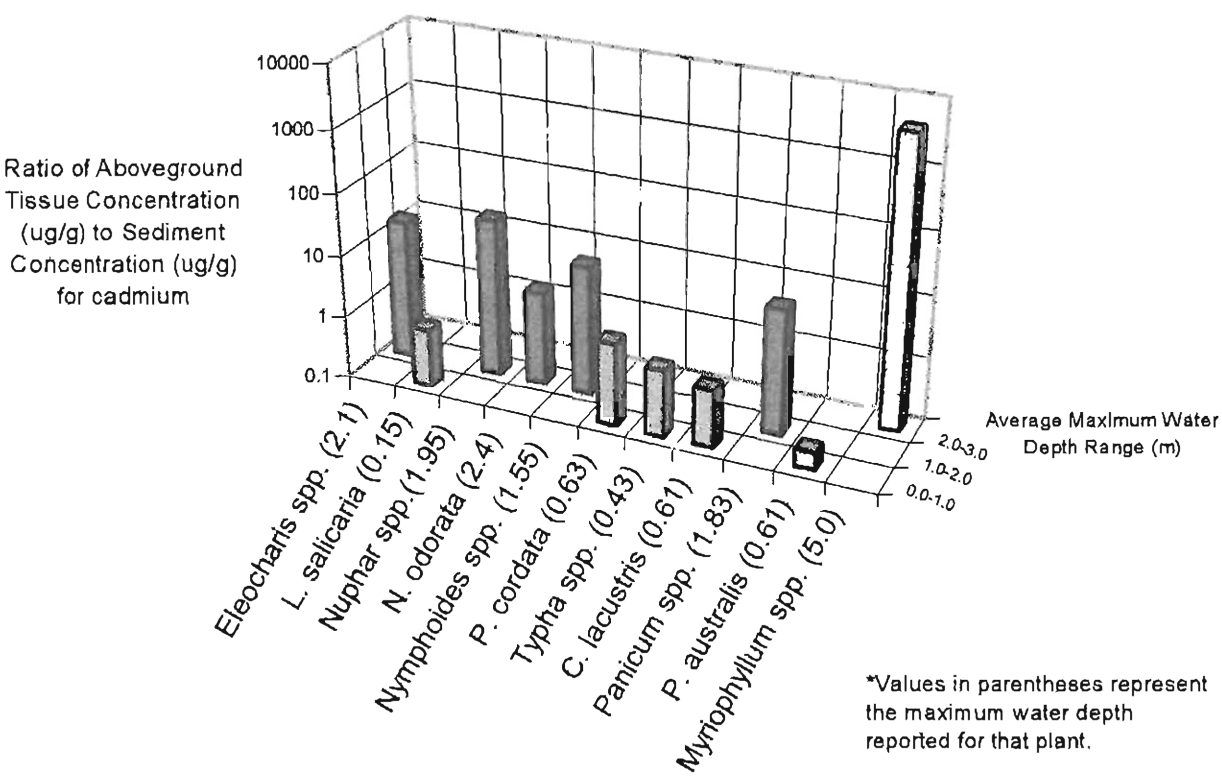


Figure 10. Ratio of AGT concentration to sediment concentration for cadmium and ranges of average maximum water depths.

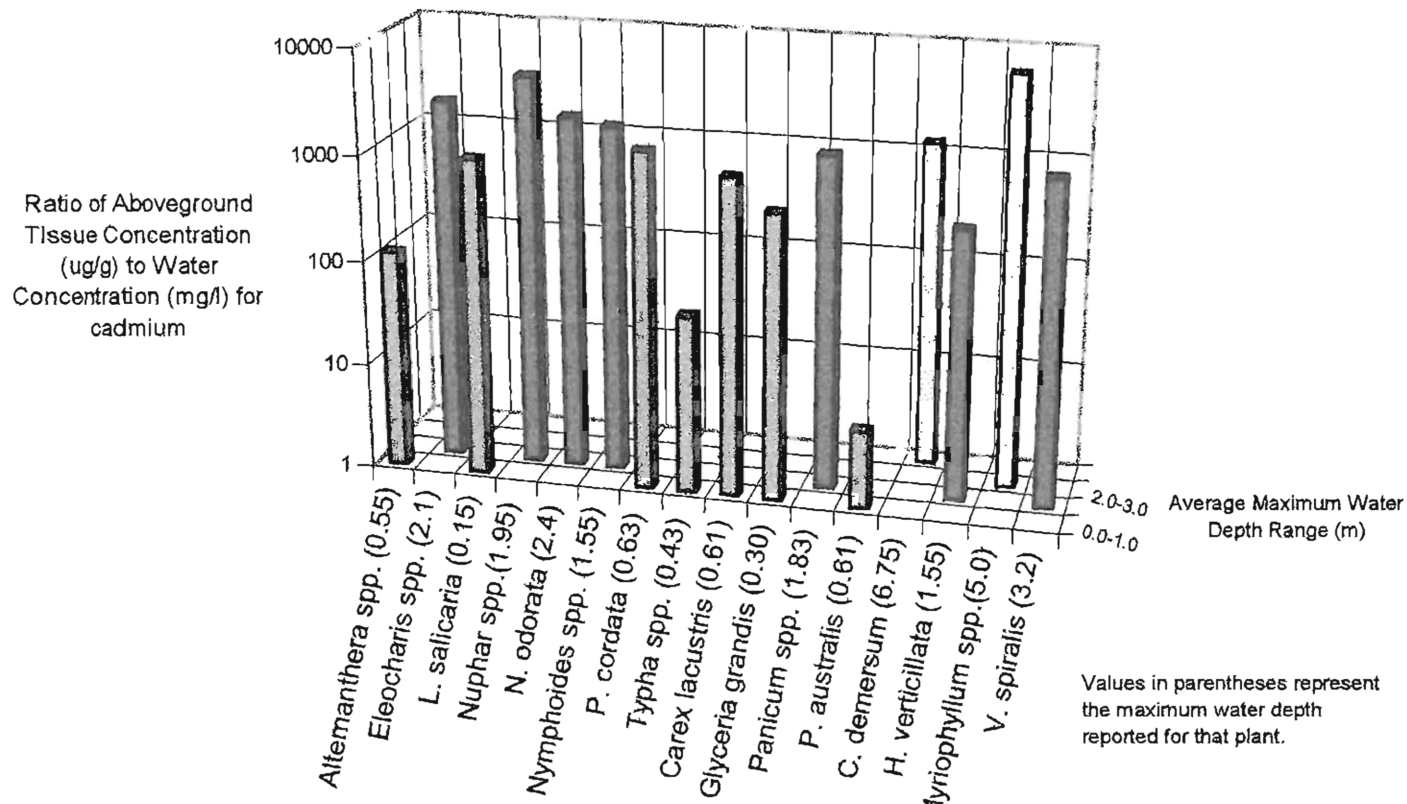


Figure 11. Ratio of AGT concentration to water concentration for cadmium and ranges of average maximum water depths.

the plants may be utilizing the substrate rather than the water column as a source of cadmium. Ratios of AGT to both sediment and water concentration were lowest for *P. australis*, suggesting that this species does not have a high affinity for cadmium.

Chromium

The greatest average AGT concentrations of chromium were reported for *Hydrilla verticillata* (925 ug/g), *Ceratophyllum demersum* (383 ug/g), *Vallisneria spiralis* (311 ug/g), all submergents and *Spirodela polyrrhiza* (395 ug/g), a floater (Figure 12). Sediment concentrations were not available for these species from the literature.

However, for other plants identified from the literature, sediment concentrations were at least one order of magnitude greater than AGT concentrations.

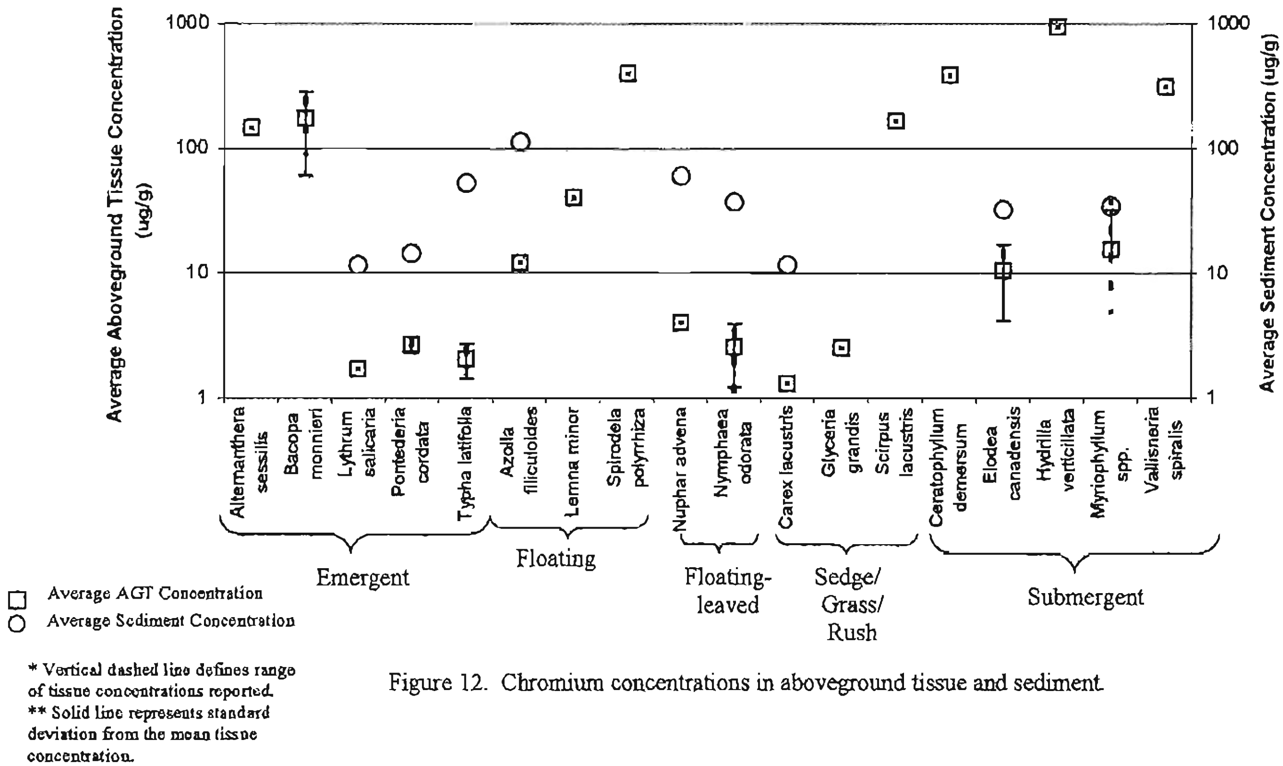


Figure 12. Chromium concentrations in aboveground tissue and sediment.

AGT concentrations of chromium were at least two orders of magnitude greater than water concentrations for all plants identified from the literature (Figure 13).

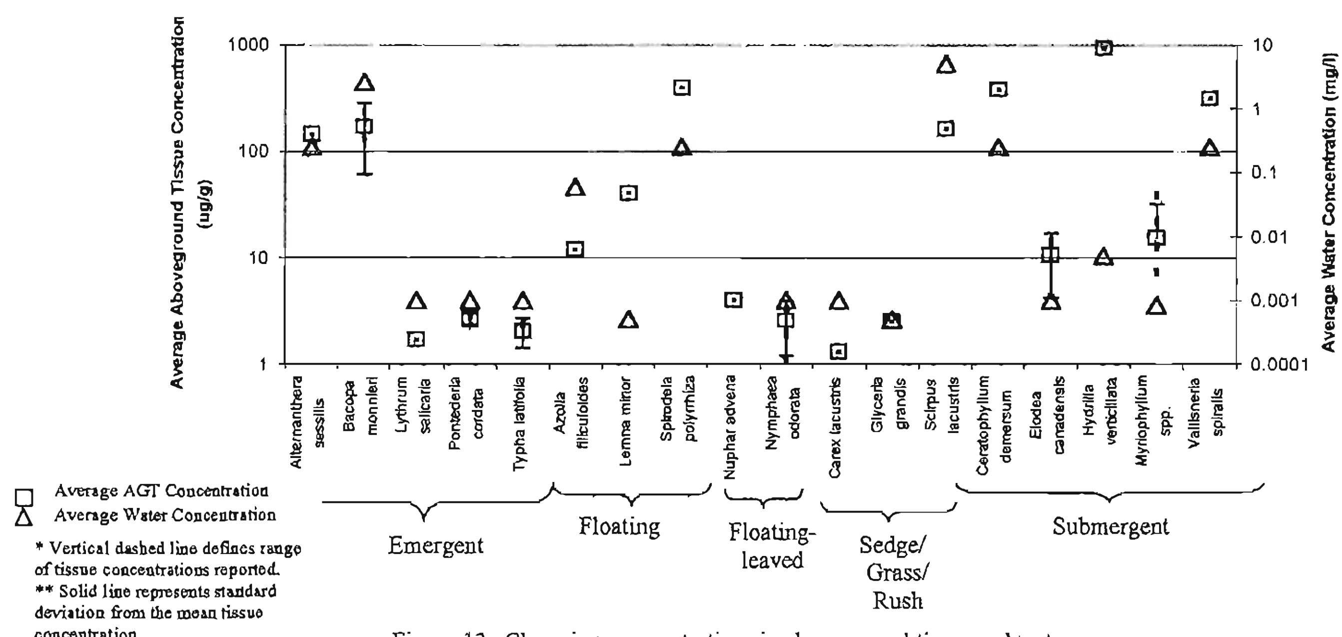


Figure 13. Chromium concentrations in aboveground tissue and water.

Root tissue concentrations for both *Bacopa monnieri* and *Scirpus lacustris* (1,600 and 739 ug/g) were several times greater than their respective AGT concentrations (171 and 163 ug/g, respectively) (Figure 14). Substrate data was not available for these species, however, roots of these plants appear to be more effective in accumulating chromium than AGT.

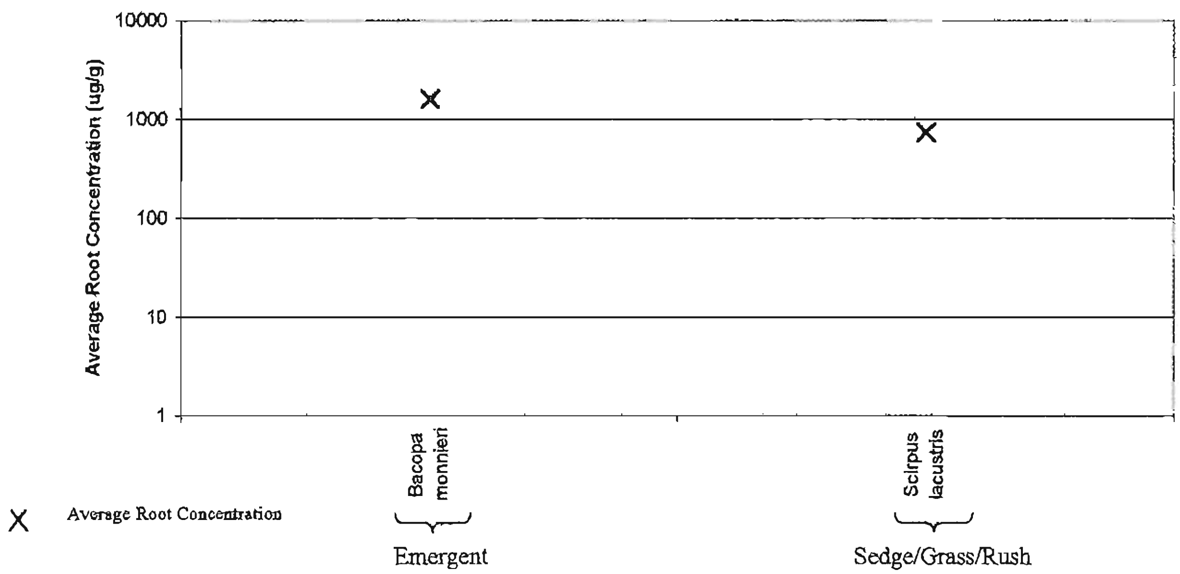


Figure 14. Chromium concentrations in root tissue.

Ratios of average AGT concentration to sediment concentration were all <1.0 (Figure 15) for all plants identified from the literature suggesting chromium may be derived from the substrate rather than the water column. Ratios for *E. canadensis* and *Myriophyllum spp.* were closest to 1.0 suggesting these plants may utilize the substrate more effectively. These plants can also tolerate the greatest water depths reported of 6.5 and 5.0 m, respectively. AGT concentrations were at least one to two orders of magnitude greater than water concentrations for all plants identified from the literature (Figure 16).

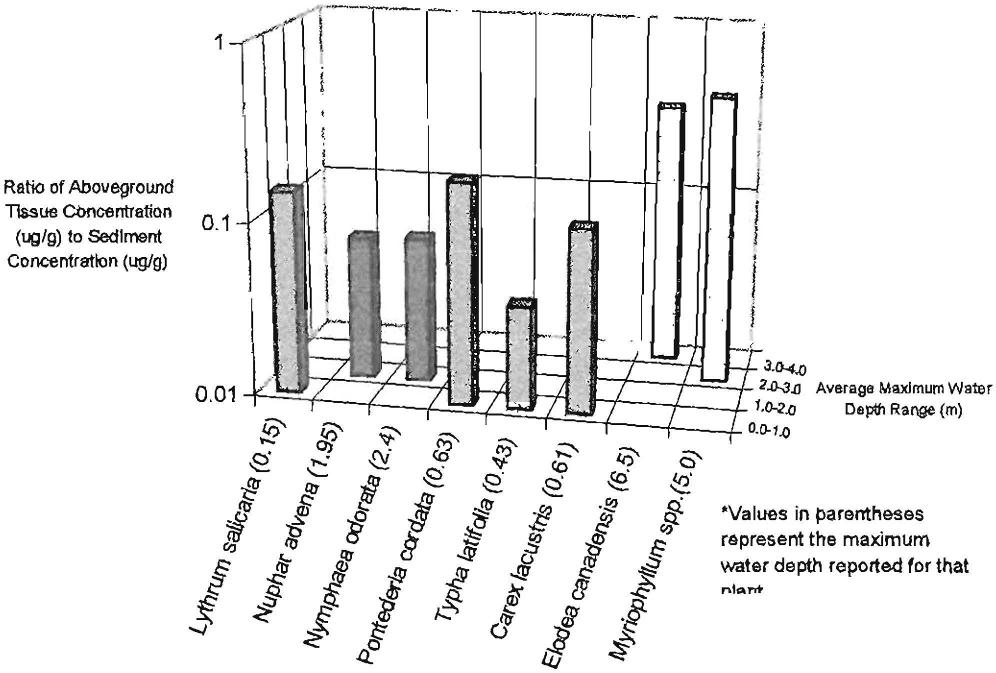


Figure 15. Ratio of AGT concentration to sediment concentration for chromium and ranges of average maximum water depths.

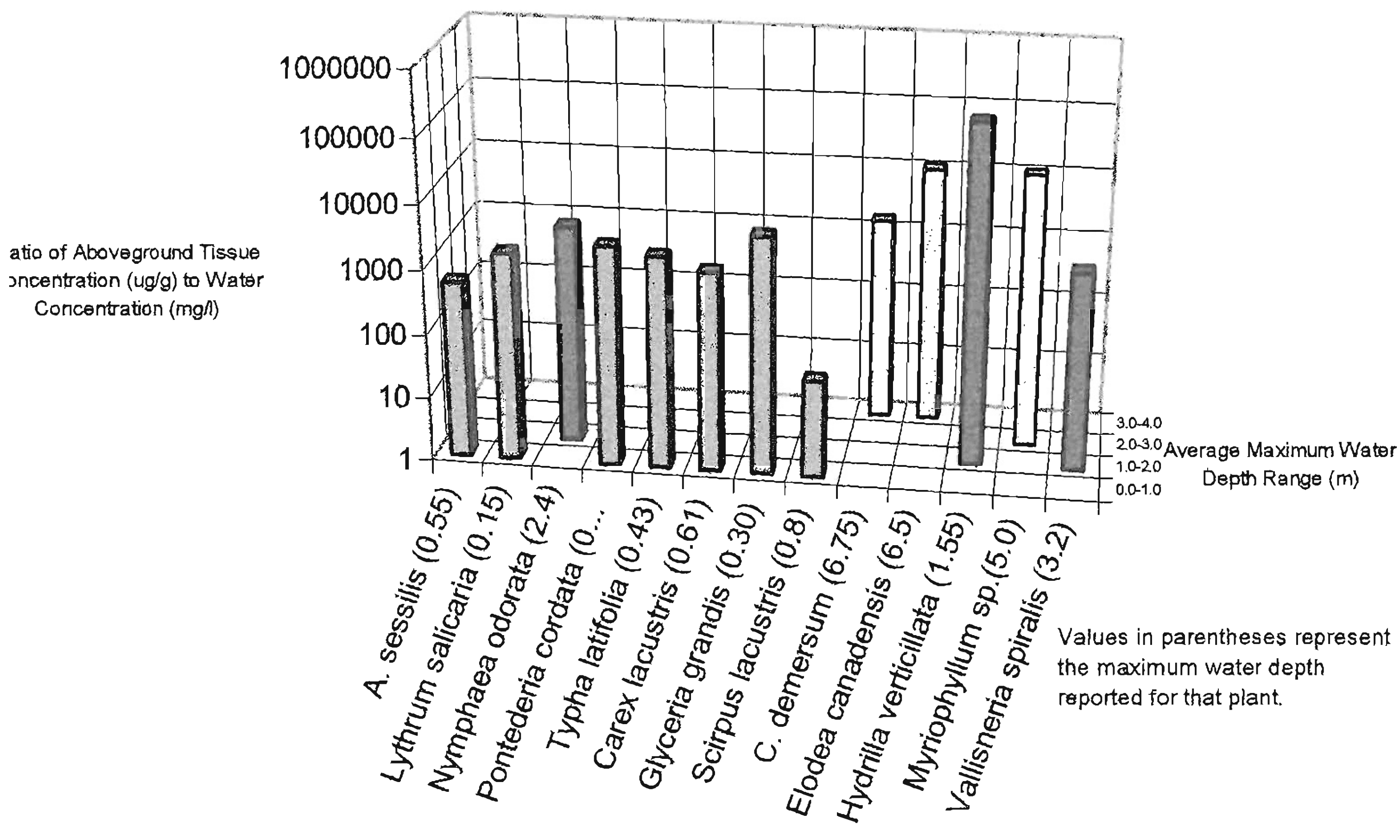


Figure 16. Ratio of AGT concentration to water concentration for chromium and ranges of average maximum water depths.

Cobalt

Azolla pinnata (261 ug/g) and *Myriophyllum spp.* (134 ug/g) had the highest average AGT concentrations of cobalt (Figure 17). Sediment concentrations of cobalt were greater than AGT concentrations for all plants identified in the literature suggesting that the species identified may utilize the substrate to take up cobalt. AGT concentrations for *Pontederia cordata, Elodea canadensis,* and *Myriophyllum spp.* were several orders of magnitude greater than water concentrations (Figure 18).

