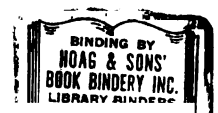




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METAL CYCLING IN MACROPHYTE
DOMINATED WASTEWATER PONDS

Thesis for the Degree of M. S.
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DOUGLAS A. BULTHUIS
1973



ABSTRACT

METAL CYCLING

IN

MACROPHYTE DOMINATED WASTEWATER PONDS

By

Douglas A. Bulthuis

Sediments and aquatic vascular plants are potential sinks for contaminating elements in wastewater stabilization ponds as they are operated in Michigan. The accumulation of several heavy metals in these sinks was studied during the growing season in an existing series of stabilization ponds. Using inflow and outflow data, an approximation of the accrual was made for each element in bottom sediments. Biomass estimates of the hydrophyte communities were used to determine the quantities of metals removable from a system by harvest of a season's crop.

The ambient concentrations of chromium, copper, iron, manganese and zinc were reduced in the ponds through accumulation in these sinks. The ambient concentrations of cadmium, cobalt and nickel were not reduced in the ponds. Estimates were made of the relative efficiencies of removal by plant absorption and by sedimentation in aerobic ponds during the growing season. Plant absorption was more efficient than sedimentation for iron and manganese. Sedimentation was more efficient than plant absorption for chromium, copper and zinc. Sedimentation and plant absorption were equally inefficient for removal of cadmium, cobalt and nickel.

METAL CYCLING
IN
MACROPHYTE DOMINATED WASTEWATER PONDS

By
1127
Douglas A. Bulthuis

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INTRODUCTION

Municipal waste treatment schemes for the Great Lakes region are currently incorporating land disposal of effluent as a means of locally trapping eutrophying elements (Anon., 1970; Anon., 1971; Bahr, 1972). Stabilization ponds or storage ponds are an ordinary part of these designs. Presumably, knowledgeable manipulation of the communities of the ponds can play a role in optimizing treatment in the system as a whole. The mechanisms controlling BOD, coliform, nitrogen and phosphorus dynamics in such ponds have received considerable attention in the literature (Fitzgerald and Rolich, 1958; Towne, Bartsch, and Davis, 1957). Evaluation of the long term feasibility of these systems requires a consideration of the mechanisms that control the dynamics of the other materials in the waste, including metals.

Many stabilization pond systems in Michigan are designed so that anaerobic, facultative and aerobic cells (cf. King, 1967) exist in a series during the summer irrigation season. Regarding plant communities, facultative cells are dominated by assemblages of chlorophycean algae of the types described by Mackenthun and McNabb (1959). Aerobic cells are dominated by submersed macrophytes. In addition to being responsible for biological aeration,

these plant communities have an influence on pH and redox potentials (Wium-Andersen and Andersen, 1972). Hence, they play a key role in pond function by exerting a control on the solubility of a variety of compounds and complexes. They also represent a sink for eutrophying elements that could be removed to take these from the site (McNabb and Tierney, 1972). Economic use of such aquatic plants have been considered by Little (1968), Bagnall, Casselmann, Kesterson, Easley and Hellwig (1971) and others.

The following hypotheses regarding the dynamics of cadmium, chromium, cobalt, copper, iron, manganese, nickel and zinc are addressed:

- 1) the concentration of each of these elements is reduced in the water as it moves through facultative and aerobic cells in a series of stabilization ponds during the growing season.
- 2) during the growing season natural aquatic macrophyte communities accumulate a larger fraction of each incoming element than do the sediments of aerobic stabilization ponds.

DESCRIPTION OF STUDY SITE

The city of Belding, located in the southwest quadrant of the lower peninsula of Michigan, has a stabilization pond system consisting of a series of five cells. The ponds cover about 23 hectares, have a maximum depth of 2 meters and serve a population of about 5000. Untreated waste from the primarily residential community enters Pond 1 and flows by gravity through Ponds 2, 3, 4 and 5 (Figure 1). There are three types of ponds within the series: anaerobic, facultative and aerobic. Pond 1, an anaerobic cell, is characterized by a lack of oxygen, apparent black colored water, and production of gas that continually breaks the surface. Pond 2, a facultative cell, is characterized by a dense phytoplackton bloom throughout the summer, high dissolved oxygen at the surface, decreasing dissolved oxygen going deeper in the water column and black, gas producing anaerobic sediments. Ponds 4 and 5 are aerobic, are dominated by submersed macrophytes, have dissolved oxygen well mixed throughout the water column and have sediments that are light colored and aerobic at the mud-water interface. Pond 3 fluctuates between the facultative and aerobic state. Light intensity at the bottom of Ponds 4 and 5 had a mean seasonal value of about 25% of the surface light and the light intensity at 2 meters corresponded to the light intensity at about 0.3 meter in the facultative pond.

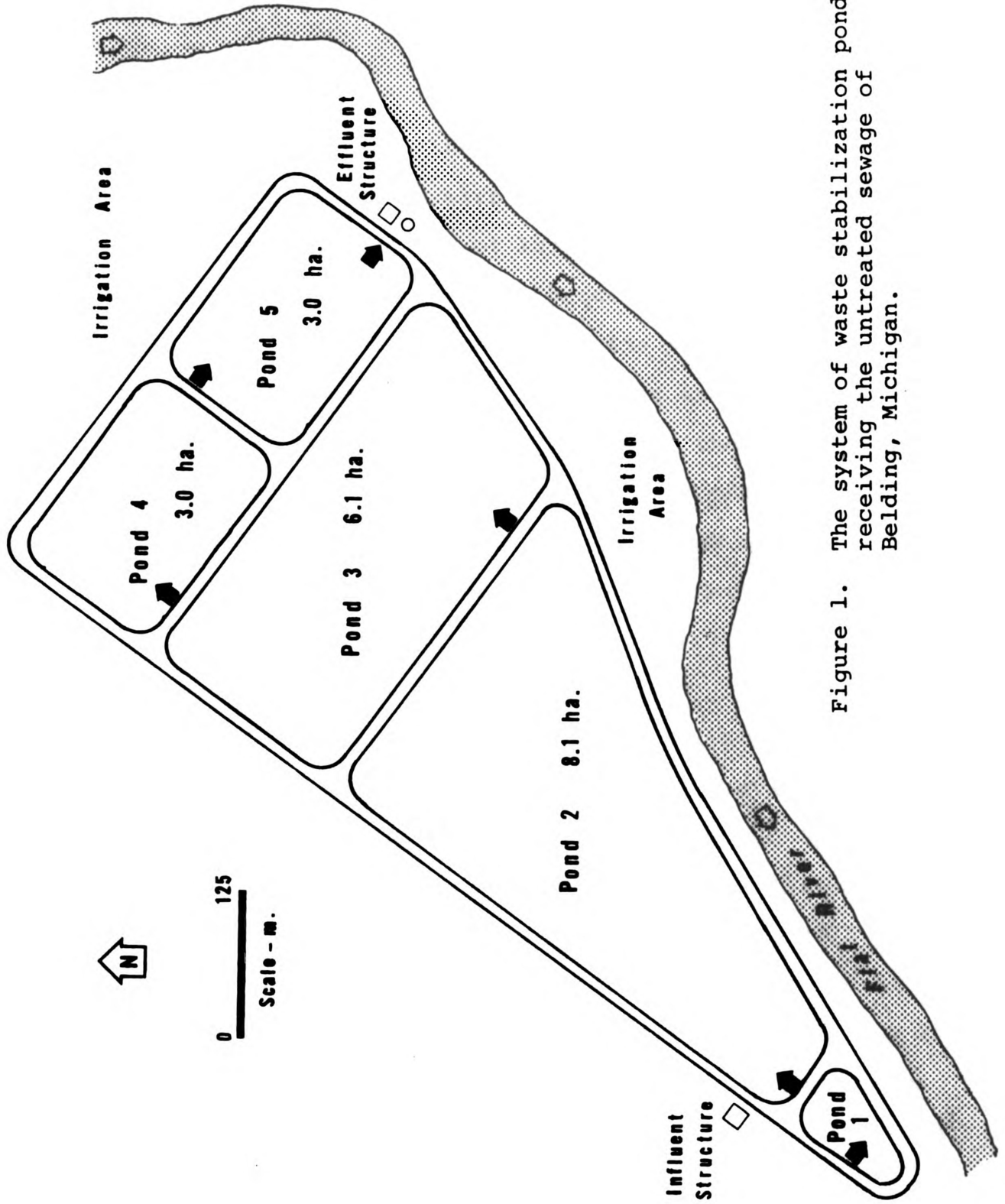


Figure 1. The system of waste stabilization ponds receiving the untreated sewage of Belding, Michigan.

METHODS

Flow between the ponds was measured every ten days in the growing season with a Gurley current meter lowered into submerged conduits of known diameter through a standpipe on the dike between the ponds. Water samples were collected in the conduits and in the ponds and concentrated by freeze drying. In early September transects of the plant communities were examined to determine the percent cover of species comprising the terminal crop of the season. Quantitative samples were taken within stands of each species for biomass estimates and metal determinations. Observations of growth early in the season indicated that this crop developed in *circa* 80 days.