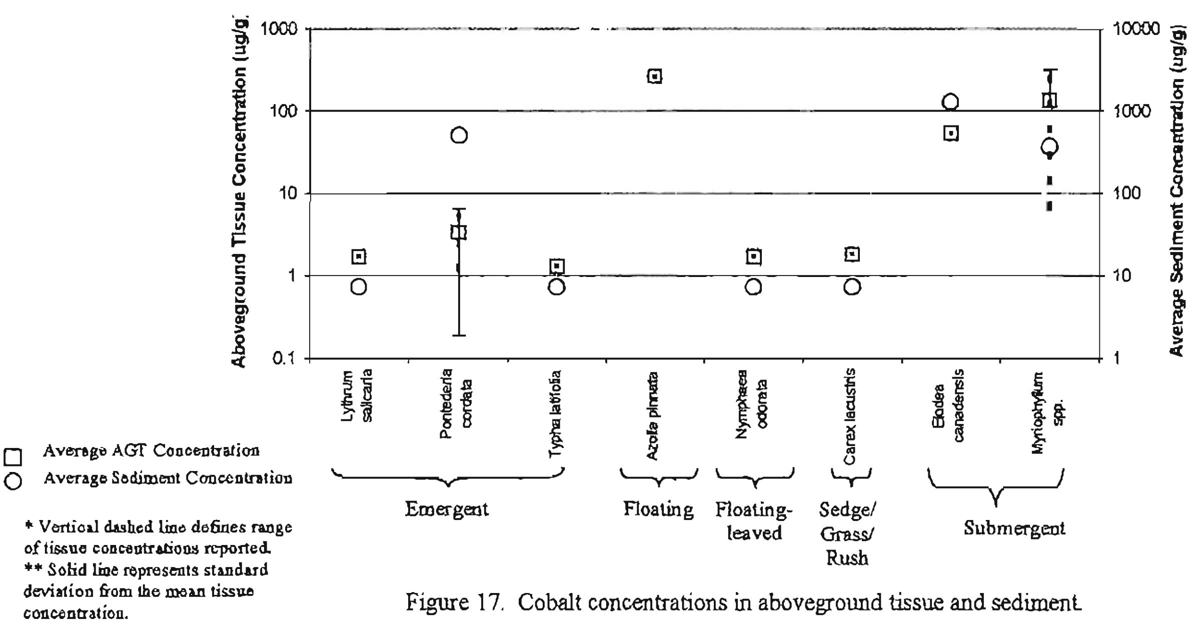


Figure 17. Cobalt concentrations in aboveground tissue and sediment.

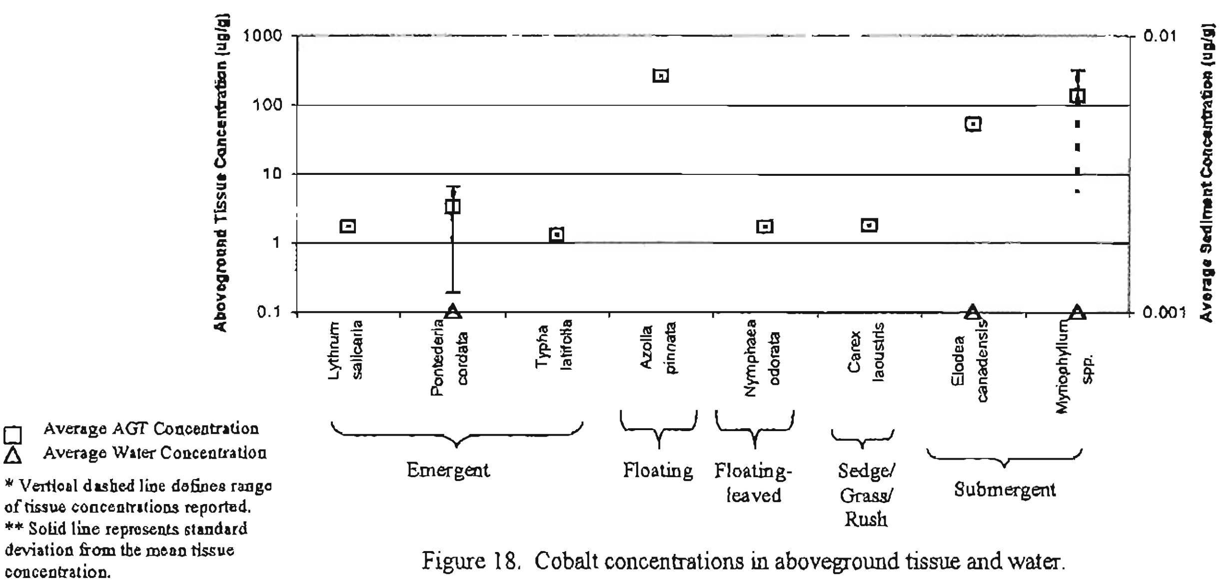


Figure 18. Cobalt concentrations in aboveground tissue and water.

Ratio of AGT to sediment concentration was closest to 1.0 for *Myriophyllum spp.* which suggests that this plant may utilize the substrate as a source of cobalt (Figure 19). AGT concentrations for *P. cordata*, *E. canadensis*, and *Myriophyllum spp.* were all several orders of magnitude higher than water concentrations (Figure 20). Of these plants, *E. canadensis*, and *Myriophyllum spp.* have the highest tolerance of deep water as they can withstand maximum depths of 6.5 m and 5.0 m, respectively.

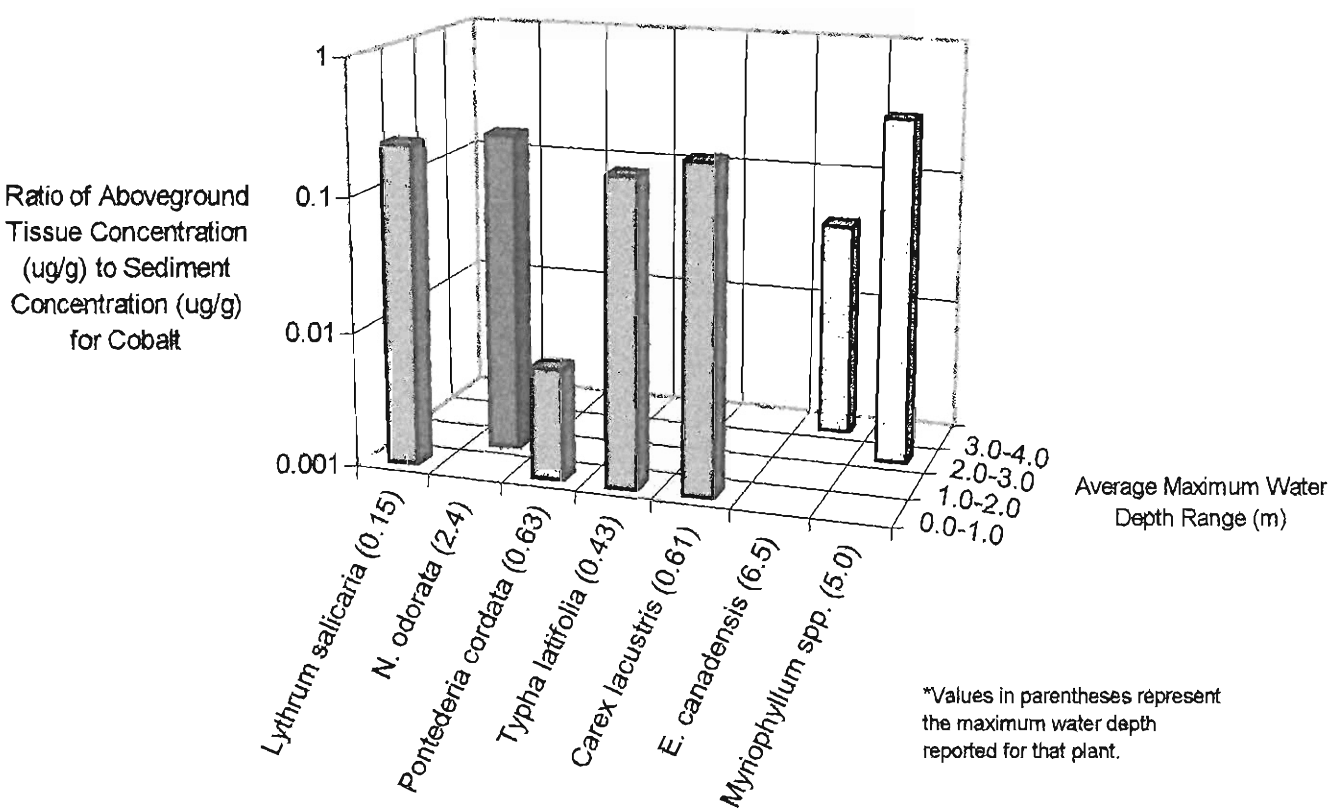


Figure 19. Ratio of AGT concentration to sediment concentration for cobalt and ranges of average maximum water depths.

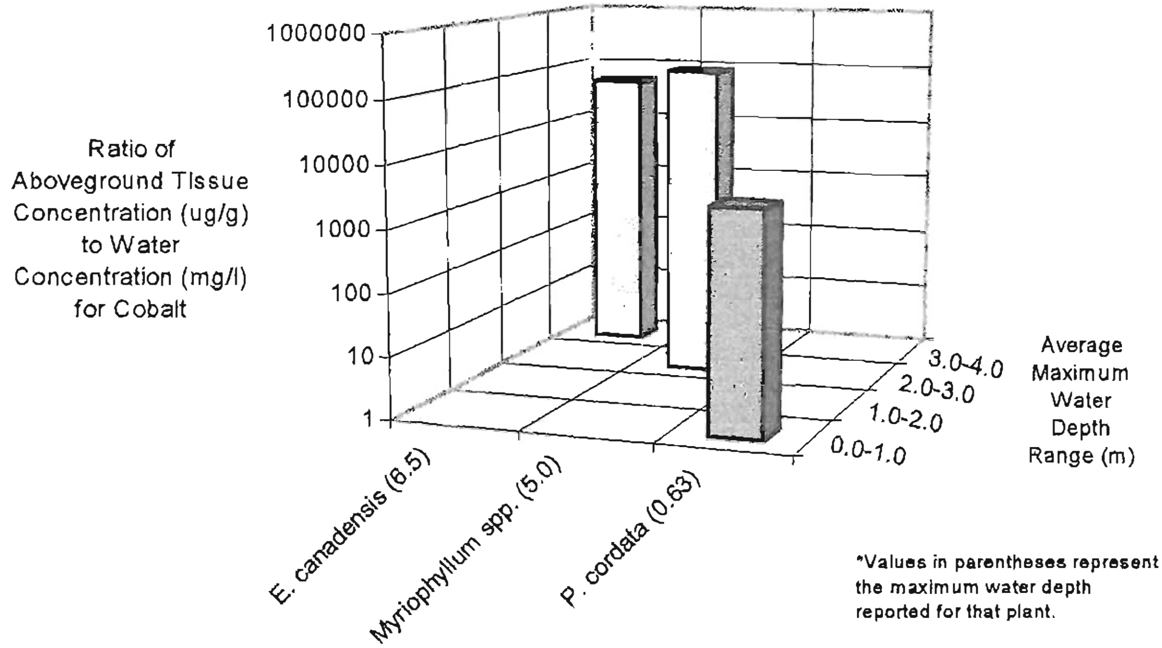


Figure 20. Ratio of AGT concentration to water concentration for cobalt and ranges of average maximcum water depths.

Copper

Lemna minor, *Azolla spp.*, *Scirpus lacustris*, and *Myriophyllum spp.* had the greatest concentration of copper in AGT (11,357, 2,686, 1,369, and 997 ug/g, respectively) (Figure 21). Floating and submergent plants concentrated more copper in their AGT, whereas emergents and sedges/grasses/rushes did not. Sediment concentrations

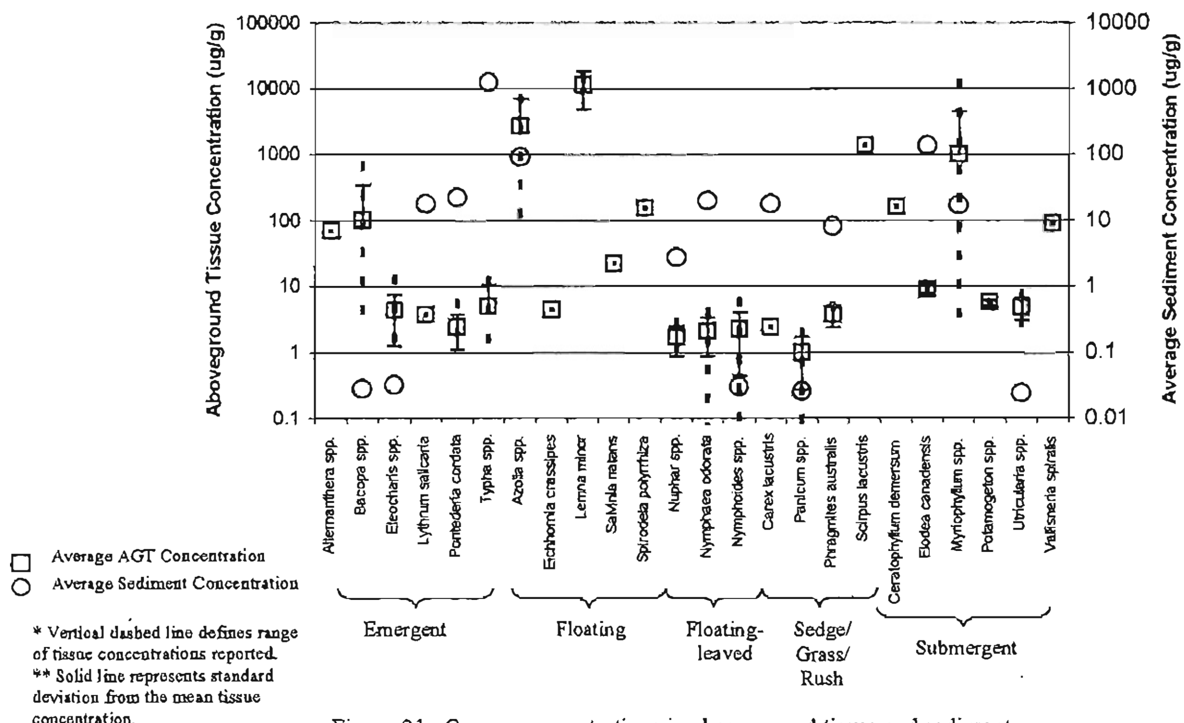


Figure 21. Copper concentrations in aboveground tissue and sediment.

corresponded closely with AGT concentrations for emergents and submergents. AGT concentrations were at least one to two orders of magnitude greater than water concentrations (Figure 22).

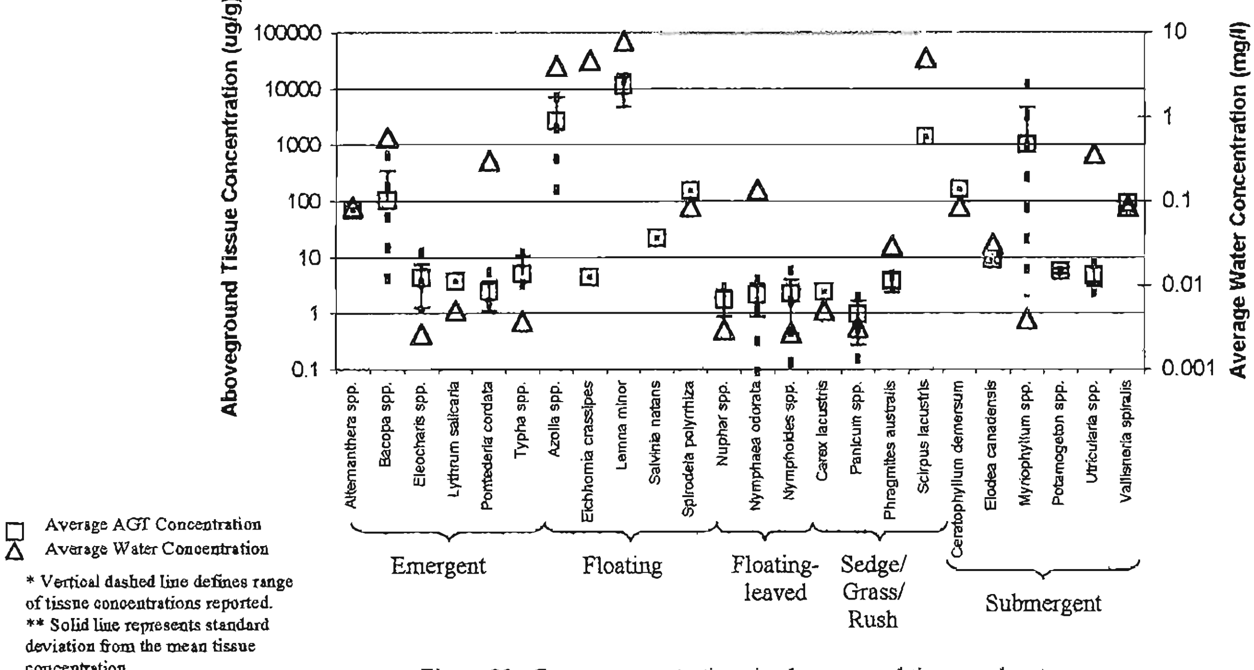


Figure 22. Copper concentrations in aboveground tissue and water.

Bacopa monnieri and *Scirpus lacustris* had the greatest root concentrations (3,821 and 2,030 ug/g, respectively) (Figure 23). Root tissue concentration for *B. monnieri* was

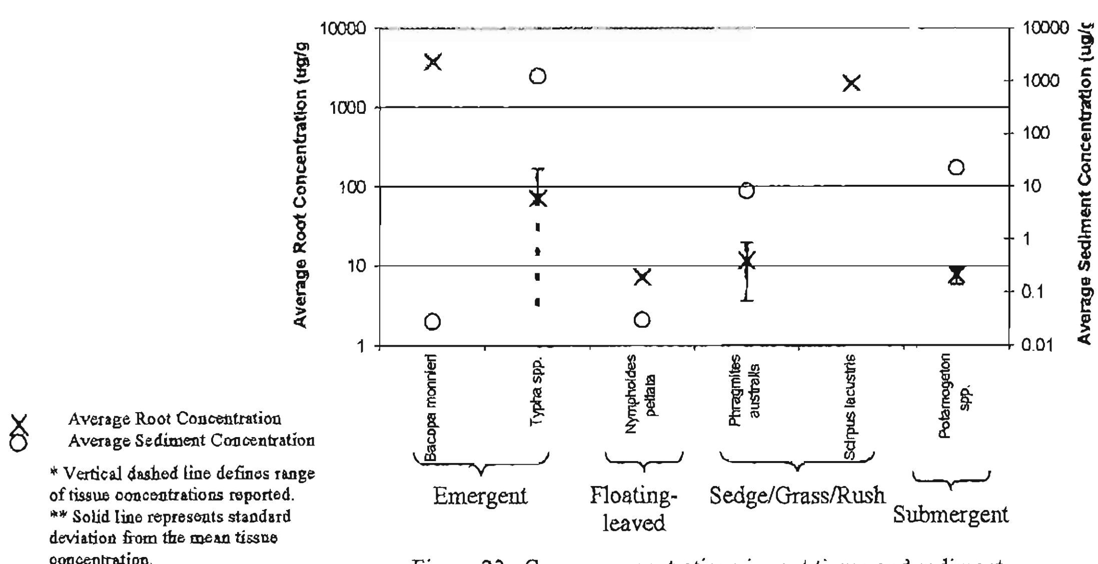


Figure 23. Copper concentrations in root tissue and sediment.

several orders of magnitude higher than sediment concentrations. *Typha latifolia* had a concentration of copper in its root tissue (71 ug/g) which was much greater than the concentration found in AGT (5 ug/g) and rhizome tissue (19 ug/g) of *Typha spp.* (Figure 24).

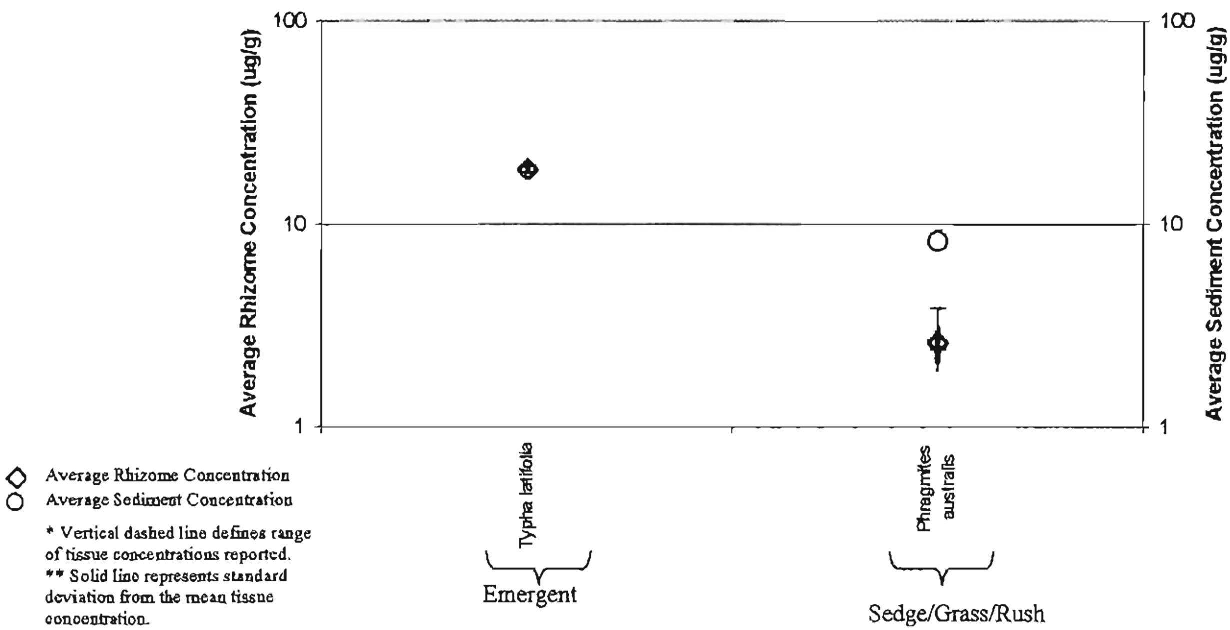


Figure 24. Copper concentrations in rhizome tissue and sediment.

Eleocharis spp., *Nymphoides spp.*, *Panicum spp.*, and *Myriophyllum spp.* were the only plants that had ratios of AGT concentration to sediment concentration that were >1.0 (Figure 25). The ratios for the remainder of the plants identified from the literature search were all <1.0. This suggests that *Eleocharis spp.*, *Nymphoides spp.*, *Panicum spp.*, and *Myriophyllum spp.* may take up less copper from the substrate than other plants identified. The lowest ratios between AGT and water concentrations were observed for

Nymphaea odorata and *Pontederia cordata*, suggesting that these species might absorb some copper from the water column (Figure 26).