Whole plants were collected, washed in pond water, placed in polyethelene bags, dried in a forced draft oven at 80°C and weighed. The plants were crushed by hand in the polyethelene bags. Five grams of plant tissue were wet ashed with 200 ml of a 20 to 1 HNO_3 and HClO_4 acid mixture in a Bethge distillation apparatus. The freeze dried residues of water samples were wet ashed with 100 ml of a 20 to 1 HNO_3 and HClO_4 acid mixture in the same apparatus. Metal determinations of the plant and water concentrates were made by atomic absorption spectrophotometry on a

Perkin Elmer model 303. Dry weight estimates are based on a mean of 12 samples; plant metal concentrations on a mean of 4 to 6 samples.

RESULTS

Measurements of the volume of flow between the ponds were used to obtain a mean that was taken as the daily input or output of each pond in the system for the 80 day growing season. A water budget constructed from these data is shown in Figure 2. During the growing season 157 million liters entered the system and 2 million liters were taken from Pond 5 for spray irrigation on adjacent land. The water level in the ponds was raised 0.3 meter so that part of the water and elements that entered each pond were accounted for by this storage. The evaporation data represent a net exchange with the atmosphere as measured by a rain gauge and evaporating dish located at the site. Percolation out of the ponds was calculated by subtraction. Pond 5 in this system was designed to act as a seepage pond and had a considerable flow through the bottom.

The last three ponds in this system were dominated by submersed hydrophytes. The community in Pond 3 consisted primarily of *Ceratophyllum demersum* L. (coontail). Late in the season the *C. demersum* floated to the surface and provided an area sheltered from wave action upon which *Lemna minor* L. (duckweed) expanded to completely cover the *C. demersum* mat. The aspect of this vegetation is shown in Figure 3. Figures 4 and 5 show the nature of the hydrophyte

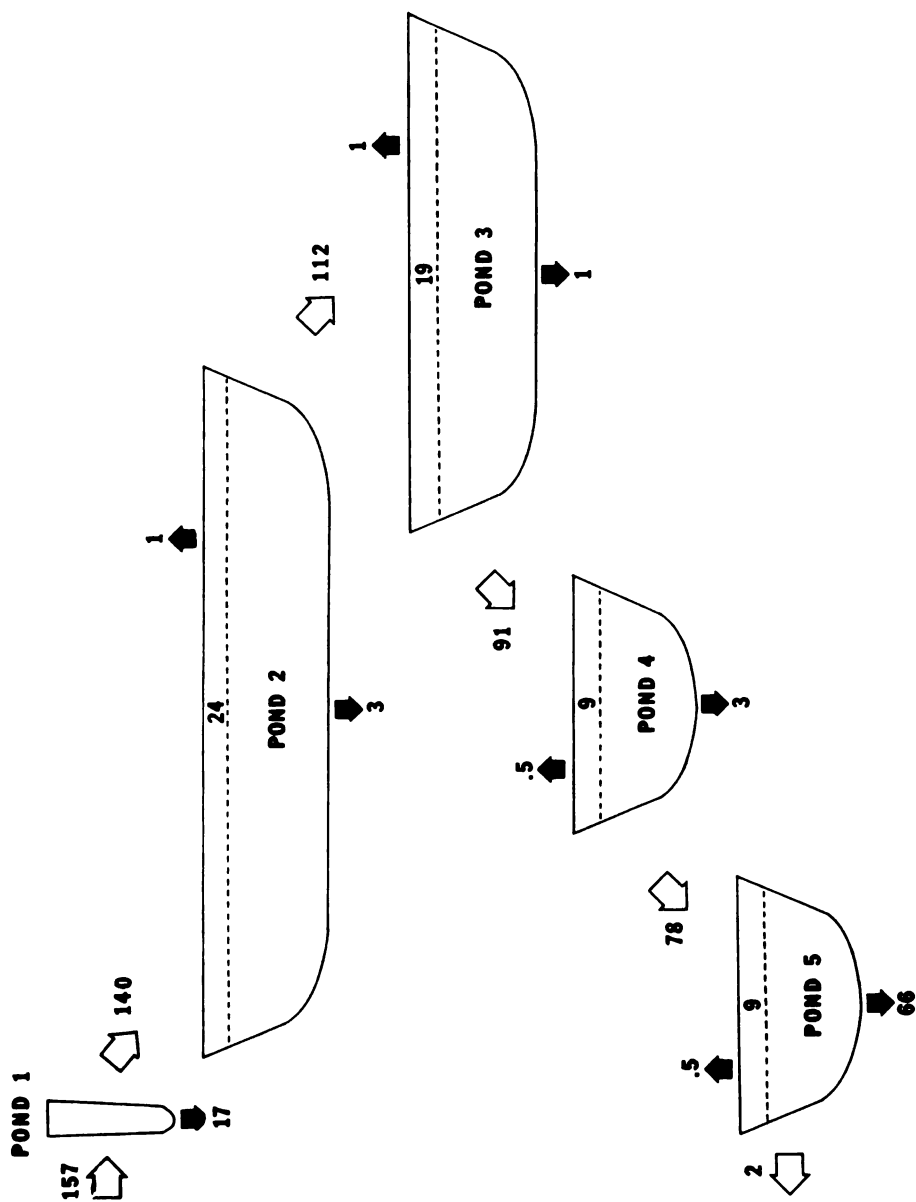


Figure 2. The volume of inflow, net storage, seepage, net evaporation and outflow in millions of liters of water for the stabilization pond system of Belding, Michigan, during the June-September interval of 1972.

Pond 3

	gm/m ² Dry Wt. (Std. Dev.)	% of Pond Covered	Kg/ha of Pond
C. demersum	138 (59.5)	30.1	433
L. minor	92 (62.6)	30.1	295
			<u>728</u>