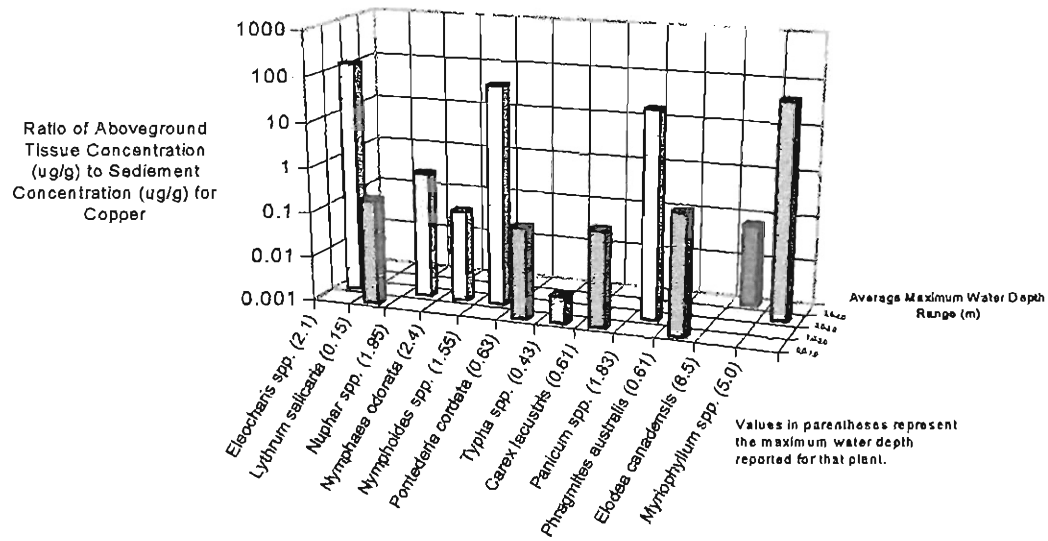


Figure 25. Ratio of AGT concentration to sediment concentration for copper and ranges of average maximum water depths.

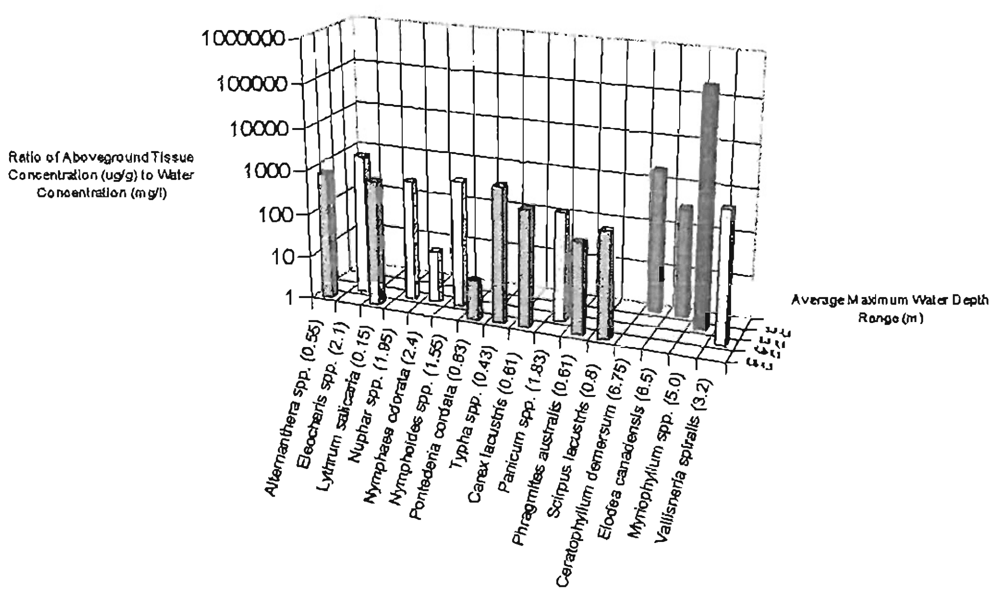


Figure 26. Ratio of AGT concentration to water concentration for copper and ranges of average maximum water depths.

Iron

AGT concentrations of iron were greatest in floating and submergent vegetation. The highest average concentrations of iron in AGT were reported for *Elodea canadensis* (10,250 ug/g), *Ceratophyllum demersum* (5,890 ug/g), *Spirodela polyrrhiza* (5,585 ug/g), *Azolla spp.* (4,800 ug/g) and *Lemna minor* (4,413 ug/g) (Figure 27).

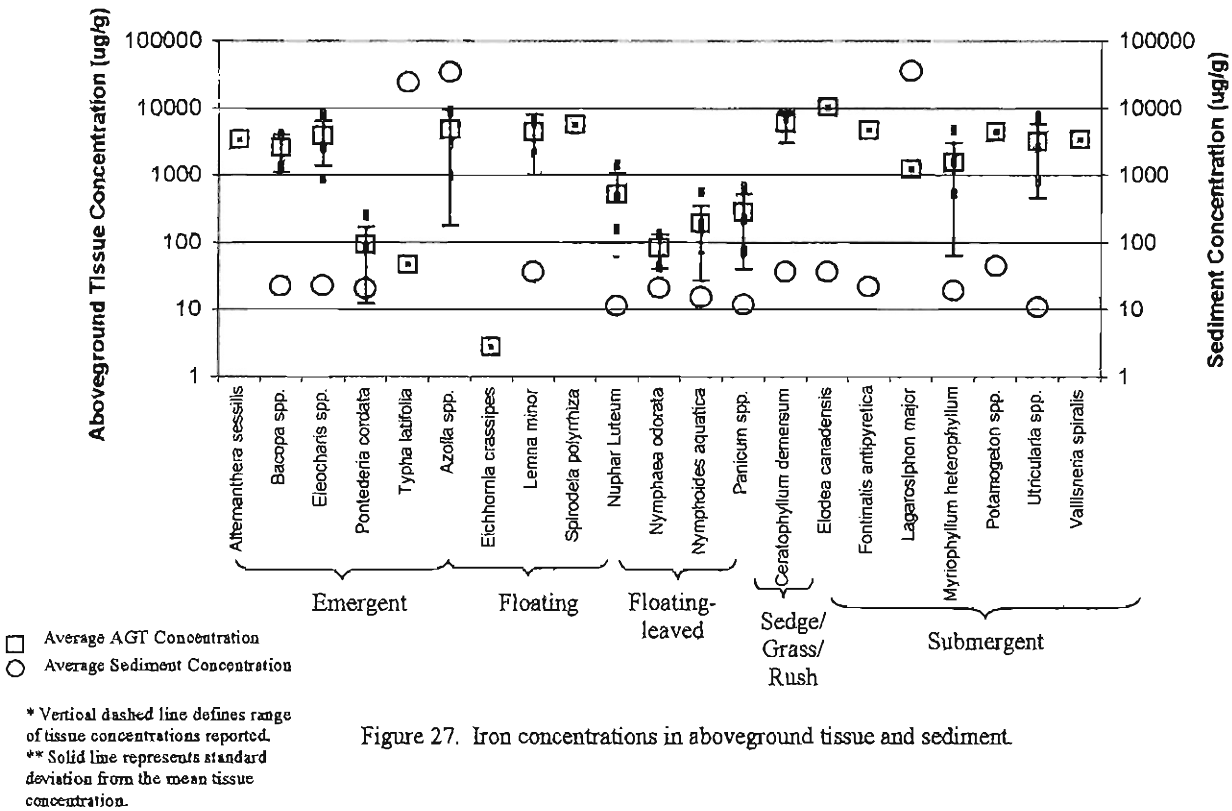


Figure 27. Iron concentrations in aboveground tissue and sediment.

Average AGT concentrations were greater than sediment concentrations for all species identified, except *Lagarosiphon major*. This suggests that many of the plants may be absorbing iron from the substrate but in small quantities. Average AGT concentrations for emergents, floaters, sedges/grasses/rushes, and submergents were all several orders of magnitude greater than water concentrations suggesting that the water column may not play an important role in providing iron to AGT (Figure 28).

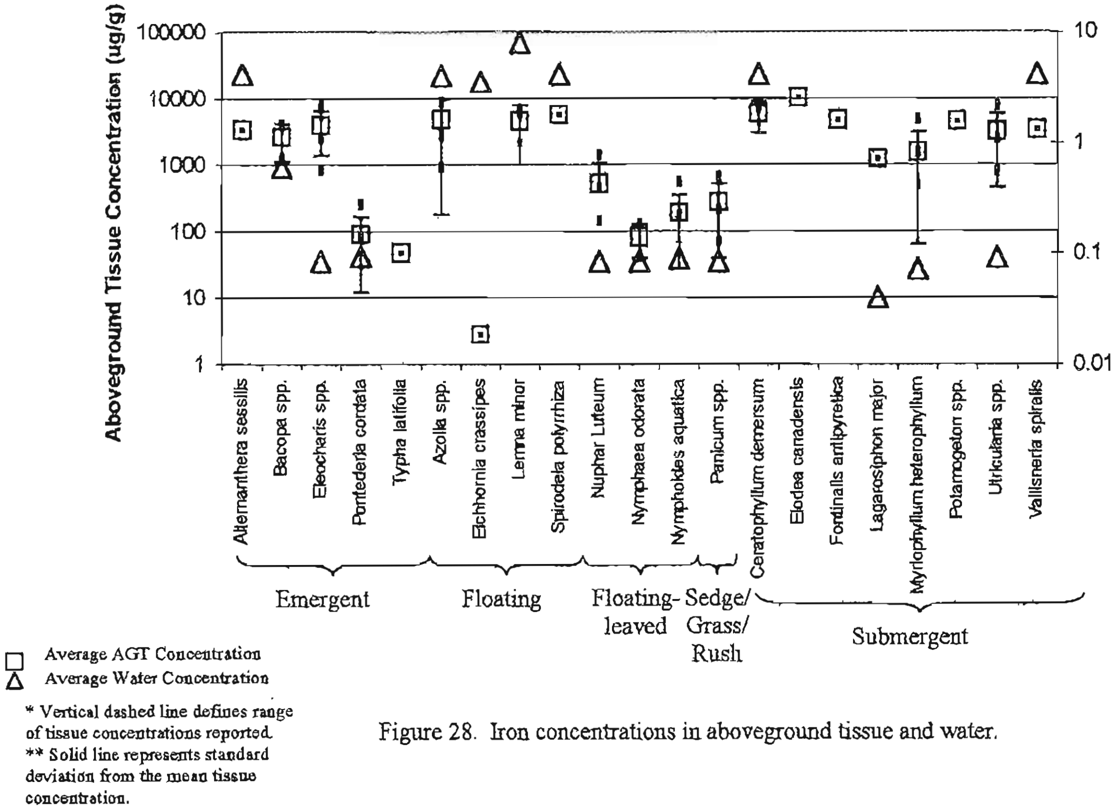


Figure 28. Iron concentrations in aboveground tissue and water.

Typha latifolia had iron concentrations in both its roots and rhizomes (28,958 and 8,634 ug/g, respectively) that well exceeded concentrations in its AGT (47 ug/g) (Figures 29 & 30). Sediment concentrations also corresponded closely with root and rhizome concentrations suggesting these parts are effectively absorbing iron from the substrate.

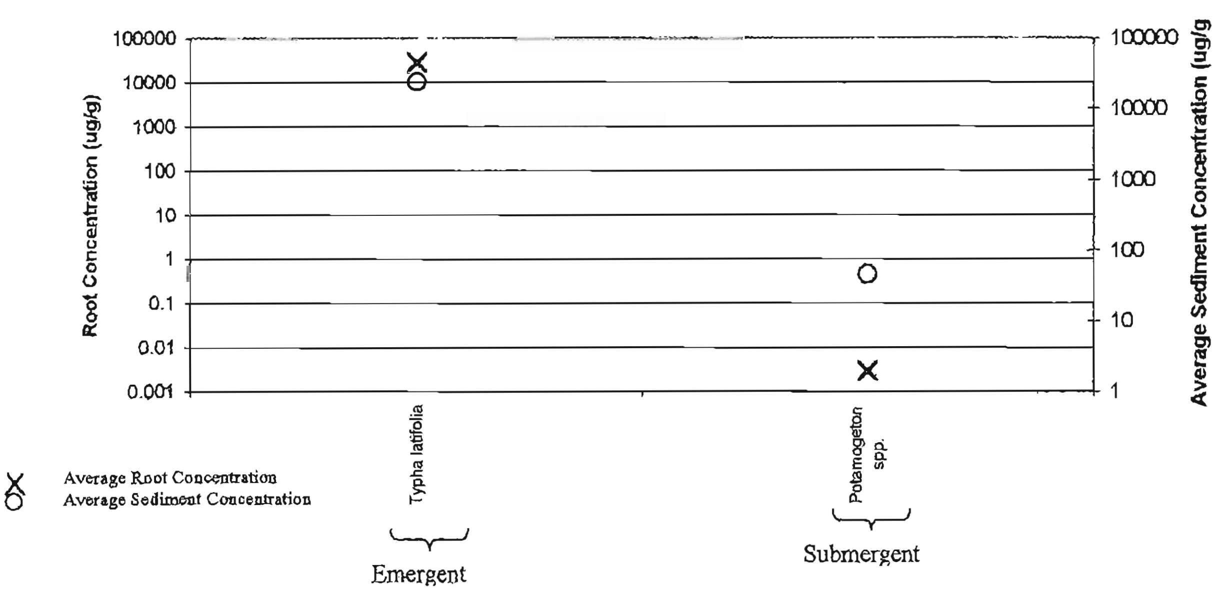


Figure 29. Iron concentrations in root tissue and sediment.

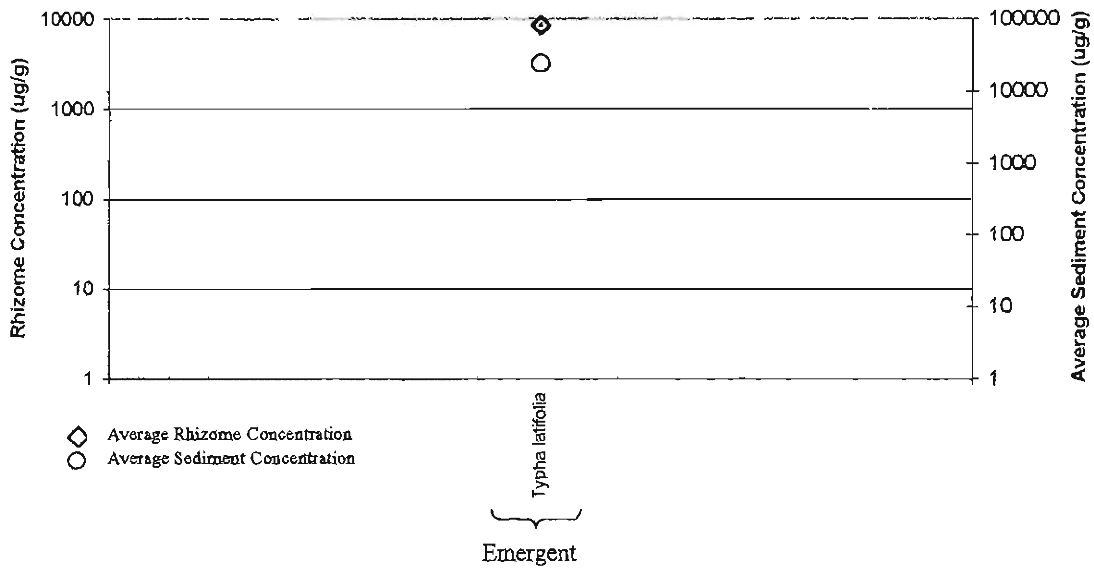


Figure 30. Iron concentrations in rhizome tissue and sediment.

With the exception of *Typha latifolia*, the average AGT concentration was one to two orders of magnitude greater than sediment concentrations, which provides further support that AGT may only be concentrating small amounts of iron from the sediment (Figure 31). Ratios were closest to 1.0 for *Nymphaea odorata* and *Pontederia cordata* suggesting

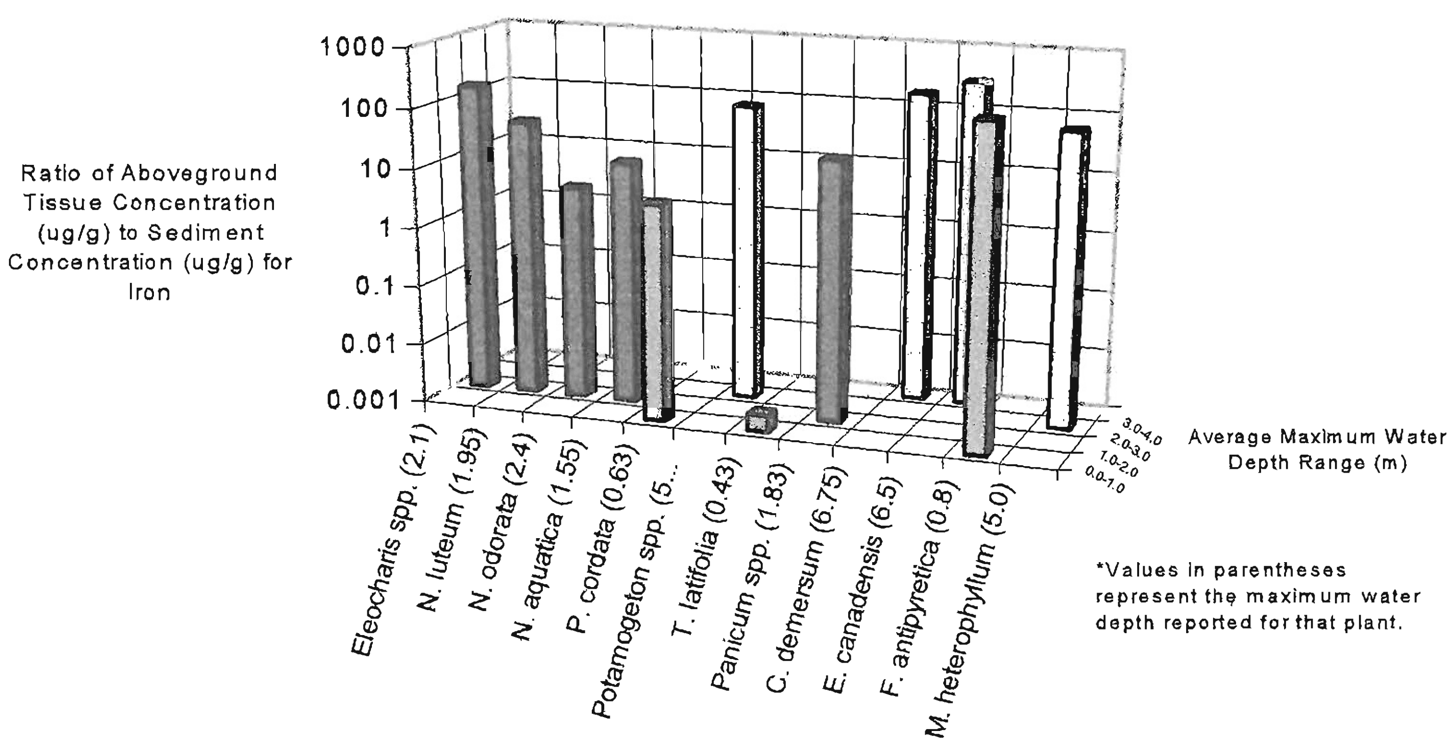


Figure 31. Ratio of AGT concentration to sediment concentration for iron and ranges of average maximum water depths.

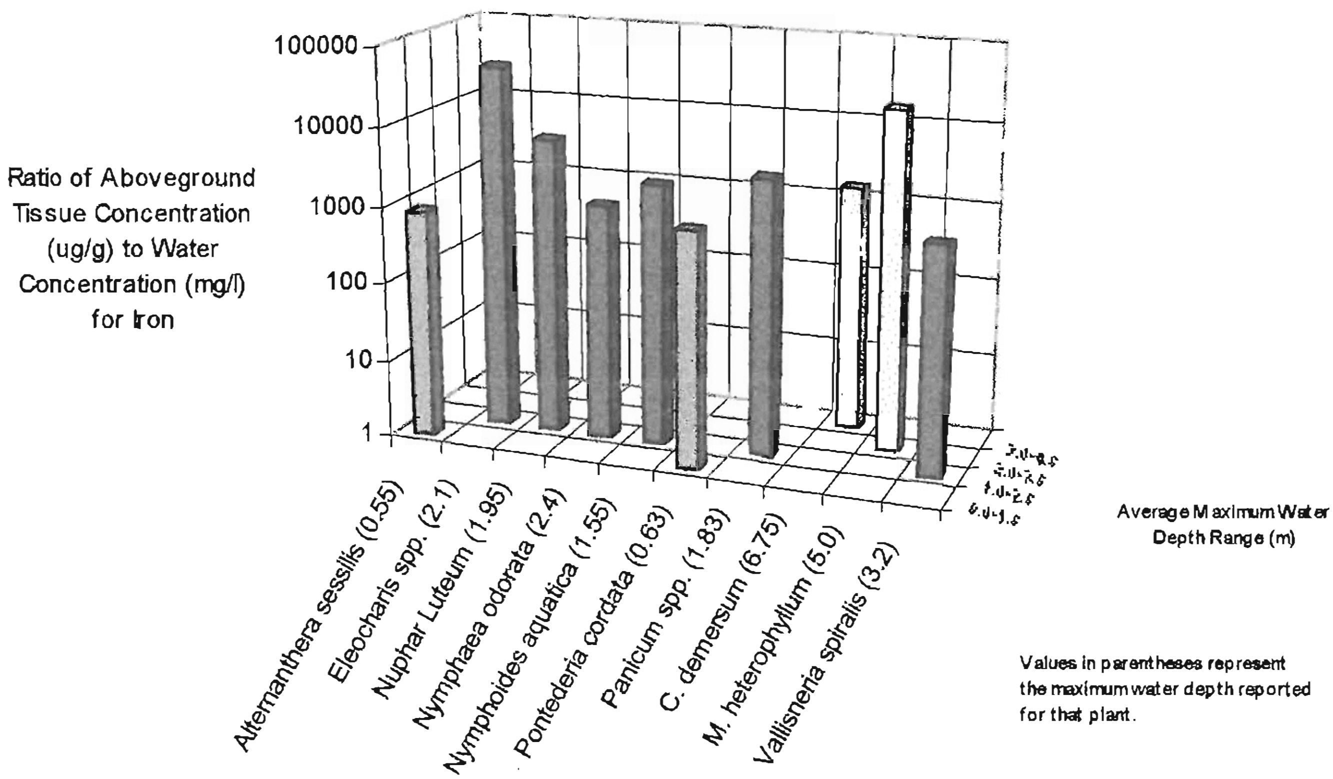


Figure 32. Ratio of AGT concentration to sediment concentration for iron and ranges of average maximum water depths.