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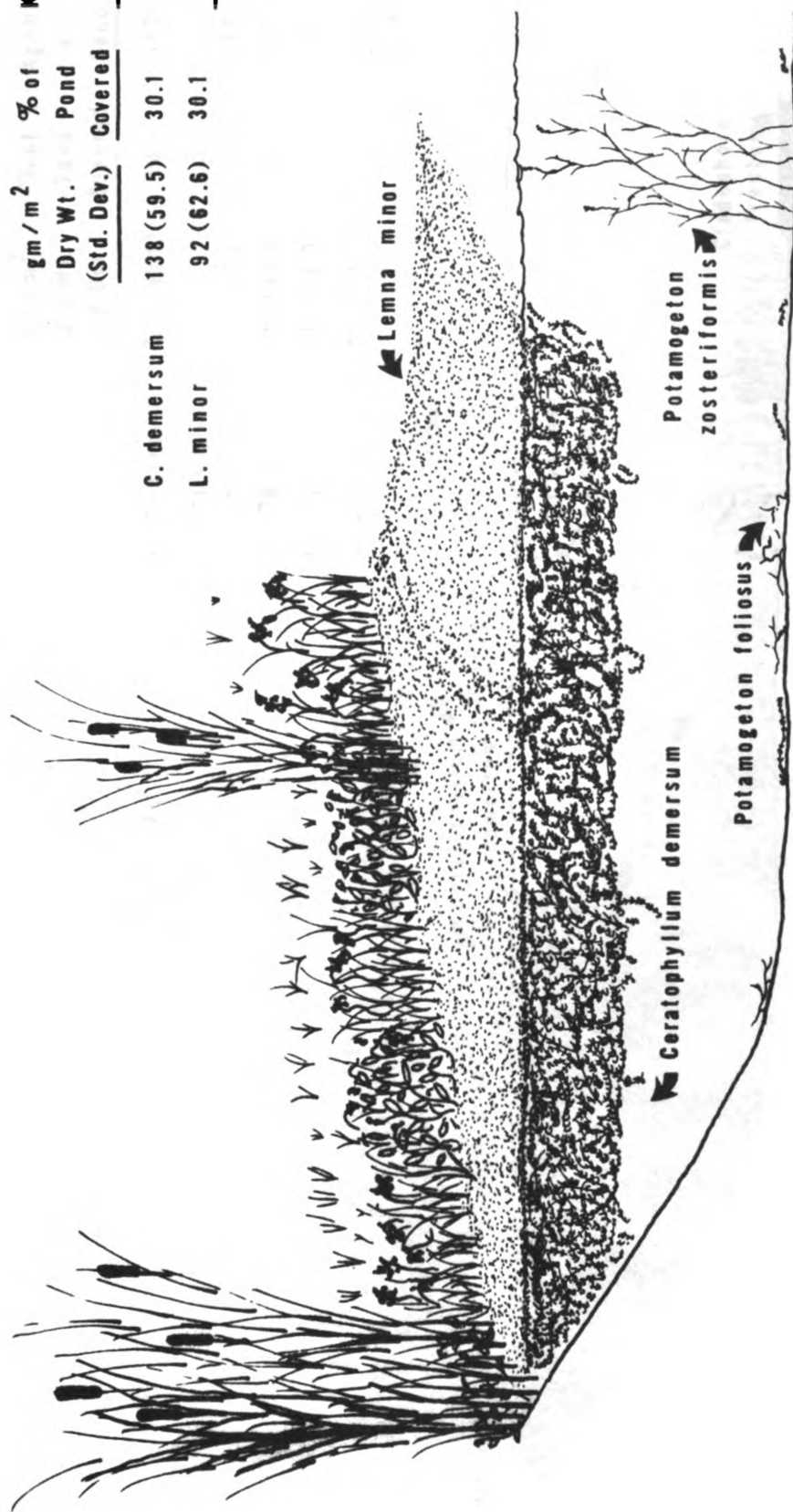


Figure 3. The submersed hydrophyte vegetation of Pond 3 in the Belding, Michigan, sewage stabilization system in September, 1972.

Pond 4

	gm/m ² Dry Wt. (Std. Dev.)	% of Pond Covered	Kg/ha of Pond
C. demersum	234 (60.6)	38.7	963
P. foliosus			
Shallow	184 (53.9)	6.6	129
Deep	36 (43.8)	50.3	190
L. trisulca	62 (18.3)	0.1	0.7
C. fracta	210 (74.7)	0.7	16
			1299

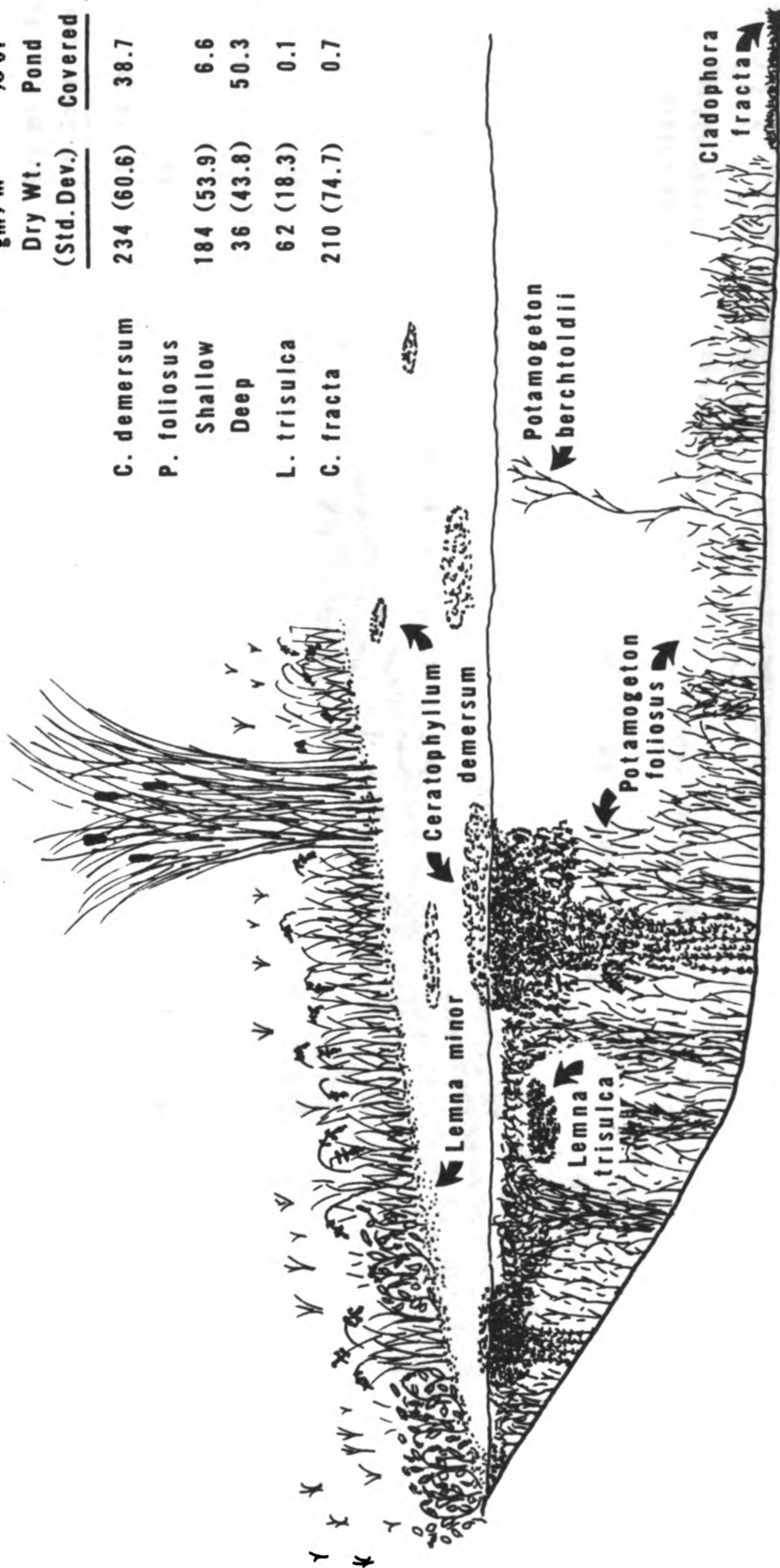


Figure 4. The submersed hydrophyte vegetation of Pond 4 in the Belding, Michigan, sewage stabilization system in September, 1972.

Pond 5

	gm/m ² Dry Wt. (Std. Dev.)	% of Pond Covered	Kg/ha of Pond
P. pectinatus	116 (48.3)	1.1	14
P. borchteldii	94 (32.4)	2.1	21
P. borchteldii Fragments	96 (43.8)	1.2	12
L. trisulca	62*	2.3	15
C. fracta	388 (74.7)	14.0	575
			637