Lead

Ceratophyllum demersum, *Myriophyllum spp.*, and *Vallisneria spiralis*, all submergents, had some of the highest levels of lead concentrated in their AGT (2,499, 4,293, and 1,637 ug/g, respectively) (Figure 33). Sediment concentrations were similar to, or slightly

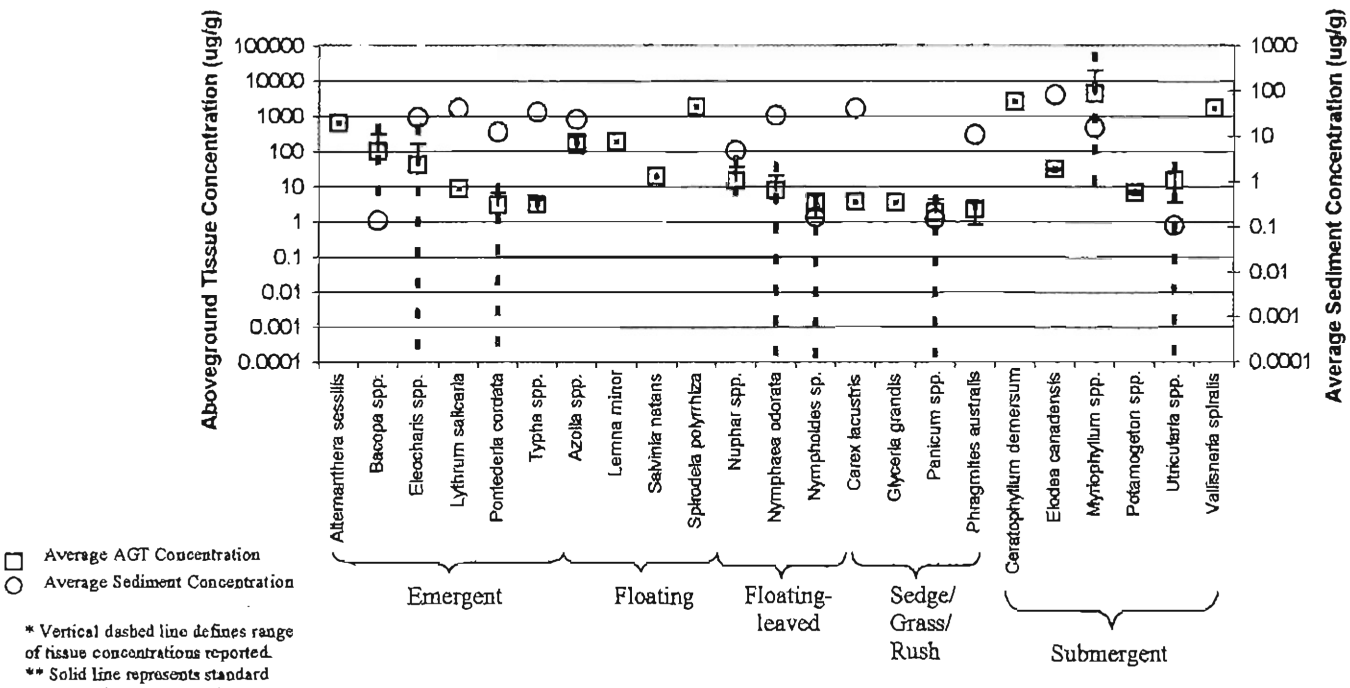
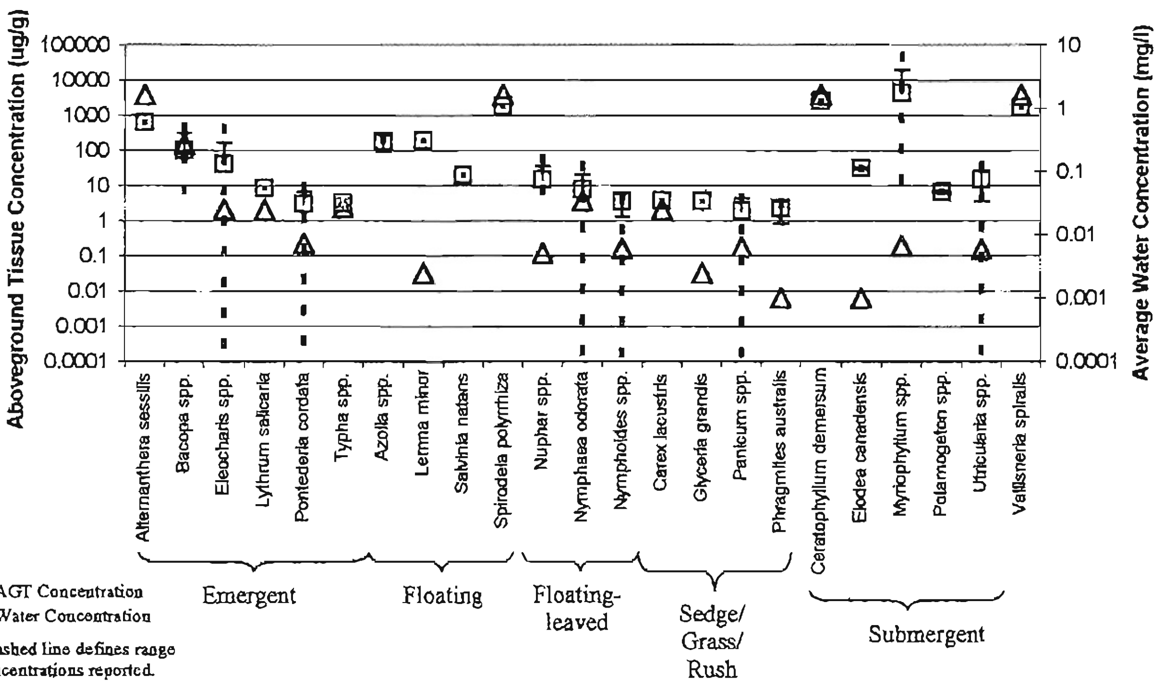


Figure 33. Lead concentrations in aboveground tissue and sediment.

greater than, AGT for several emergents (e.g., *Eleocharis spp.*, *Lythrum salicaria*, *Nuphar spp.*, *Nymphaea odorata*, and *Pontederia cordata*). These macrophytes are most likely accumulating lead in their AGT directly from the sediment. Several floaters, including *Azolla spp.*, *Lemna minor*, and *Spirodela polyrrhiza*, also concentrated relatively high levels of lead in their AGT (182, 190, and 1823 ug/g, respectively). Additionally, *Alternanthera sessilis* also concentrated a high level of lead in its AGT (622 ug/g). Average AGT concentrations of iron were at least one order of magnitude higher than water concentrations for all plants identified throughout the literature (Figure 34).

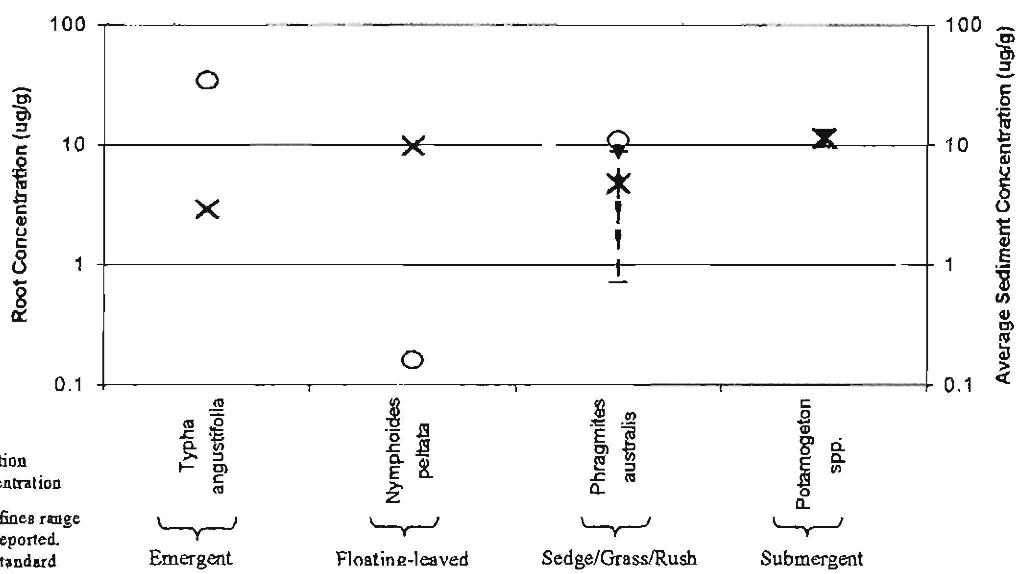


Average AGT Concentration
Average Water Concentration

* Vertical dashed line defines range of tissue concentrations reported.
** Solid line represents standard deviation from the mean tissue concentration.

Figure 34. Lead concentrations in aboveground tissue and water.

Root tissues *of Nymphoides peltata* and *Potamogeton spp.*, both emergents, had the greatest iron concentrations reported (9.8 and 11.5 ug/g, respectively) which was slightly greater than AGT concentration for these species (3.6 and 6.7 ug/g, respectively) (Figure 35).



Average Root Concentration
Average Sediment Concentration

* Vertical dashed line defines range of tissue concentrations reported.
** Solid line represents standard deviation from the mean tissue concentration.

Figure 35. Lead concentrations in root tissue and sediment.

Root tissue concentration of *P. australis* (4.8 ug/g) exceeded both AGT (1 ug/g) and rhizome concentrations (2.2 ug/g) (Figure 36).

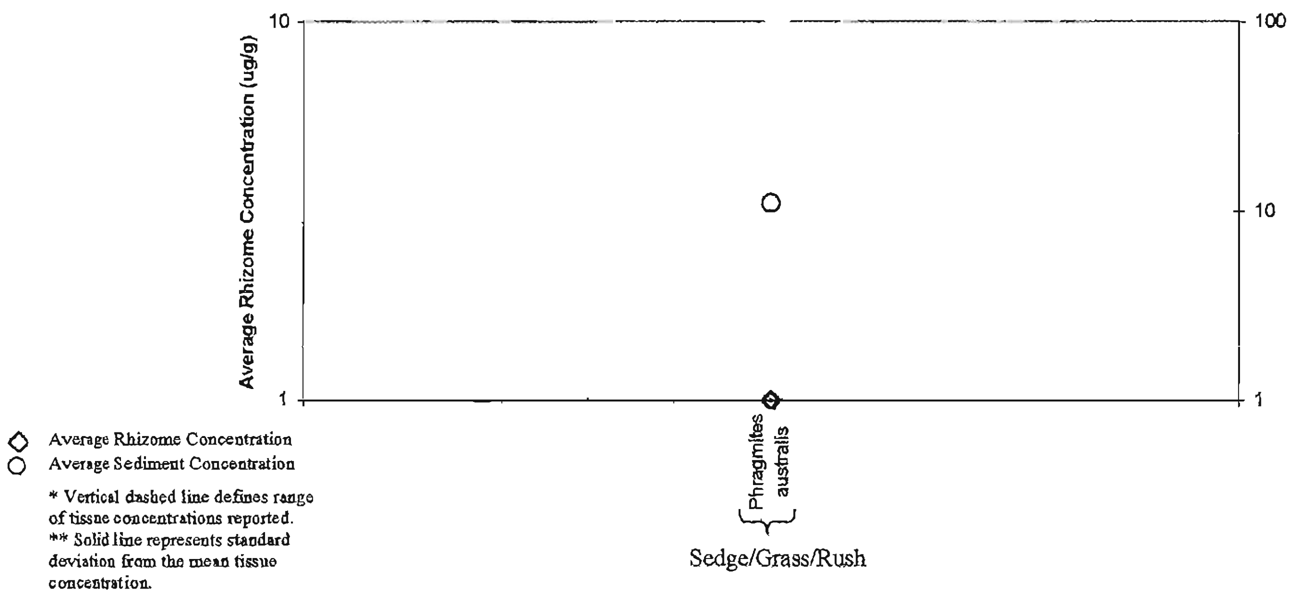


Figure 36. Lead concentrations in rhizome tissue and sediment.

The ratio of AGT concentration to sediment concentration was slightly >1.0 for *Eleocharis spp.*, *Nuphar luteum*, *Nymphoides aquatica*, and *Panicum sp.*, suggesting that these macrophytes are concentrating lead from the sediment (Figure 37). These plants, which are all emergents, can tolerate an average maximum water depth of 1.0 to 2.0 m. AGT is most likely not accumulating lead from the water column since AGT concentrations were at least two orders of magnitude greater than water concentration (Figure 38).

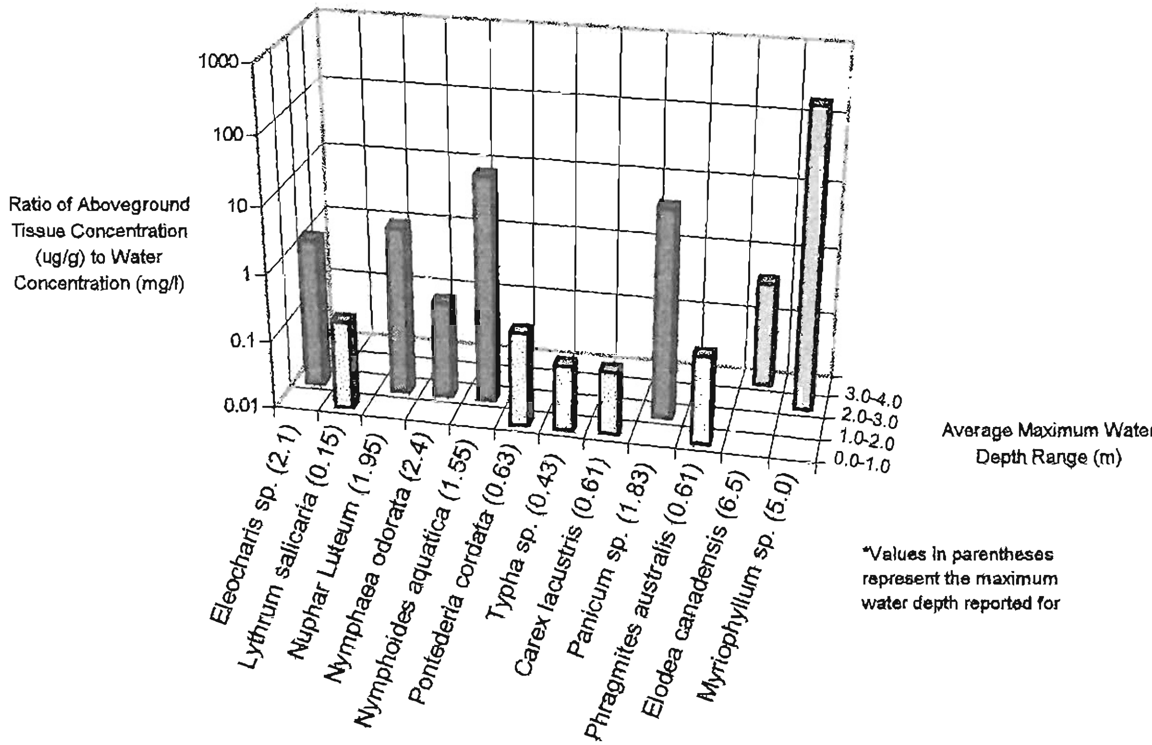


Figure 37. Ratio of AGT concentration to sediment concentration for lead and ranges of average maximum water depths.

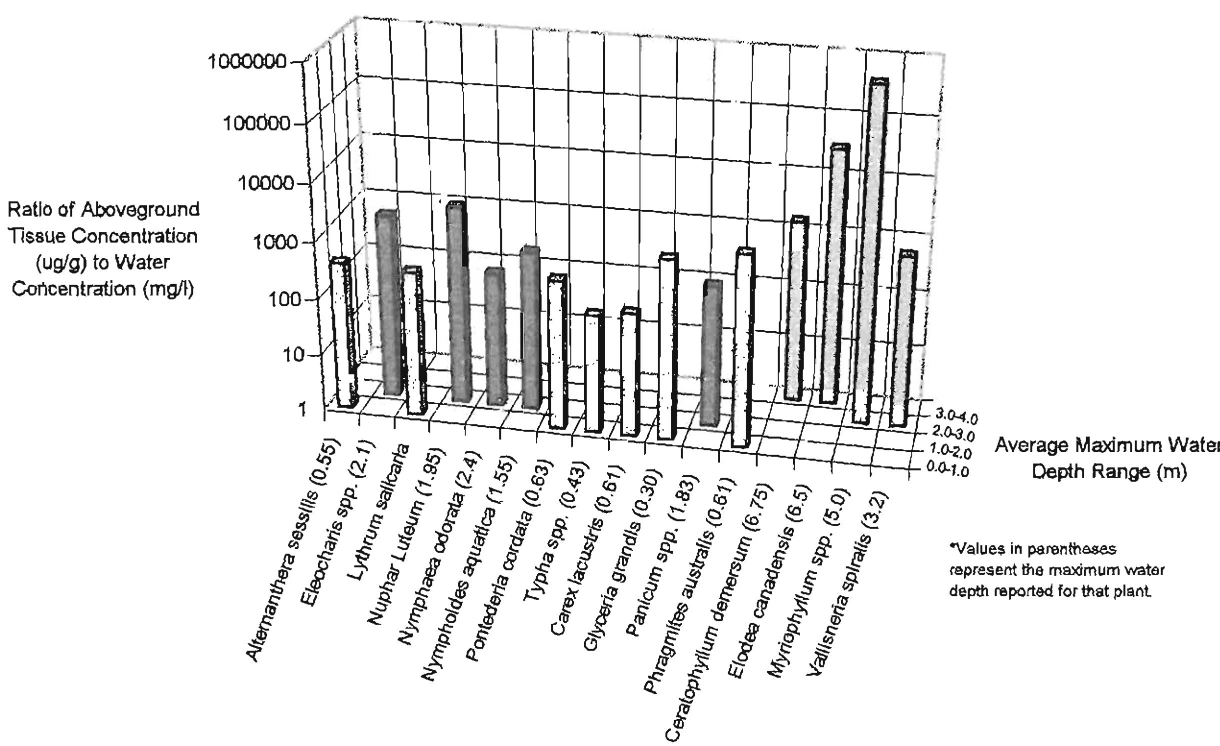


Figure 38. Ratio of AGT concentration to water concentration for lead and ranges of average maximum water depths.

Manganese

Salvinia natans, a floater, had the greatest AGT concentration of manganese (7,133 ug/g) (Figure 39). Average AGT concentrations of manganese for emergents and floating-leaved vegetation were 1 to 2 orders of magnitude higher than both sediment and water concentrations (Figure 40). A similar trend was also observed for some submergents, including *Myriophyllum heterophyllum*, *Lagarosiphon major* and *Utricularia spp.*

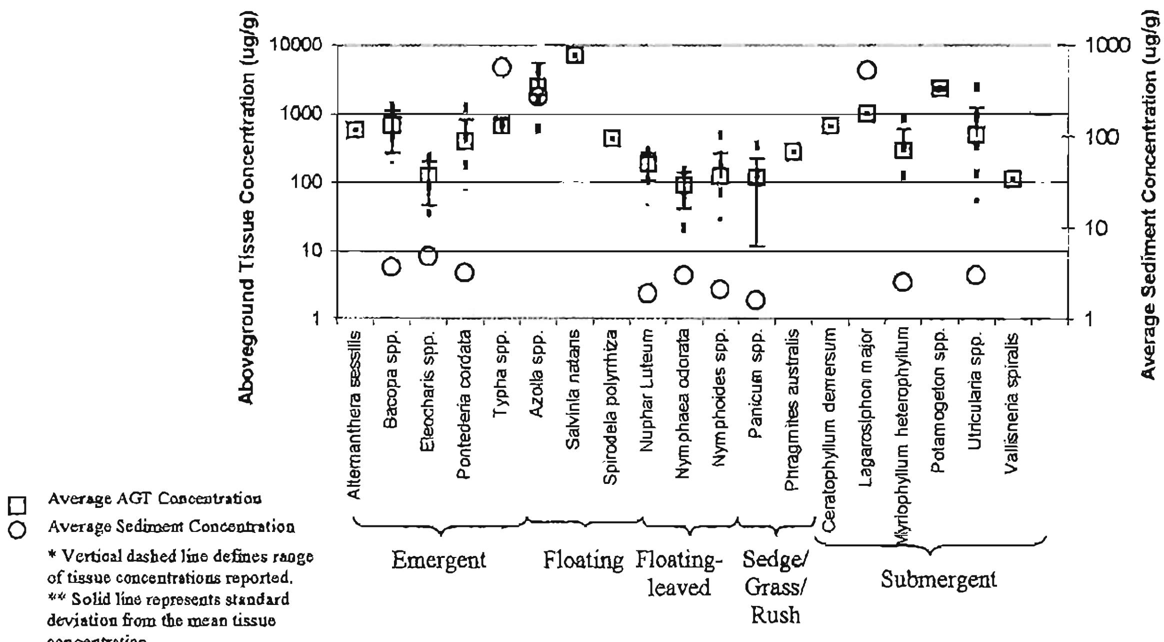


Figure 39. Manganese concentrations in aboveground tissue and sediment.

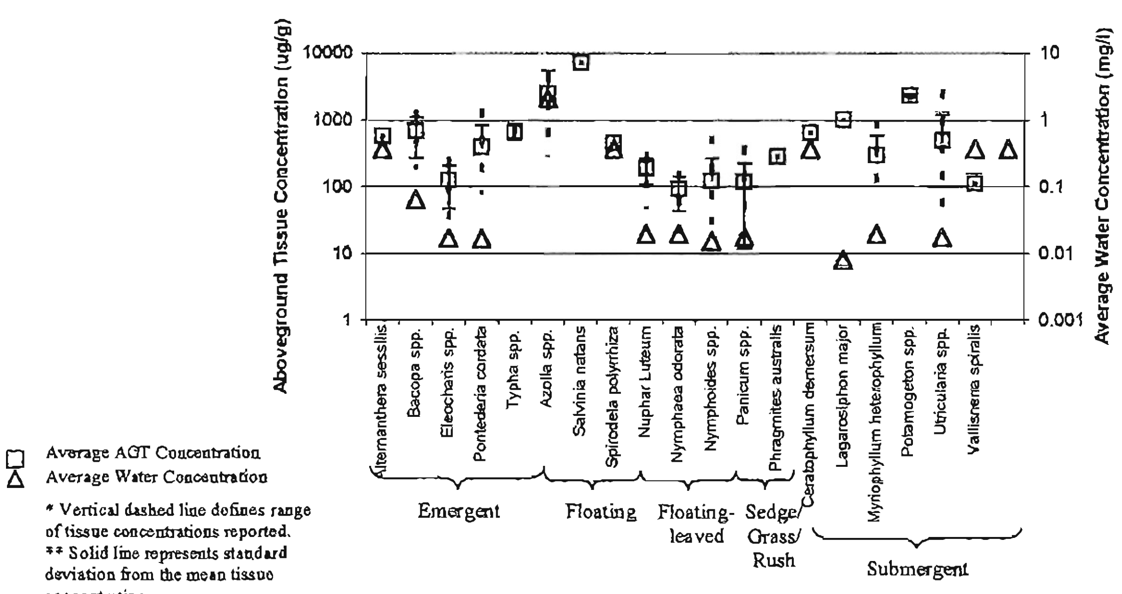


Figure 40. Manganese concentrations in aboveground tissue and water.