*From Pond 4

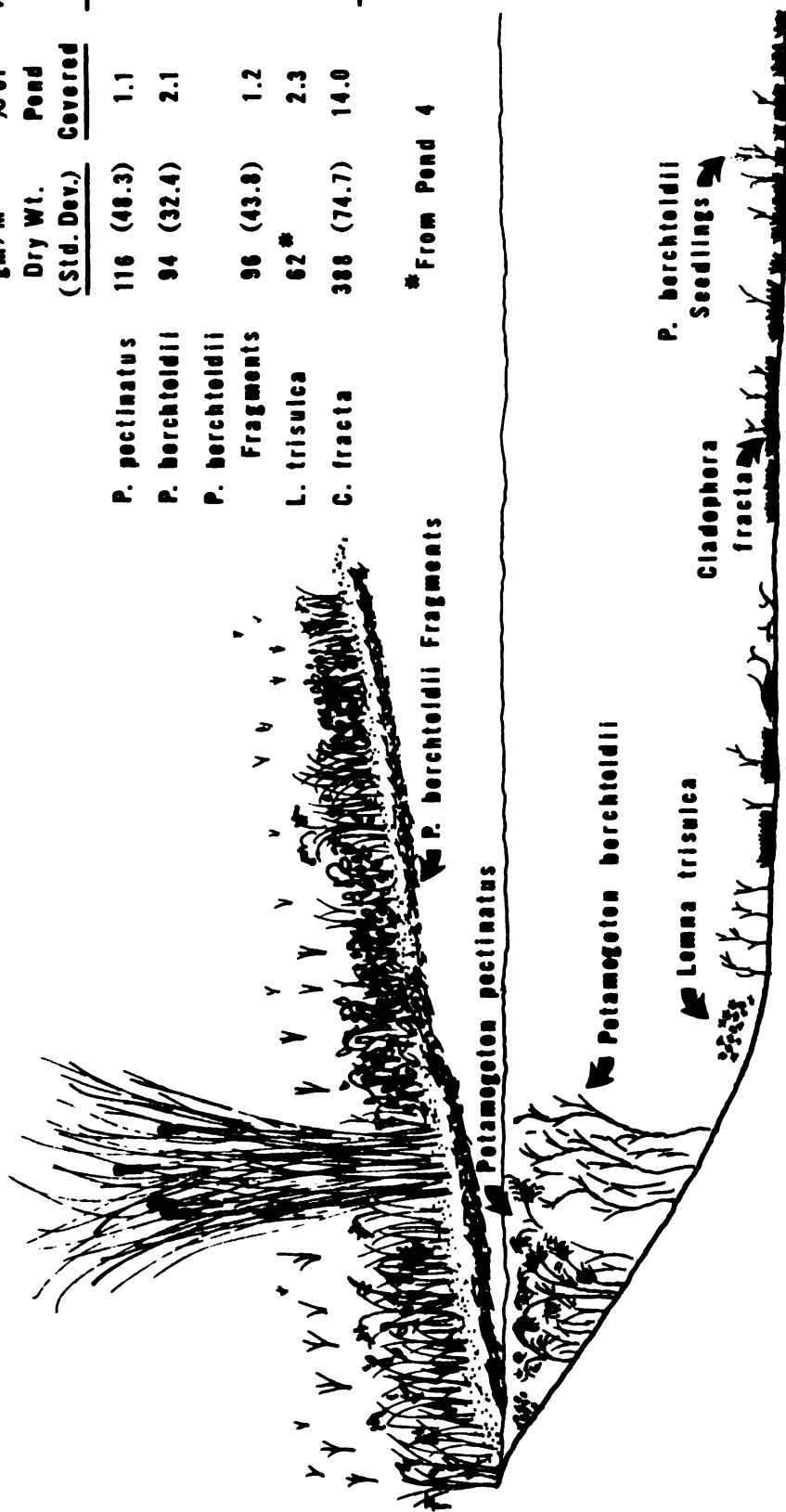


Figure 5. The submersed hydrophyte vegetation of Pond 5 in the Belding, Michigan, sewage stabilization system in September, 1972.