In addition to having fairly high AGT concentrations, *Potamogeton spp*. (2,300 ug/g) and *Typha spp*. (670 ug/g) also concentrated high levels of manganese in their root tissue (835 and 329 ug/g, respectively) (Figure 41). No data were available for substrate concentrations for these plants. *Nymphoides peltata* also had high reported levels of

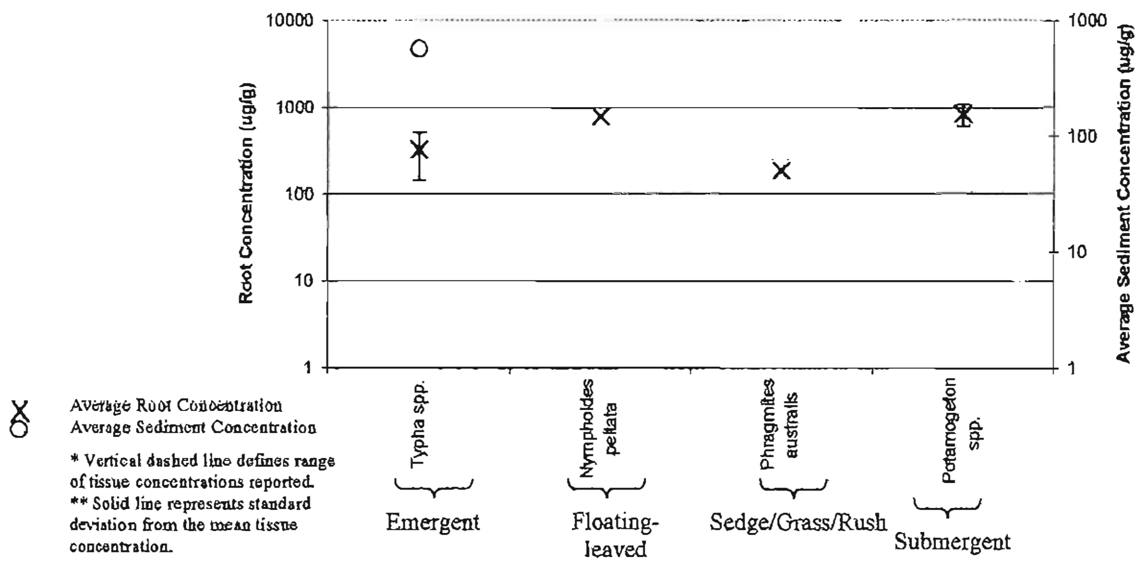


Figure 41. Manganese concentrations in root tissue and sediment.

manganese in its roots (792 ug/g) but lower levels in its AGT (122 ug/g). The rhizome concentration for *Typha latifolia* was 284 ug/g and was relatively close to sediment concentration (Figure 42).

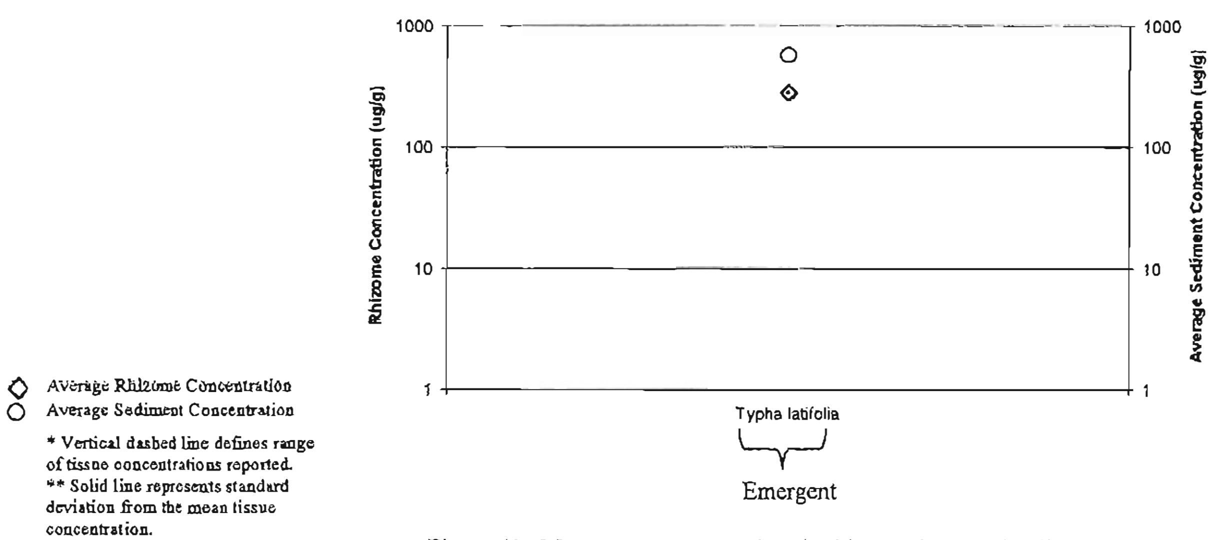


Figure 42. Manganese concentrations in rhizome tissue and sediment.

The ratio of AGT to sediment concentration for *Typha spp.* was very close to 1.0 which suggests that this plant relies on the substrate to take up manganese. It can only tolerate a maximum depth of 0.43 m, though (Figure 43).

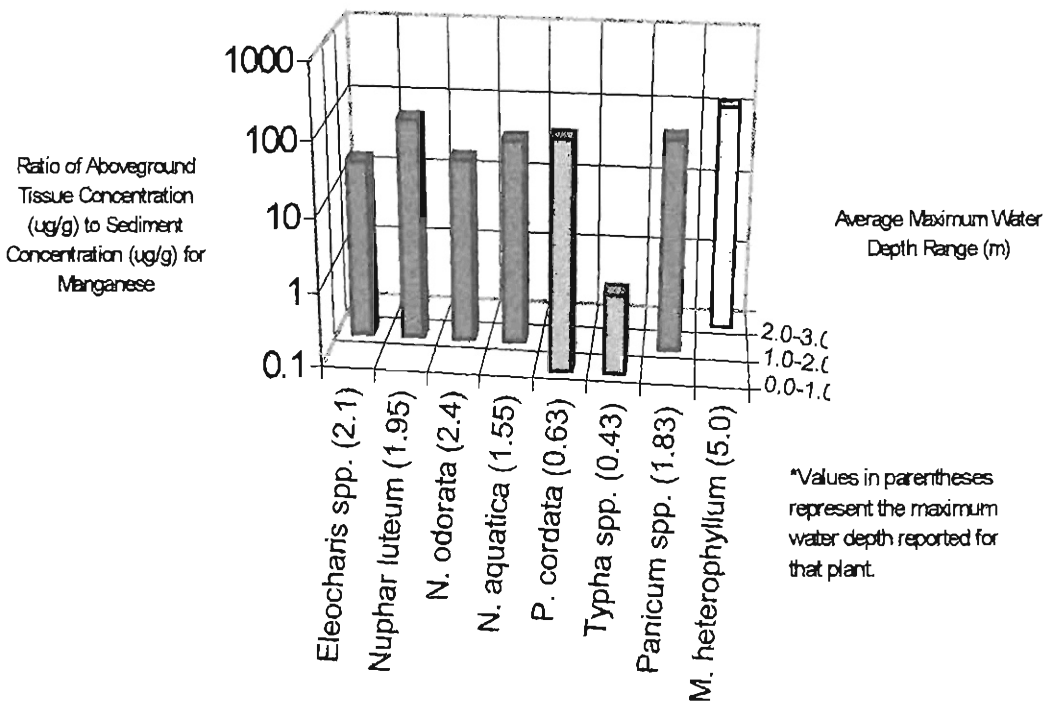


Figure 43. Ratio of AGT concentration to sediment concentration for manganese and ranges of average maximum water depths.

AGT concentrations for all plants identified from the literature were at least two orders of magnitude greater than water concentrations (Figure 44). This suggests that these plants may be accumulating more manganese from the substrate rather than the water column.

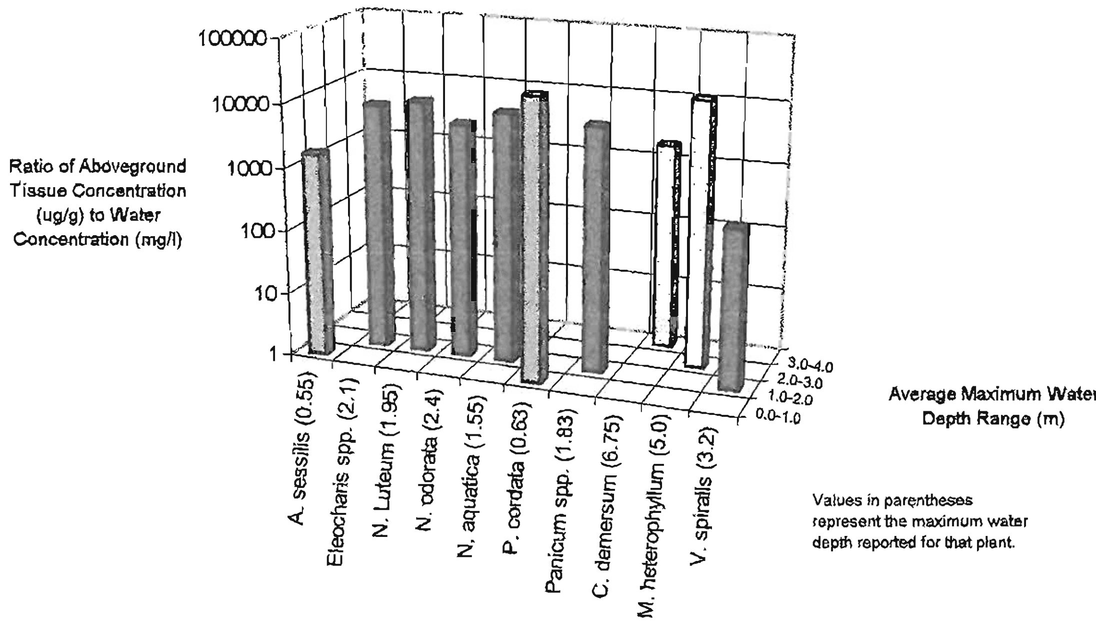


Figure 44. Ratio of AGT concentration to water concentration for managanese and ranges of average maximum water depths.

Mercury

Very little data were available for mercury uptake. Tissue concentrations were only reported for *Eriocaulon septangulare*, an emergent species (Figure 45). AGT concentration (0.25 ug/g) was approximately half of the sediment concentration and two orders of magnitude greater than the water concentration.

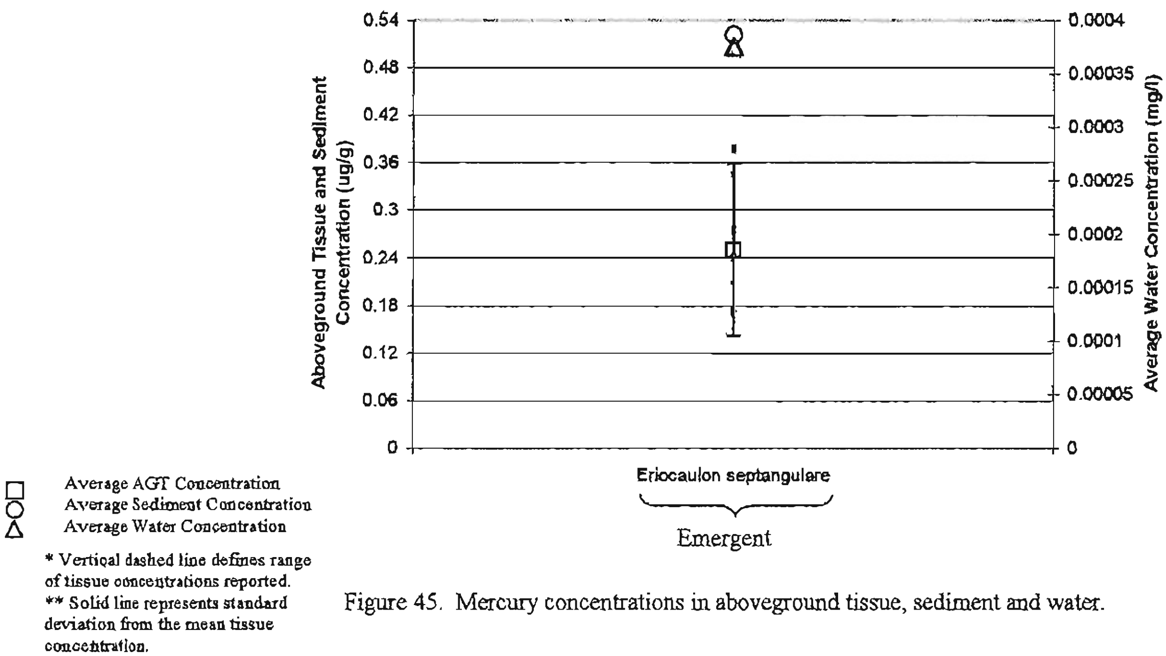
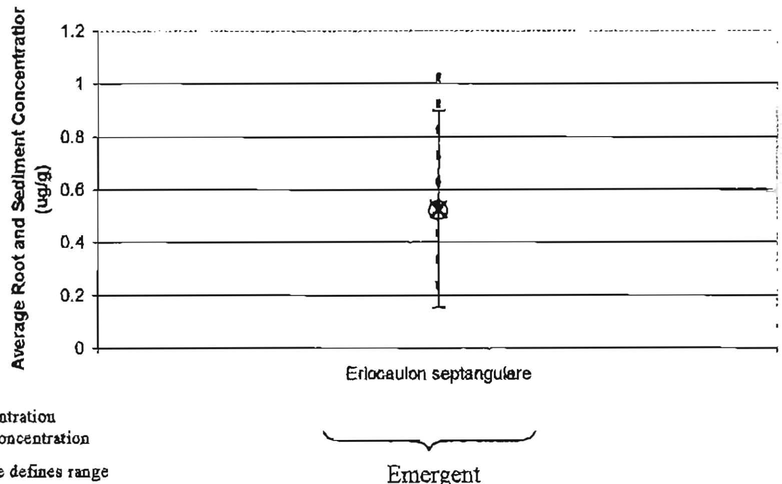


Figure 45. Mercury concentrations in aboveground tissue, sediment and water.

Root concentrations were somewhat higher (0.525 ug/g), but showed a close relationship to sediment concentration (Figure 46). Overall, *E. septangulare*, does not appear to accumulate high levels of mercury.



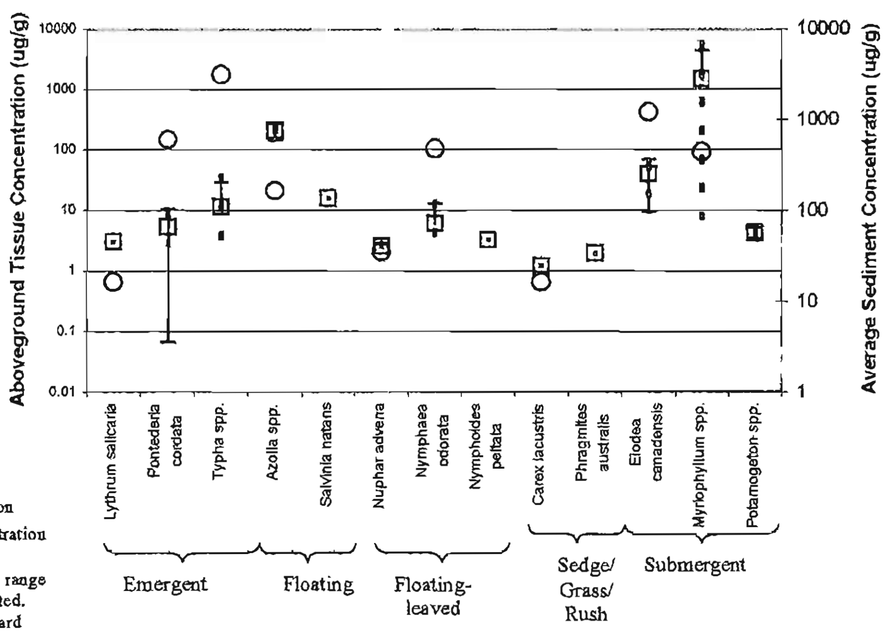
Average Root Concentration
Average Sediment Concentration

* Vertical dashed line defines range of tissue concentrations reported.
** Solid line represents standard deviation from the mean tissue concentration.

Figure 46. Mercury concentrations in root tissue and sediment.

Nickel

The largest average AGT concentrations of nickel were found in *Myriophyllum spp.* and *Azolla spp.* (1,473 and 204 ug/g, respectively) (Figure 47). Several plants, including



Average AGT Concentration
Average Sediment Concentration

* Vertical dashed line defines range of tissue concentrations reported.
** Solid line represents standard deviation from the mean tissue concentration.

Figure 47. Nickel concentrations in aboveground tissue and sediment.

Lythrum salicaria, Nuphar advena, Carex lacustris, and *Myriophyllum sp.*, corresponded closely to sediment concentrations. AGT concentration for *Nymphaea odorata* corresponded closely to water concentration (Figure 48), but AGT concentrations for the remainder of the identified plants were several orders of magnitude greater than water concentrations.

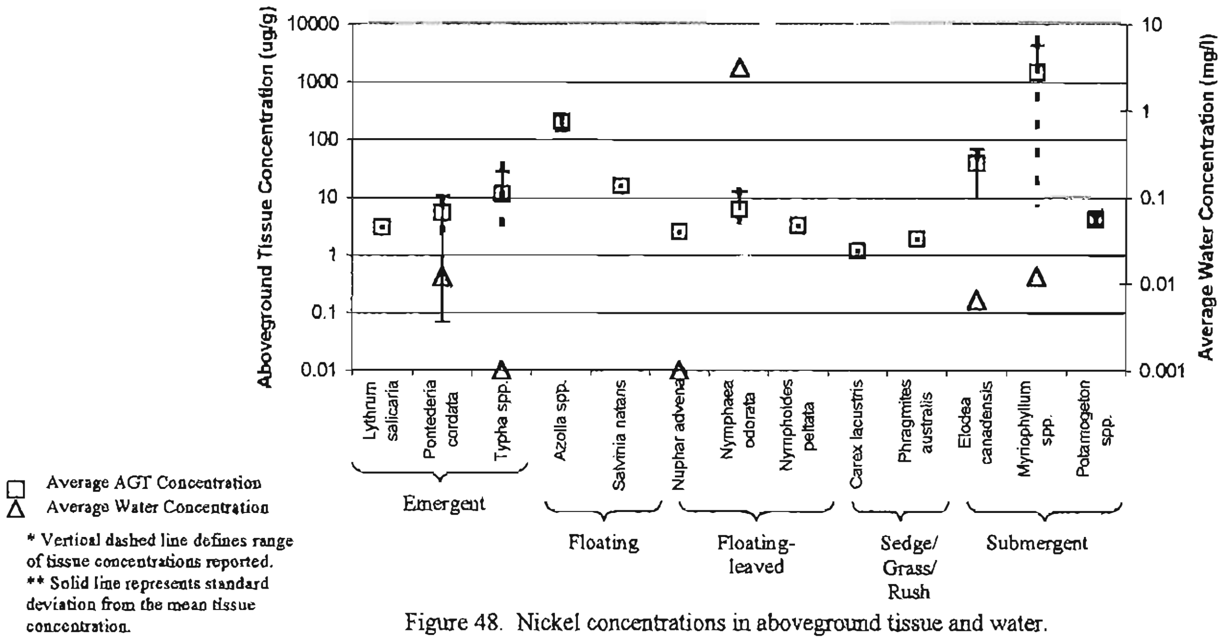


Figure 48. Nickel concentrations in aboveground tissue and water.

Typha spp. had the greatest root tissue concentration of nickel (194 ug/g) (Figure 49)

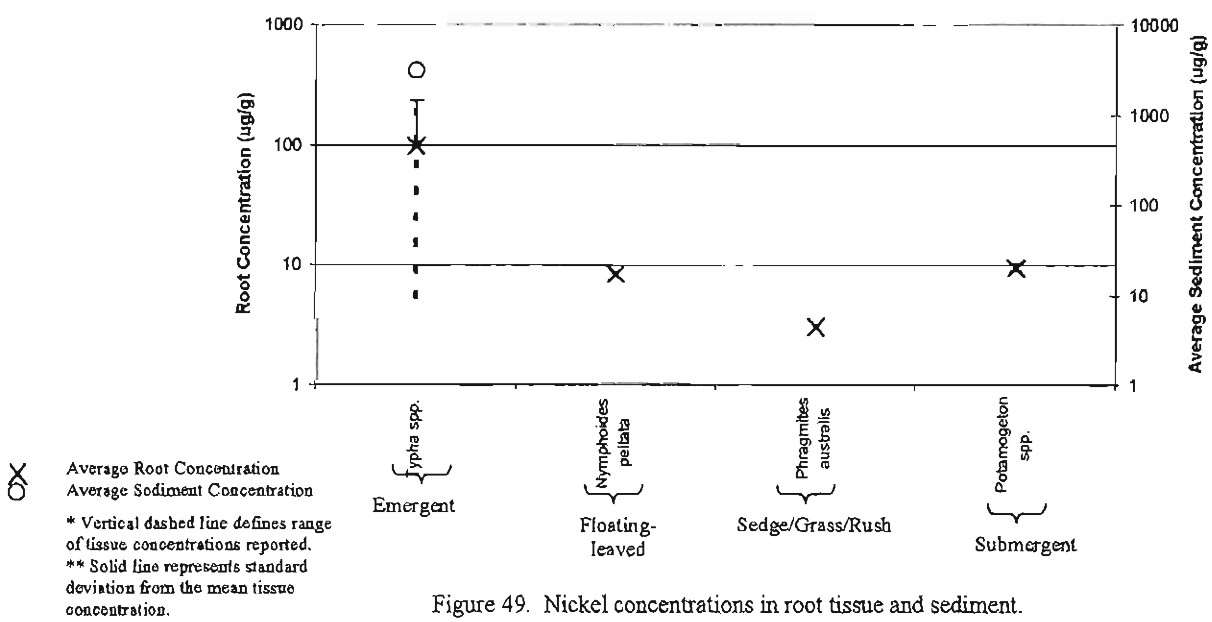


Figure 49. Nickel concentrations in root tissue and sediment.

which was greater than both AGT concentration (11 ug/g) and rhizome concentration (40 ug/g) (Figure 50) for this species. Sediment concentration far exceeded tissue concentrations in all cases (3,138 ug/g).

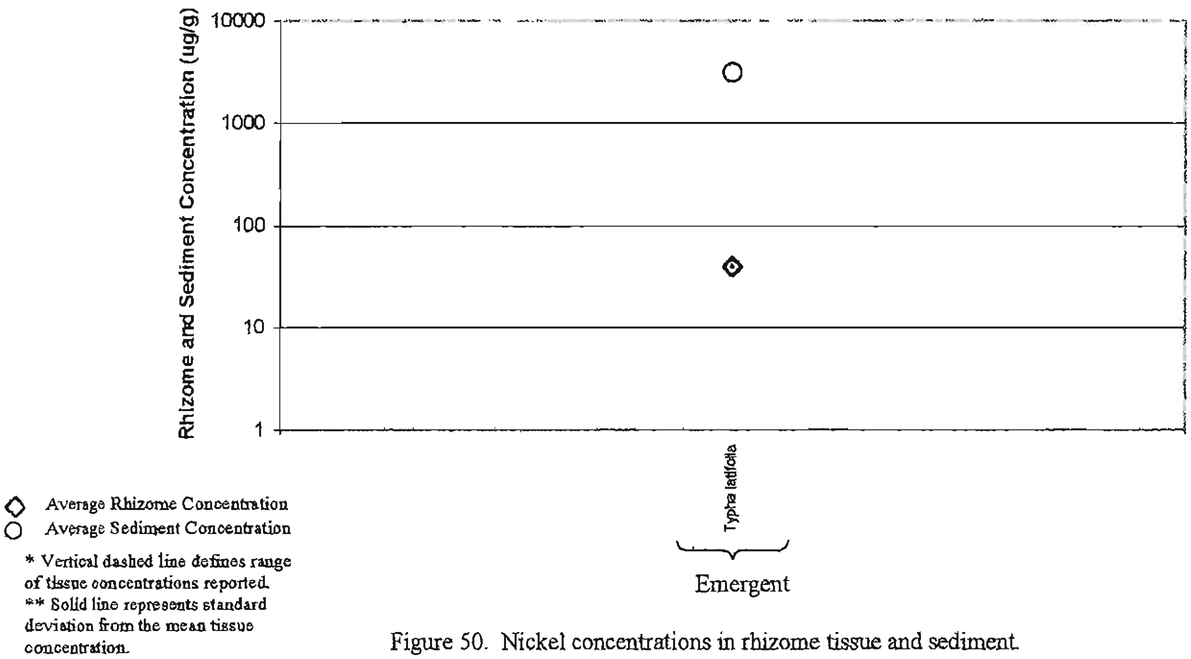


Figure 50. Nickel concentrations in rhizome tissue and sediment.

All ratios of AGT to sediment concentrations (Figure 51) were <1.0 with the exception of

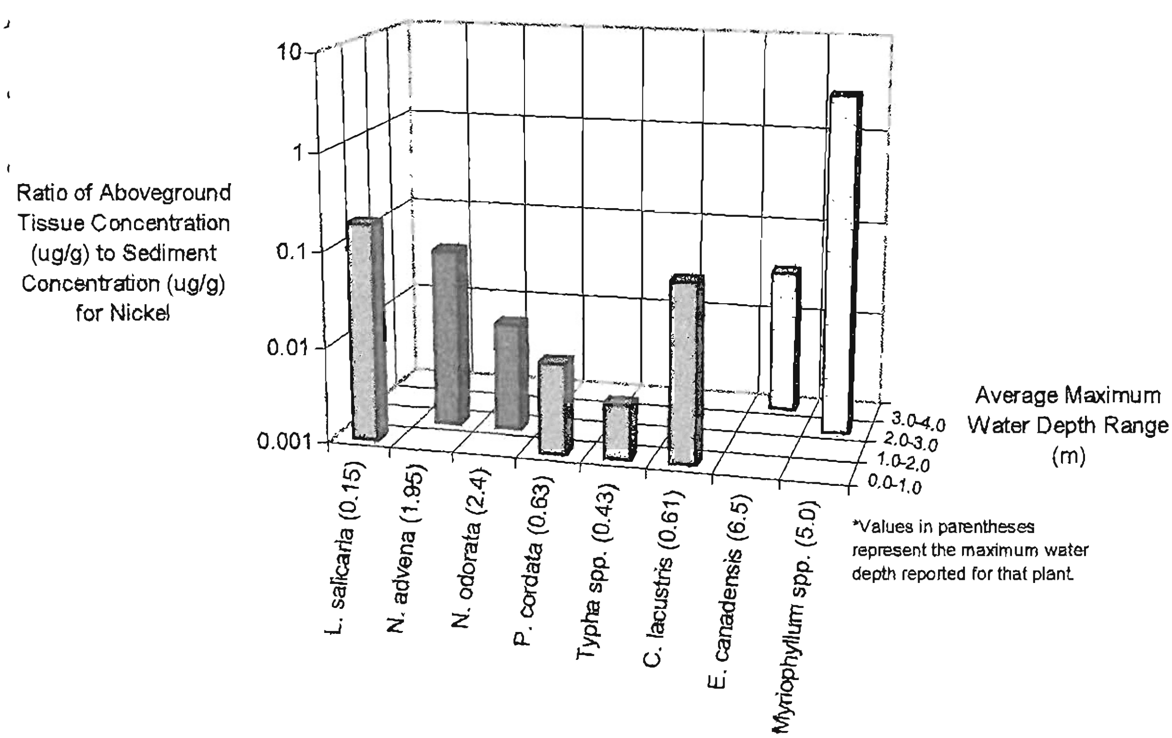


Figure 51. Ratio of AGT concentration to sediment concentration for nickel and ranges of average maximum water depths.

Myriophyllum spp., whose ratio was slightly >1.0, suggesting that this plant may be actively taking up nickel from the sediment. AGT concentrations were at least two orders of magnitude greater than water concentrations, with the exception of *Nymphaea odorata,* which may be accumulating nickel from the water column (Figure 52).

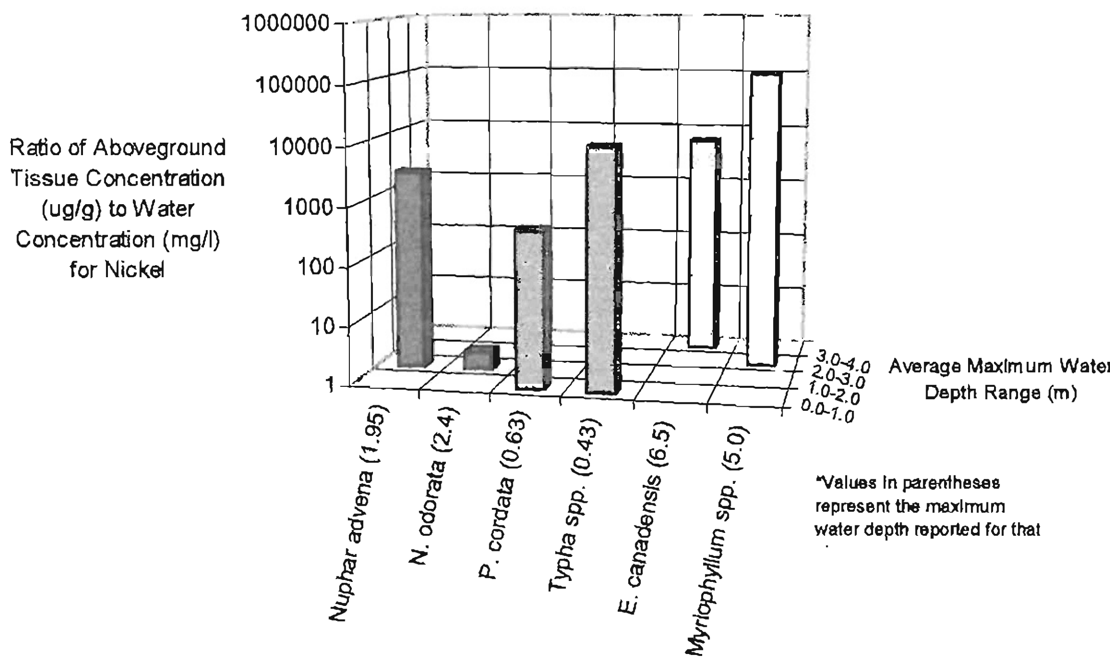


Figure 52. Ratio of AGT concentration to water concentration for nickel and ranges of average maximum water depths.

Zinc

Lemna minor had the highest average AGT concentration of zinc (10,450 ug/g) (Figure 53). In many instances, sediment concentrations were similar to or greater than AGT concentrations for emergents , floating-leaved vegetation submergents. *Bacopa caroliniana, Eleocharis spp., Nuphar spp., Nymphaea odorata, Nymphoides sp., Panicum sp., Myriophyllum sp.*, and *Utricularia sp.* appeared to be concentrating zinc from the substrate. AGT concentrations were at least 2 orders of magnitude greater than water concentrations for all plants with the exception of *Eichhornia crassipes* (Figure 54).

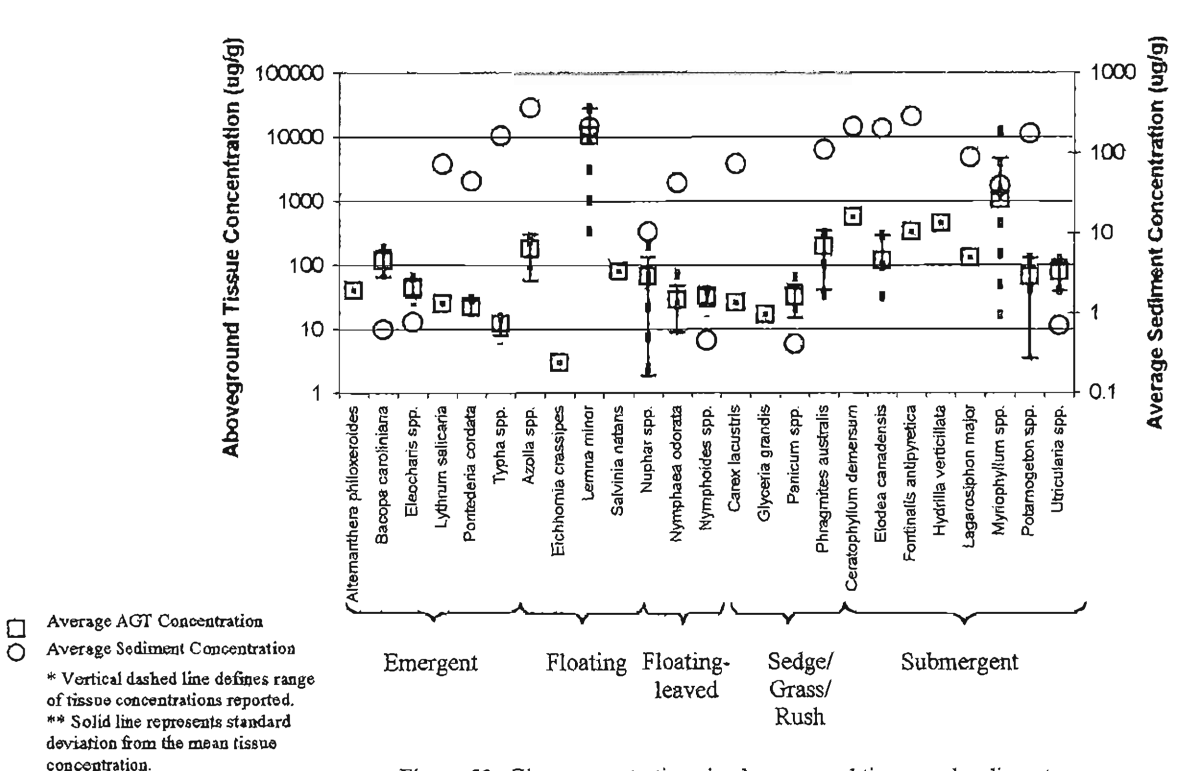


Figure 53. Zinc concentrations in aboveground tissue and sediment.

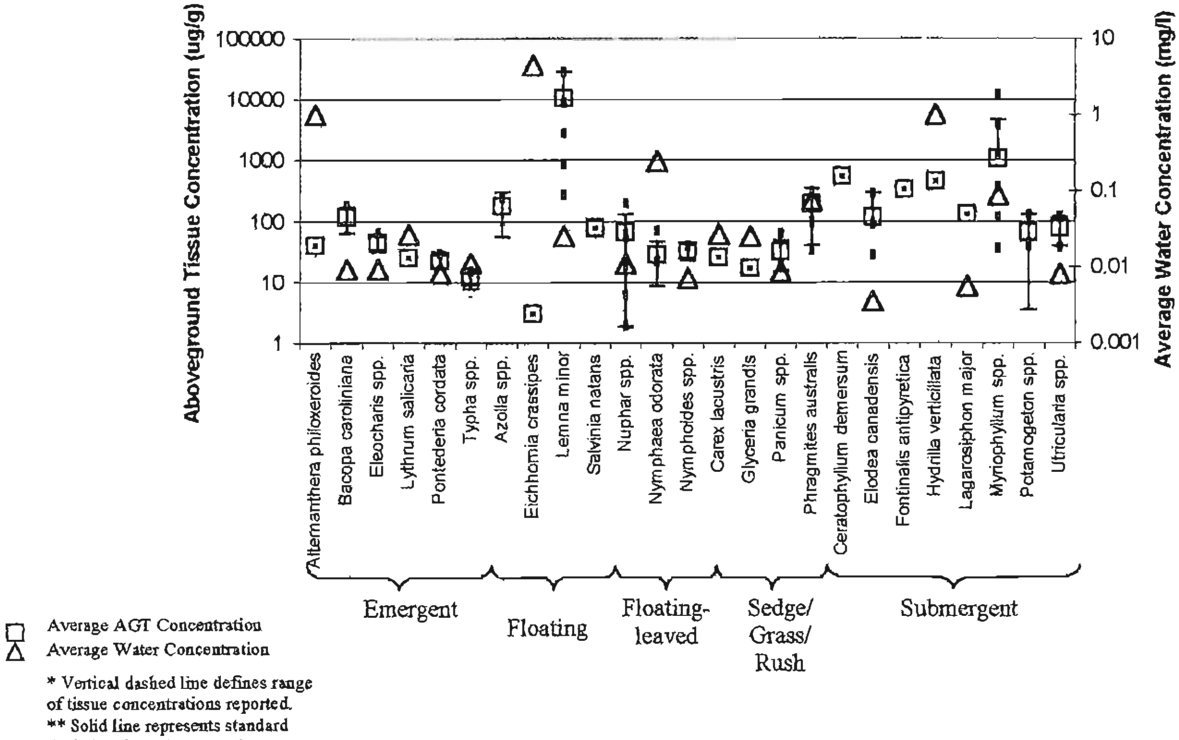


Figure 54. Zinc concentrations in aboveground tissue and water.

Phragmites australis, *Typha spp.*, and *Potamogeton spp.* all had high root tissue concentrations (140, 104, 63 ug/g, respectively), which corresponded closely with sediment concentrations (Figure 55).

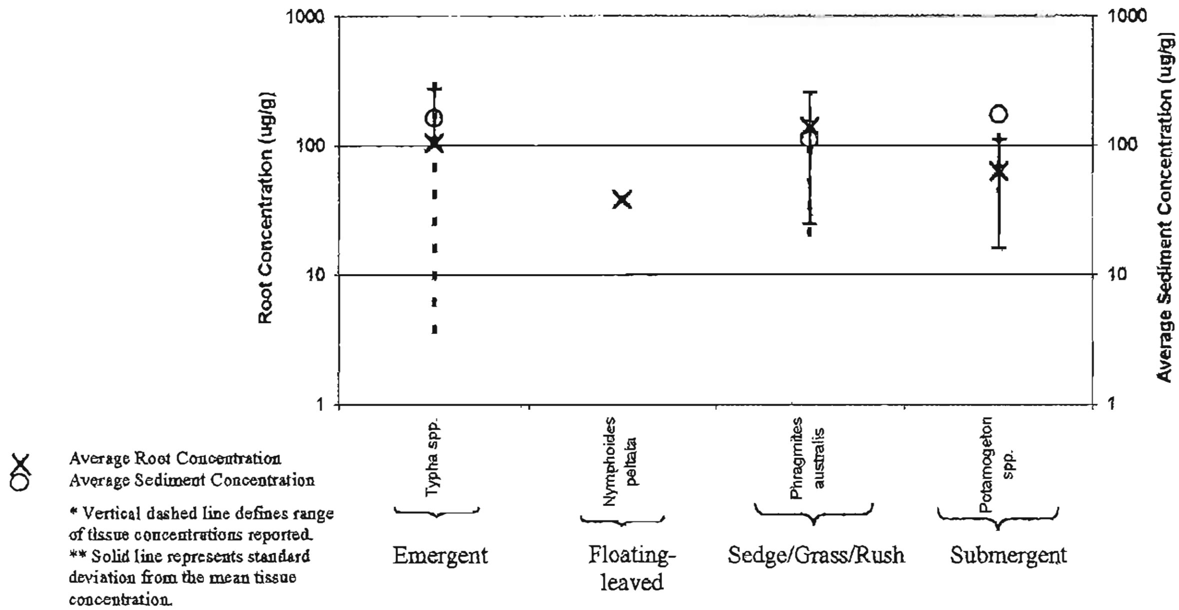


Figure 55. Zinc concentrations in root tissue and sediment.

Rhizome concentrations of zinc were similar for both *Typha latifolia* and *P. australis* (35 and 36 ug/g, respectively) but lower than their respective root concentrations (Figure 56). Substrate concentrations (163 and 110 ug/g) were much greater than rhizome concentrations for these plants.

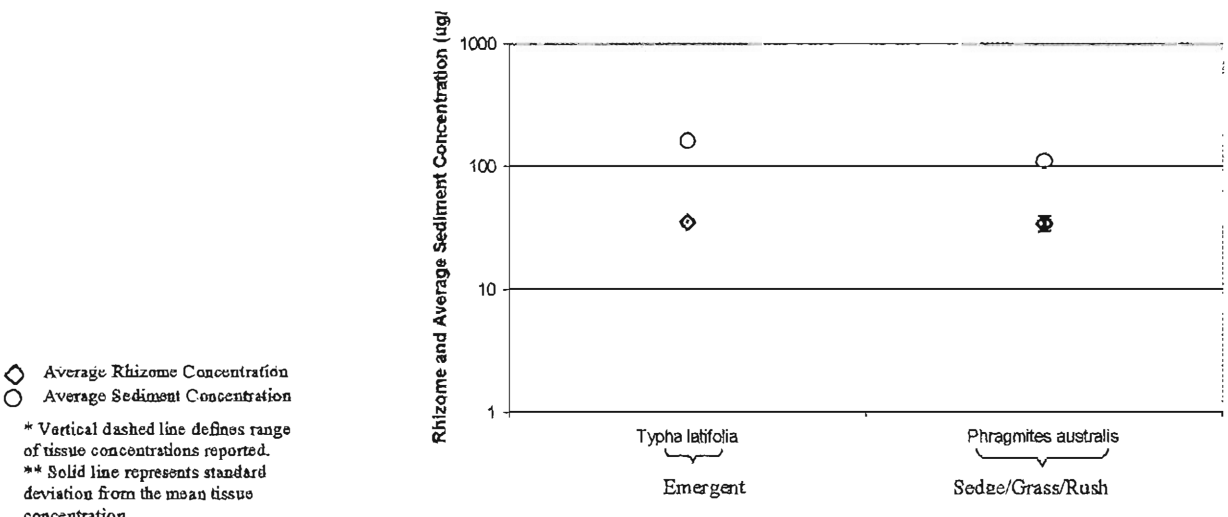


Figure 56. Zinc concentrations in rhizome tissue and sediment.

Ratios of AGT concentration to sediment concentration slightly >1.0 were observed for *Nuphar spp.*, *Phragmites australis, Ceratophyllum demersum,* and *Fontinalis antipyretica* (Figure 57), suggesting that these plants may accumulate zinc from the sediment. *C. demersum* can tolerate the greatest reported maximum water depth of 6.75

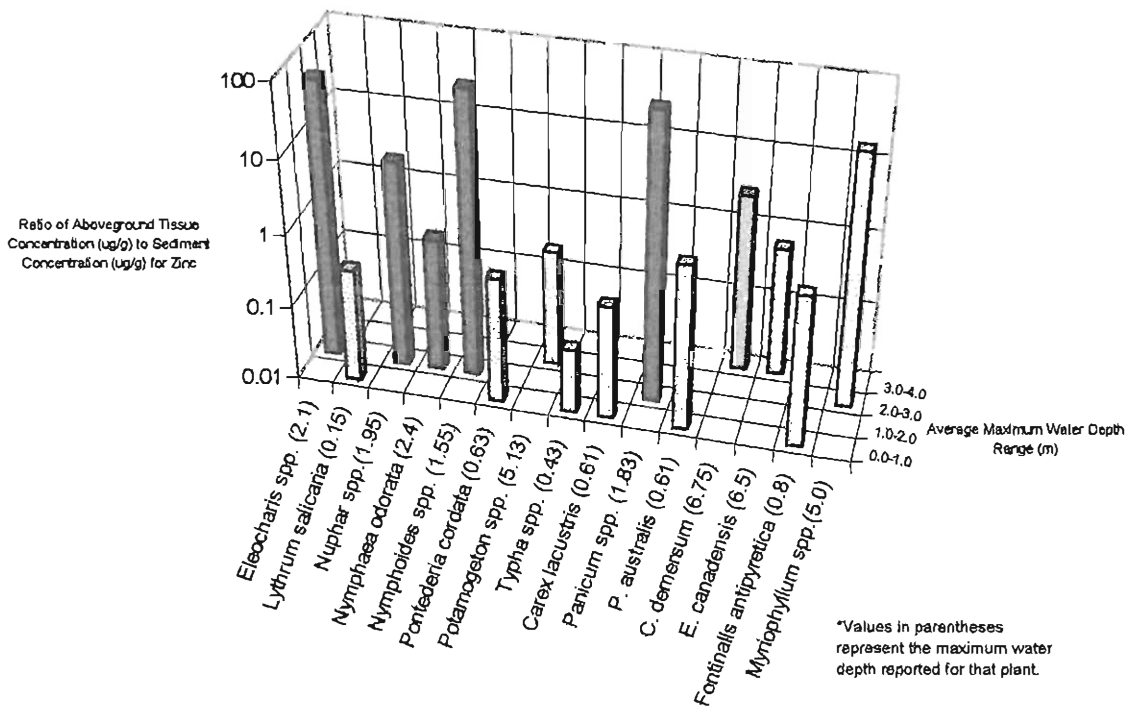


Figure 57. Ratio of AGT concentration to sediment concentration of zinc and ranges of average maximum water depths.

m., whereas *Nuphar spp.*, *P. australis* and *F. antipyretica* can only tolerate much shallower depths (1.95, 0.61, and 0.8 m, respectively). AGT concentrations were at least one to two orders of magnitude greater than water concentrations for all plants (Figure 58). The smallest ratio was observed for *Alternanthera philoxeroides* (40), which may suggest that this plant may be absorbing some zinc from the water column. Sediment concentrations were not available for this species, so it is difficult to determine exactly the source of zinc.

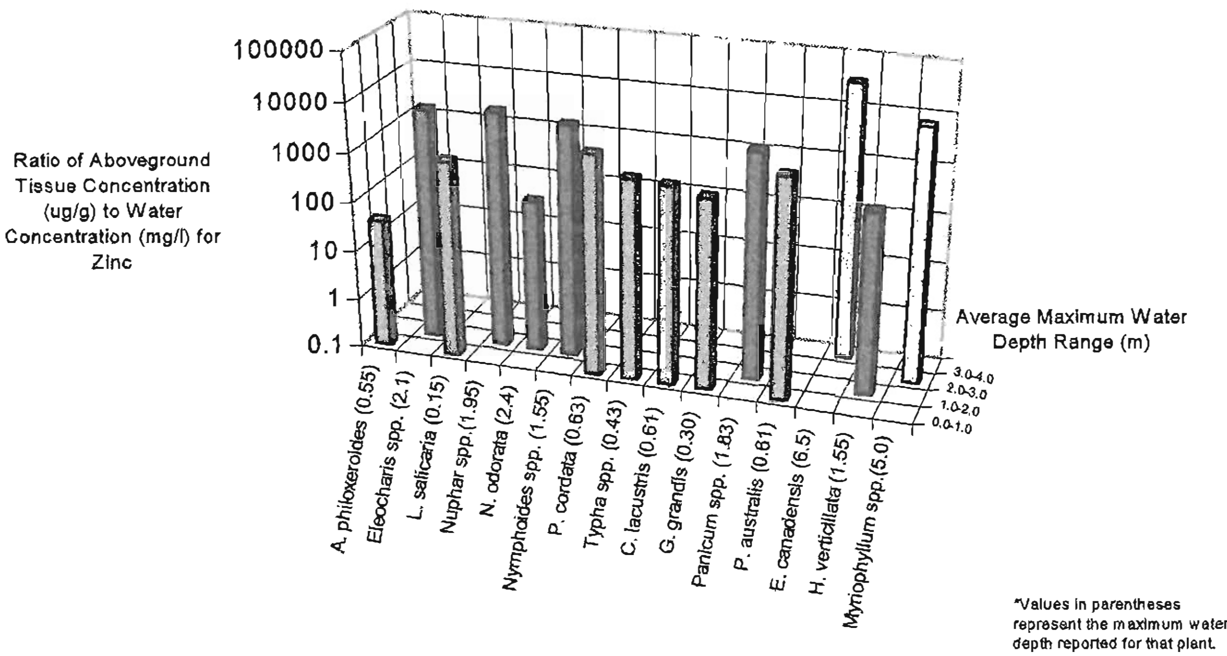


Figure 58. Ratio of AGT concentration to water concentration of zinc and ranges of average maximum water depths.

Nitrogen

Average AGT concentrations of nitrogen were high for all plants identified throughout the literature (>10,000 ug/g) (Figure 59). With the exception of *Lagarosiphon major*, AGT concentrations were much greater than sediment concentrations. All AGT concentrations were at least three orders of magnitude greater than water concentrations (Figure 60).

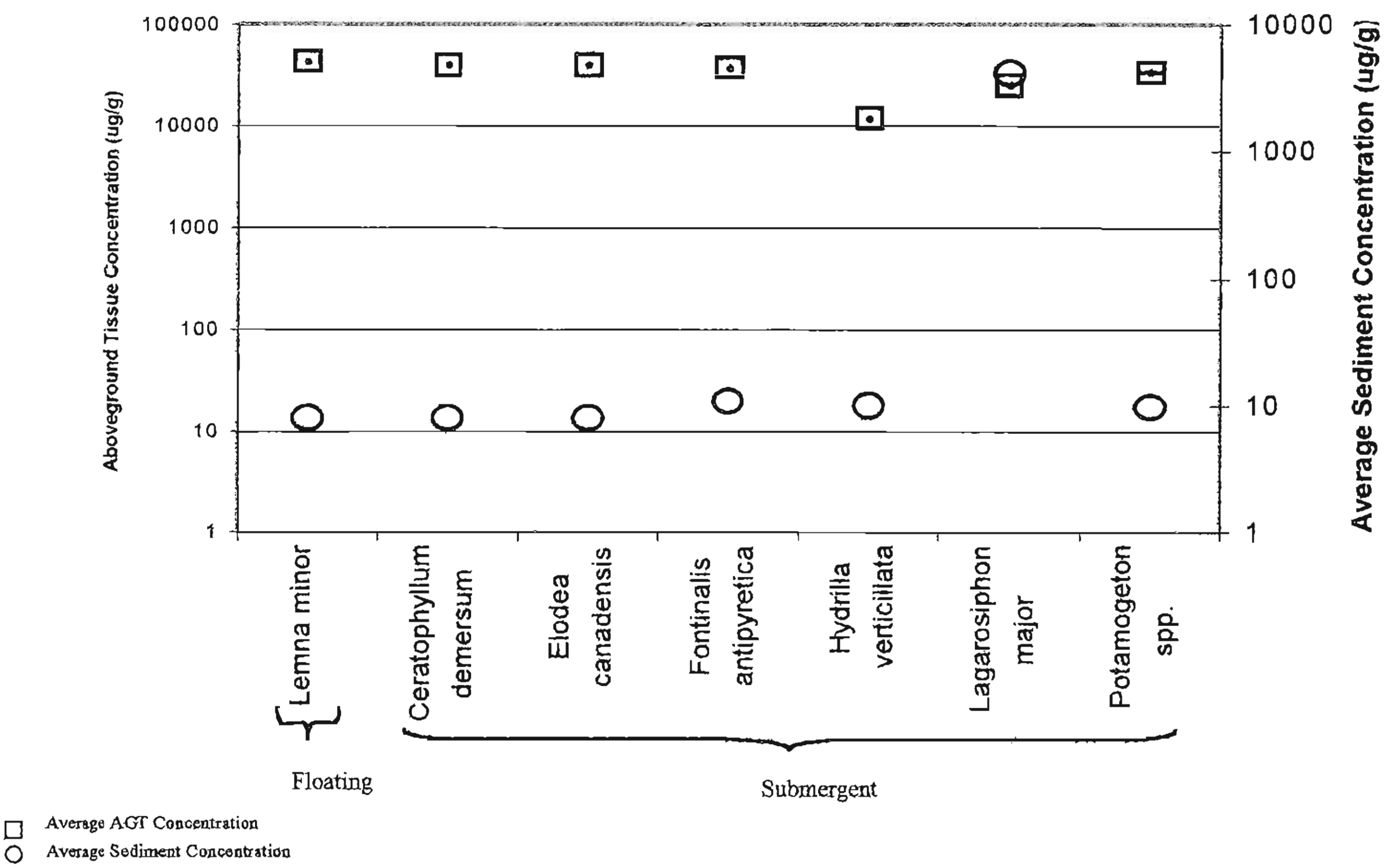


Figure 59. Nitrogen concentrations in aboveground tissue and sediment.

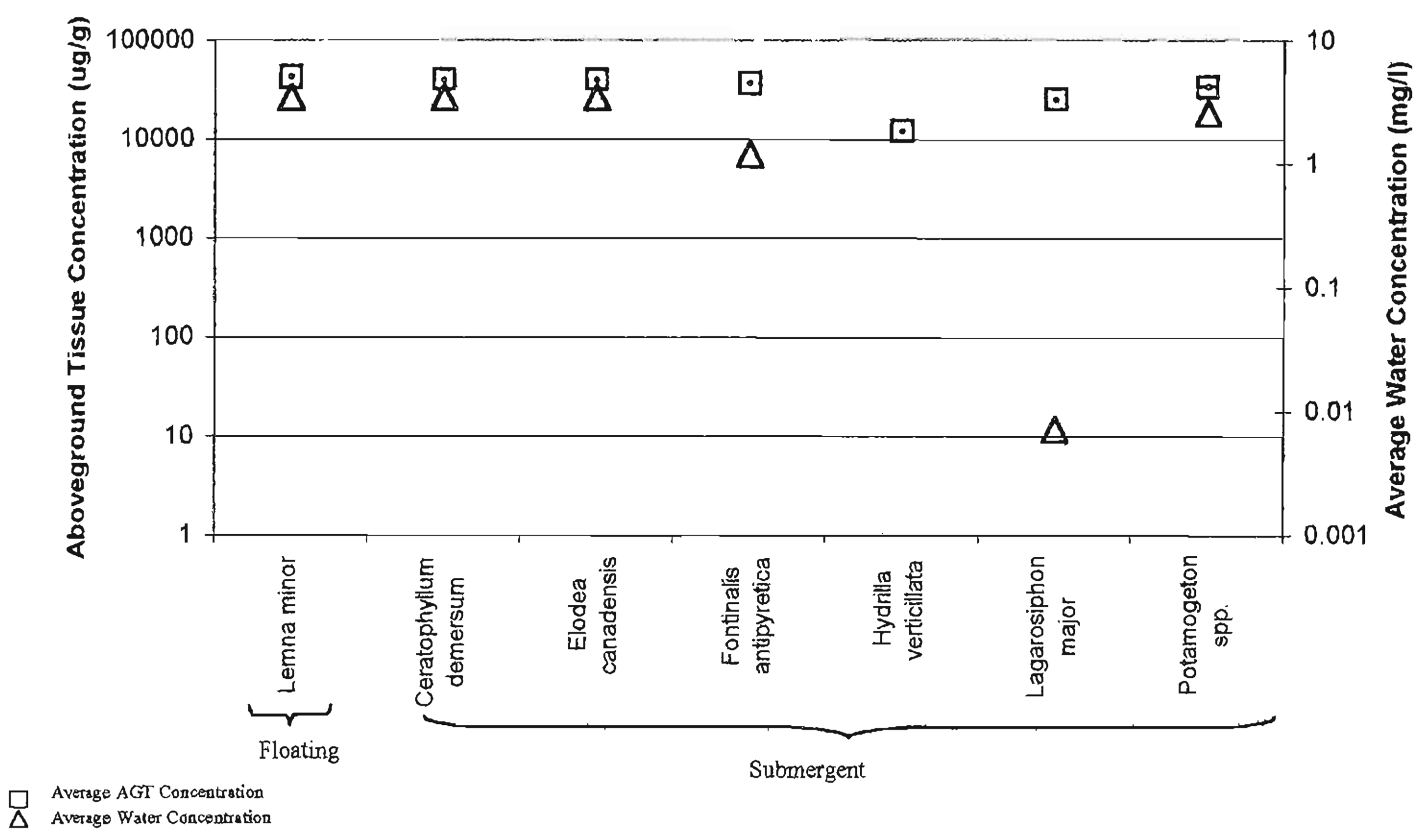


Figure 60. Nitrogen concentrations in aboveground tissue and water.

The only nitrogen concentration reported for root tissue was for *Potamogeton spp.* (30,350 ug/g). Both sediment and water concentrations were several orders of magnitude lower than root concentration (Figure 61).

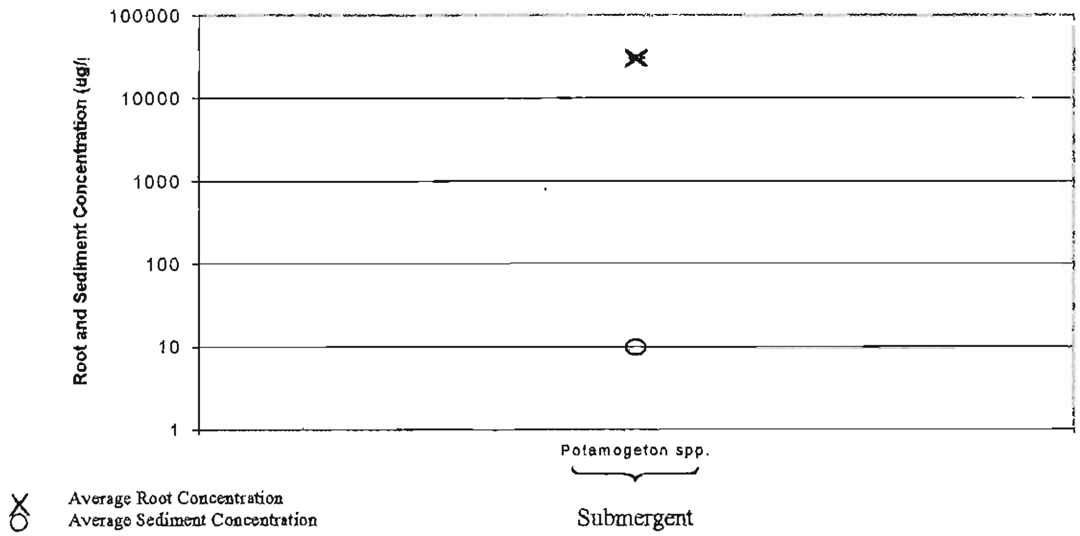


Figure 61. Nitrogen concentrations in root tissue and sediment.

Average AGT concentrations of nitrogen were at least 1000 times greater than sediment concentrations and at least 10,000 times greater than water concentrations (Figures 62 & 63).

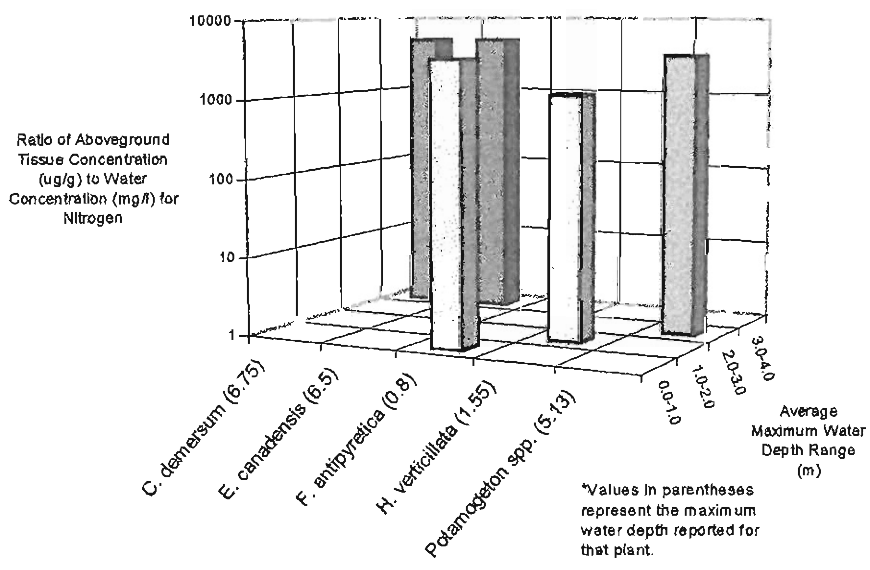


Figure 62. Ratio of AGT concentration to sediment concentration for nitrogen and ranges of average maximum water depths.

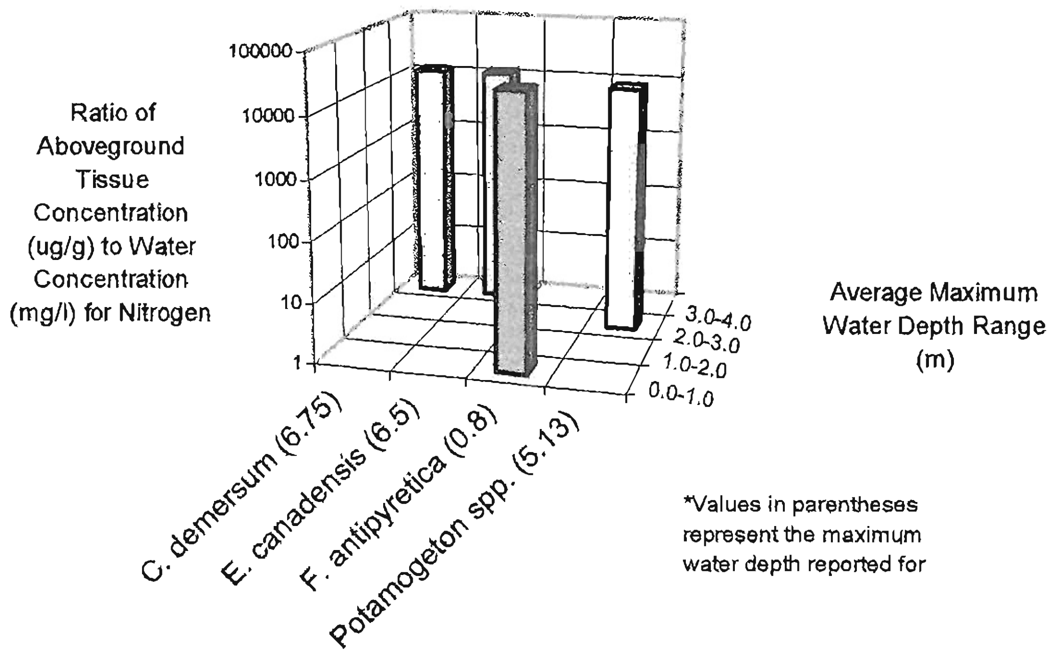


Figure 63. Ratio of AGT concentration to water concentration for nitrogen and ranges of average maximum water depths.

Phosphorus

Phosphorus levels in AGT were high for al plants identified from the literature (>1,000 ug/g) (Figures 64 & 65). Levels in AGT, sediment and water displayed trends similar to

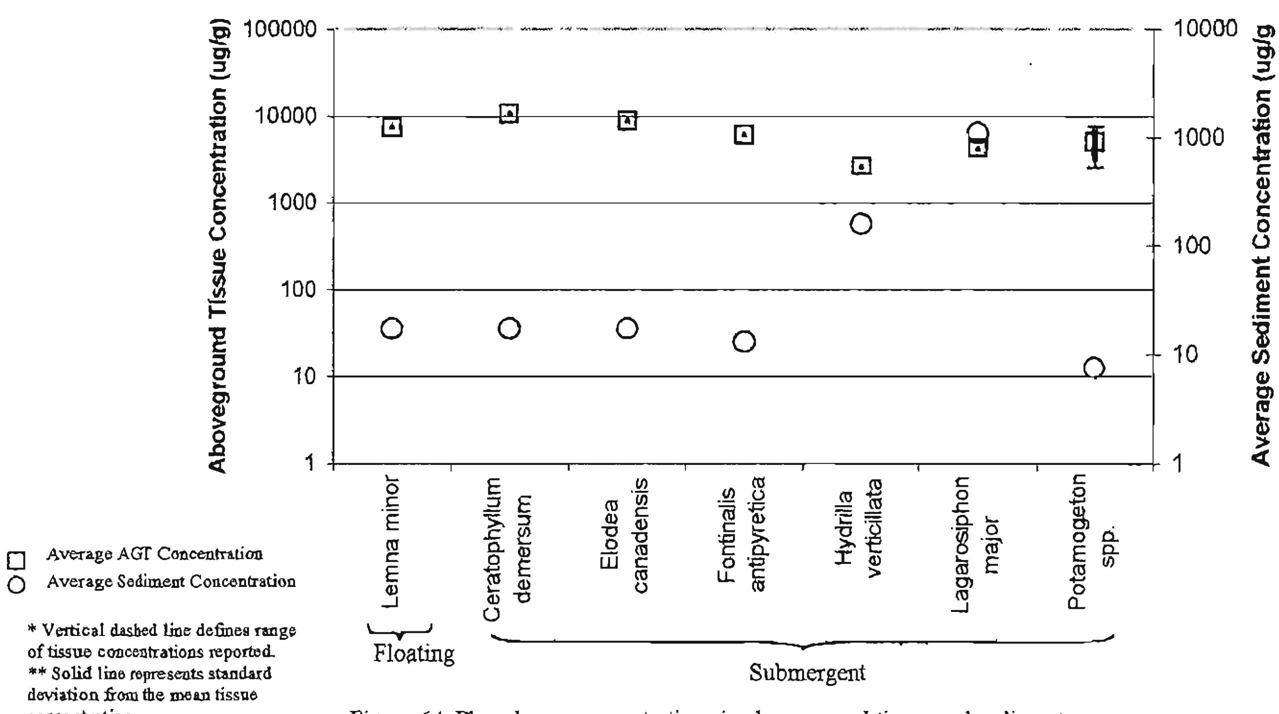


Figure 64. Phosphorus concentrations in aboveground tissue and sediment.

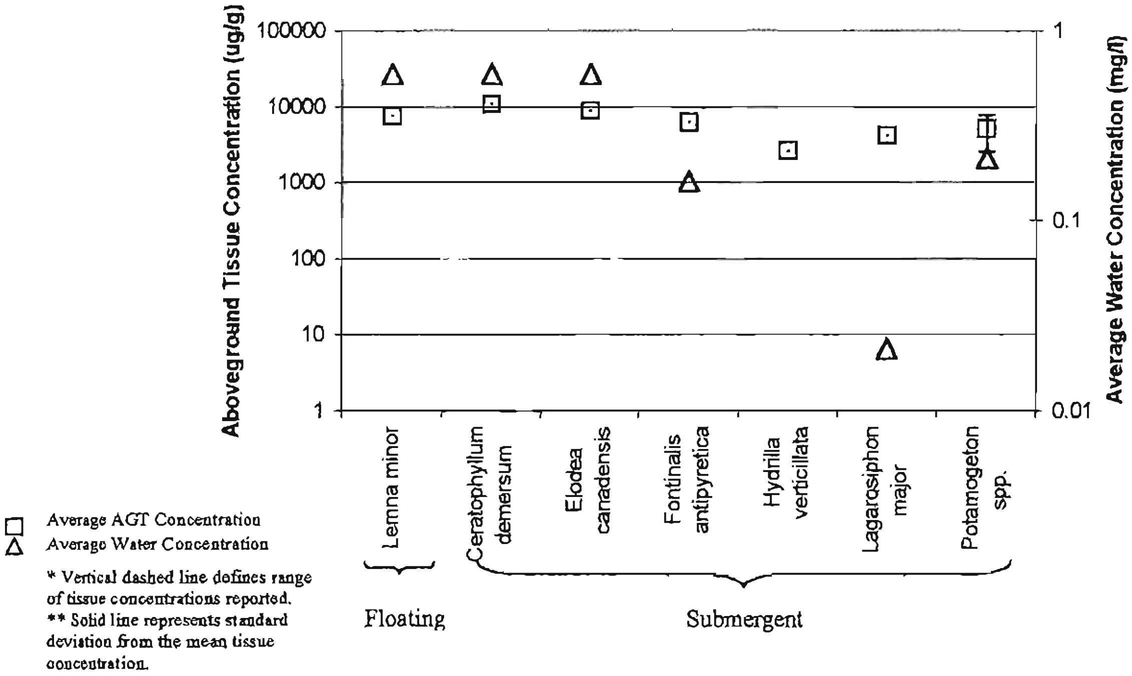


Figure 65. Phosphorus concentrations in aboveground tissue and water.

those observed for nitrogen, but at lower concentrations. Root concentrations for phosphorus were reported only for Potamogeton spp. (6,650 ug/g) (Figure 66) which was slightly greater than its AGT concentration (5,075 ug/g).

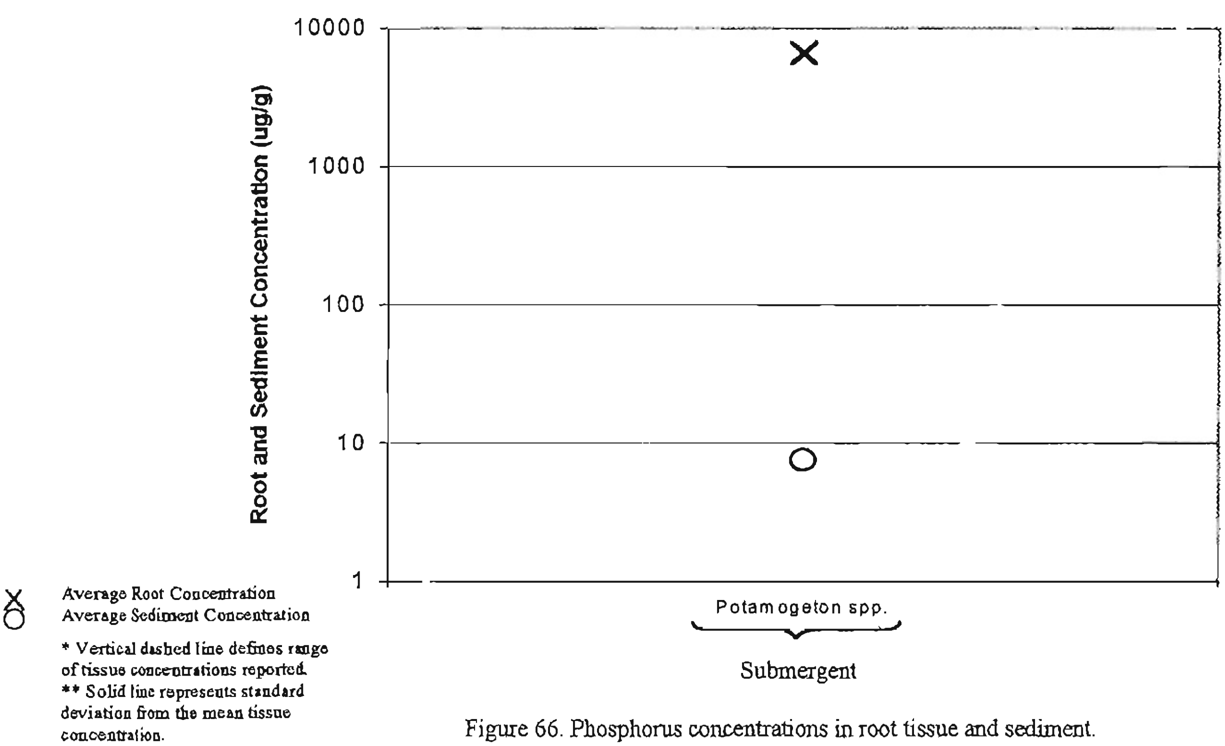


Figure 66. Phosphorus concentrations in root tissue and sediment.

All AGT concentrations of phosphorus were at least 400 times greater than sediment concentrations with the exception of *Hydrilla verticillata*, whose AGT concentration was approximately 16 times greater than sediment concentration (Figure 67). All AGT concentrations were at least four orders of magnitude greater than water concentration (Figure 68).

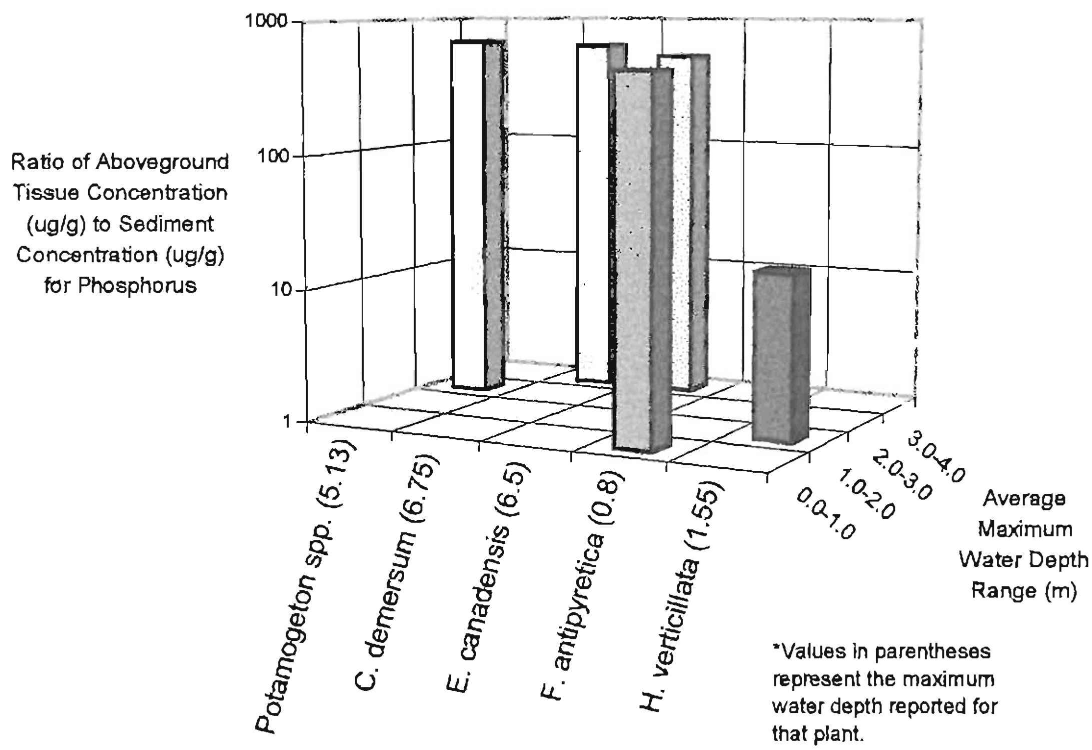


Figure 67. Ratio of AGT concentration to sediment concentration for phosphorus and ranges of average maximum water depths.

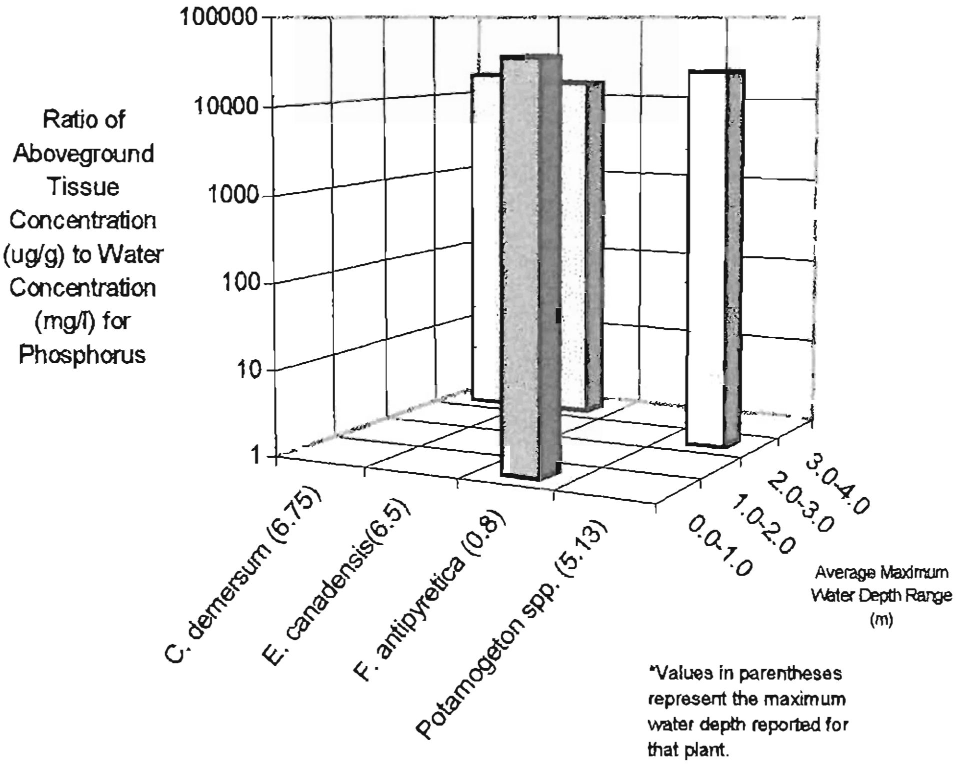


Figure 68. Ratio of AGT concentration to water concentration for phosphorus and ranges of average maximum water depths.

Areal Concentrations and Uptake Rates

Other methods of reporting uptake were based on areal concentrations (g/m^2) and actual rates(g/m^2/day). Uptake reported as either an areal concentration or as a rate, was reported primarily for nitrogen and phosphorus with few data reported for metals.

Areal Concentrations (g/m^2)

Overall, emergents had slightly greater AGT uptake than sedges/grasses/rushes for both nitrogen and phosphorus, with the exception of *Typha glauca* (Figure 69). Uptake for metals was reported only for *Phragmites australis*, which had the greatest affinity for zinc (0.02 g/m^2). Average root uptake for only *Phragmites australis* was obtained from the literature. Root uptake was greatest for nitrogen (24 g/m^2) (Figure 70).

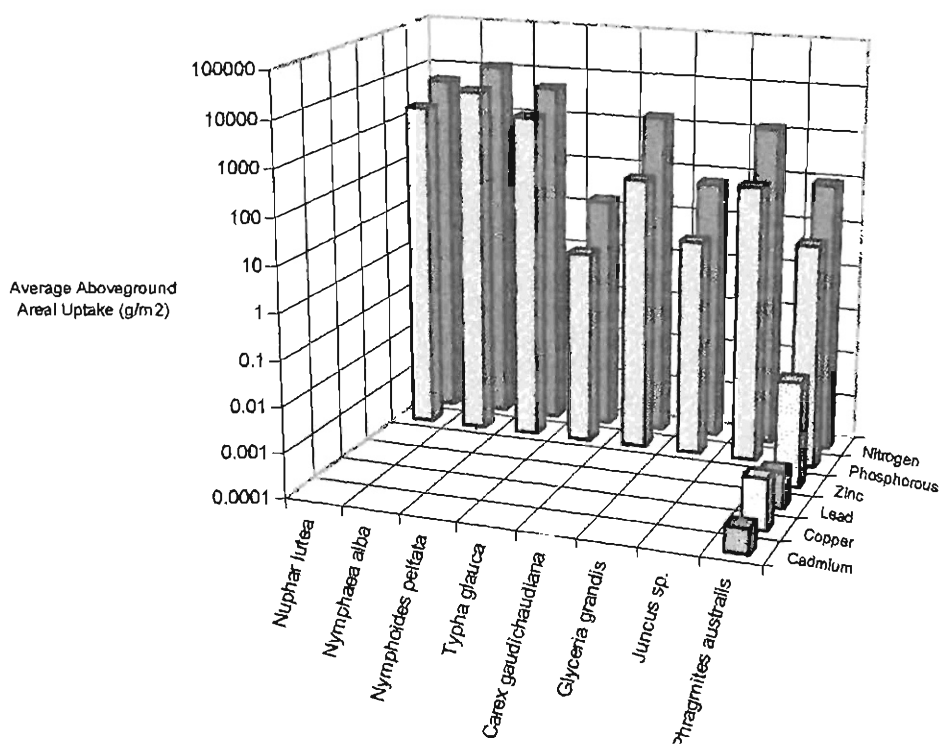


Figure 69. Average aboveground areal uptake (g/m^2)

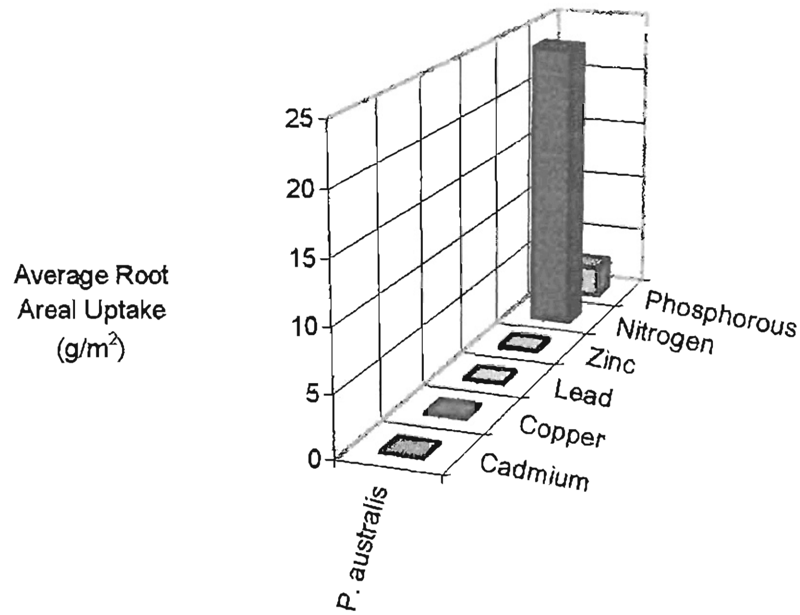


Figure 70. Average root areal uptake (g/m^2)

Metal uptake was low for this species with the greatest uptake reported for zinc (0.113 g/m^2). Information on rhizome uptake was also limited. *Typha glauca* had the greatest uptake for nitrogen (8.76 g/m^2), while *Phragmites australis* had the greatest affinity for zinc (0.06 g.m^2) (Figure 71).

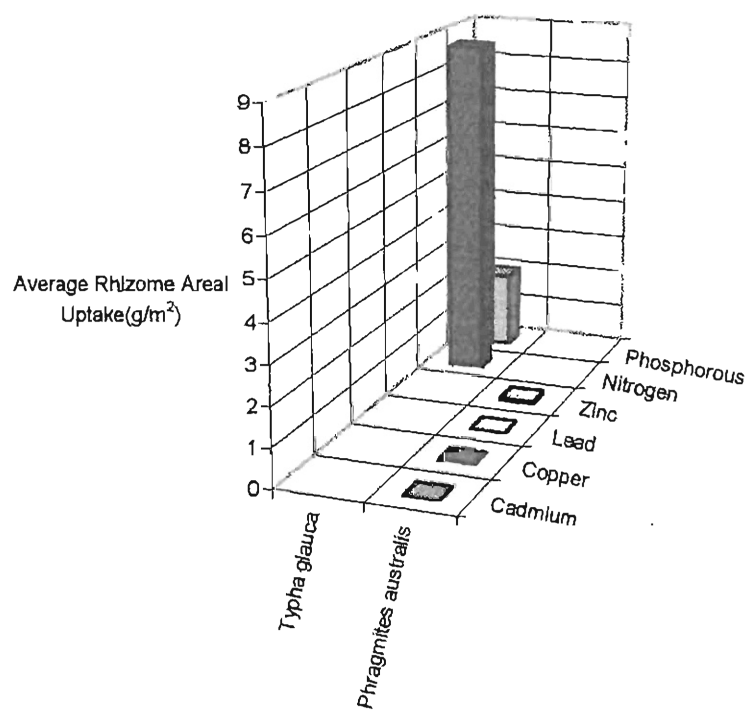


Figure 71. Average rhizome areal uptake (g/m^2)

Uptake Rates (g/m²/day)

In every case, average AGT uptake rates were greater for nitrogen than for phosphorus for all plants identified from the literature search (Figure 72). AGT uptake rates of nitrogen and phosphorus were greater for emergent and floating vegetation. Sedges/grasses/rushes had the poorest ability to uptake nitrogen and phosphorus. The only metal uptake rate was reported for chromium, which was taken up by *Lemna minor* at a rate of 0.667 $g/m^2/day$.

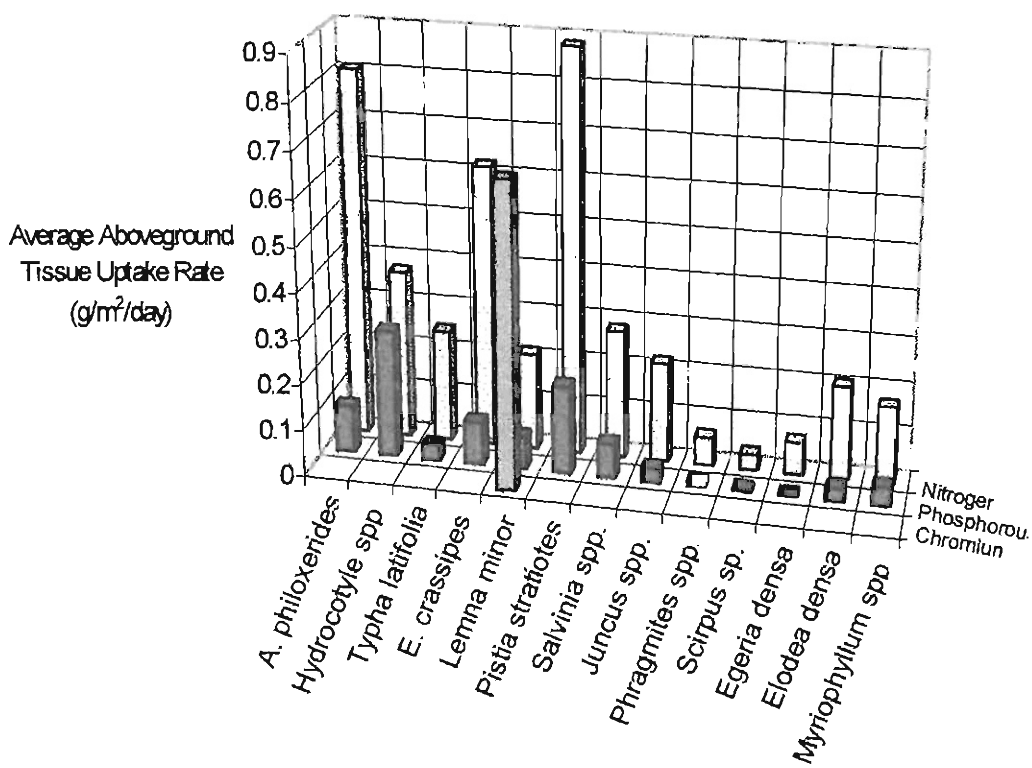


Figure 72. Average aboveground uptake rates ($g/m^2/day$)

Average root uptake rates were limited to *Eichhornia crassipes.* and *Myriophyllum spicatum* (Figure 73). *Eichhornia crassipes.* roots had a high affinity for nitrogen (0.38 $g/m^2/day$) while *Myriophyllum spicatum* had a lower affinity for phosphorus (0.006 $g/m^2/day$).

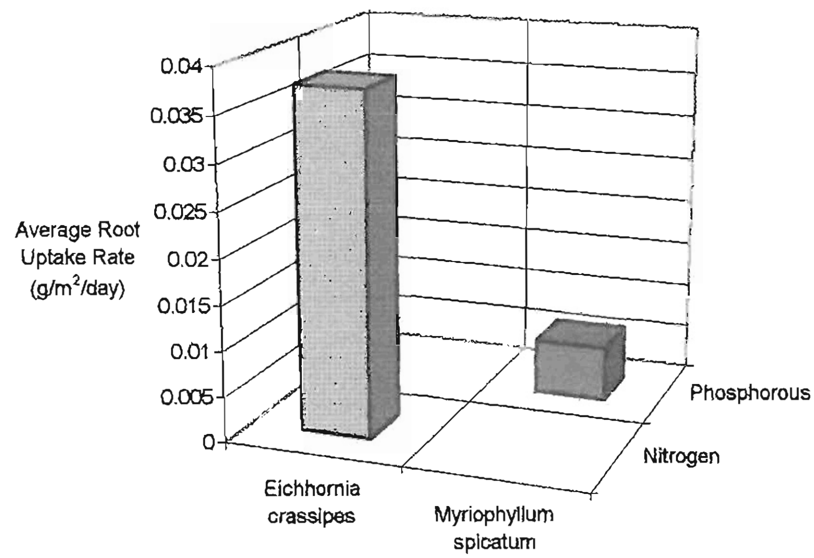


Figure 73. Average root uptake rates (g/m^2/day)

Summary

An extensive literature search was performed to compile data on uptake abilities of various wetland and aquatic macrophytes. *Myriophyllum spp.*, a submergent plant, accumulated some of the highest levels of metals in its AGT including arsenic, cadmium, cobalt, copper, iron, lead, manganese and zinc. This plant also tolerates the greatest maximum water depth reported of 6.5 m. Data for duration of inundation were not available for this particular plant. Other submergent macrophytes with notable accumulation of metals in AGT include *Elodea canadensis* (arsenic, cobalt, and iron), *Hydrilla verticillata* (cadmium and chromium), *Pistia stratiotes* (cadmium), *Ceratophyllum demersum* (chromium, iron and lead) and *Vallisneria spiralis* (chromium and lead). Several species of floating vegetation were also able to accumulate high levels of metals in their tissue including *Azolla spp.*, (cadmium, cobalt, copper, iron, lead, manganese and nickel), *Lemna minor* (copper, iron and zinc), *Spirodela polyrrhiza* (chromium, iron, lead) and *Salvinia natans* (manganese). Since these plants are not rooted in the sediment, they can withstand deep water depths and can tolerate flooding durations of 85-90% of the growing season.

Data on metal accumulation by root and rhizome tissue were limited mainly to sedges and emergents. Root and rhizome tissues typically accumulated higher levels of metals than AGT. High levels of metals in root tissue were observed for *Phragmites australis* (cadmium and zinc), *Bacopa spp.* (chromium and copper), *Typha spp.* (iron, manganese, nickel and zinc), *Scirpus lacustris* (chromium and copper), *Nymphoides spp.* (arsenic,

lead and manganese) and *Potamogeton spp.* (lead, manganese and zinc). Elevated levels of metals were found in rhizome tissues of *Typha spp.* (copper, iron, manganese and zinc) and *Phragmites australis* (zinc).

Nitrogen and phosphorus levels were high in AGT for all plants identified from the literature search (>10,000 and >1,000 ug/g, respectively). To determine which plants take up these nutrients most effectively, areal concentrations and uptake rates were examined. AGT areal uptake of nitrogen and phosphorus (g/m^2) was greatest for floating-leaved emergents, specifically *Nuphar lutea*, *Nymphaea alba* and *Nymphoides peltata.* With respect to time (g/m^2/day), *Alternanthera philoxerides*, *Eichhornia crassipes* and *Pistia stratiotes* had the highest uptake rates of nitrogen. *Hydrocotyle spp.* and *Pistia stratiotes* had the highest AGT uptake rates of phosphorus.

A number of the plants identified as being effective in accumulating metals and nutrients are also exotic species. These include some species of *Myriophyllum and Salvinia, Alternanthera spp., Eichhornia crassipes, Pistia spp.,* and *Hydrilla spp.* Exotic species are considered to be nuisances since they spread rapidly and out compete and displace indigenous species. However, by identifying their ability to accumulate high levels of some metals and nutirents, these plants can serve a beneficial purpose in treatment wetlands.

The uptake of metal ions by aquatic plants will ultimately depend upon the nature and amount of aquatic biomass, its stage of development and earlier treatment, as well as the volume of influent water and its metal ion content (Jain et. al., 1988). The potential rate of uptake of nutrients by a plant is limited by its growth rate and concentrations in its tissue, whereas storage is dependent on both tissue nutrient concentrations as well as the ultimate potential for biomass accumulation. Therefore, desirable traits of a plant used for nutrient assimilation and storage should include rapid growth, high tissue nutrient content, and the capability to attain a high standing crop (Reddy and Smith (eds.), 1987). Since the findings of this study are only an estimate of uptake abilities of certain plants, one should evaluate the previously mentioned parameters before selecting an aquatic plant species for removal of both metals and nutrients.

Once metals and nutrients have been accumulated in plant tissue, subsequent harvest of plant biomass should be performed, which results in the permanent removal of stored contaminants from the treatment system (Reddy and Smith (eds.), 1987). If harvesting is not performed metals and nutrients accumulated in plant tissue will be returned to the system in the form of detritus after the onset of senescence (Mudroch and Capobianco, 1978).

Macrophytes are not the sole means for uptake, as microbial activity plays an important role in the assimilation, transformation, and recycling of chemical constituents present in wastewater (Kadlec and Knight, 1996). However, by serving as a means for uptake and providing a substrate for microbial populations, macrophytes are an integral part of any wetland treatment system. The hydrologic regime of a wetland regulates which types of plants can survive in a particular wetland and is the key feature to which water quality wetland functions can be connected (Reddy and Smith (eds.), 1987). By understanding which plants can accumulate high levels of contaminants and the types of water conditions they can tolerate, one can effectively enhance the treatment goals of a wetland system.

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