Pond 5

	gm/m ²	% of Pond Covered	Kg/ha of Pond
P. pectinatus	116 (48.3)	1.1	14
P. borchtoldii	94 (32.4)	2.1	21
P. borchtoldii Fragments	96 (43.8)	1.2	12
L. trisulca	62*	2.3	15
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* From Pond 4

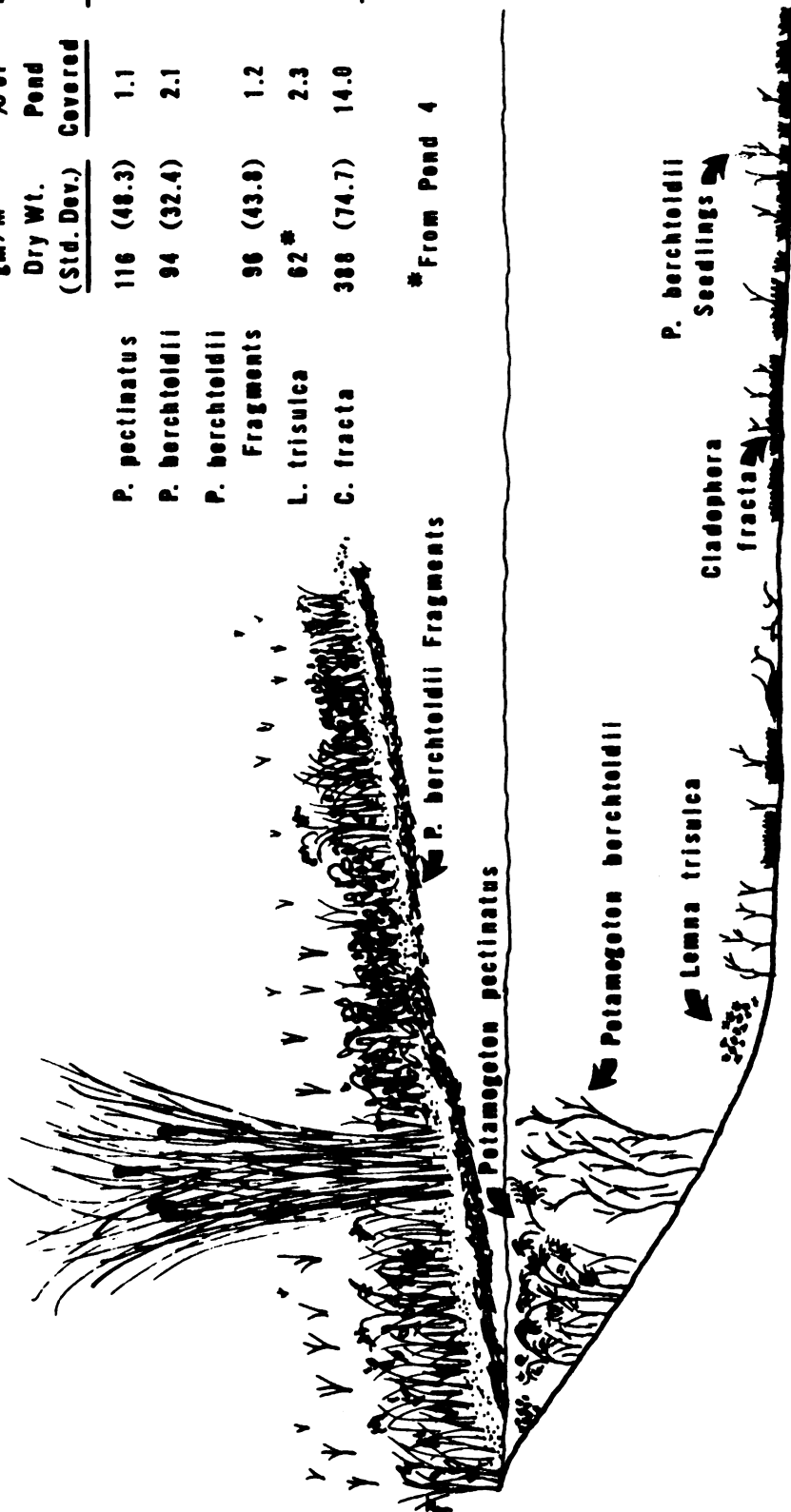


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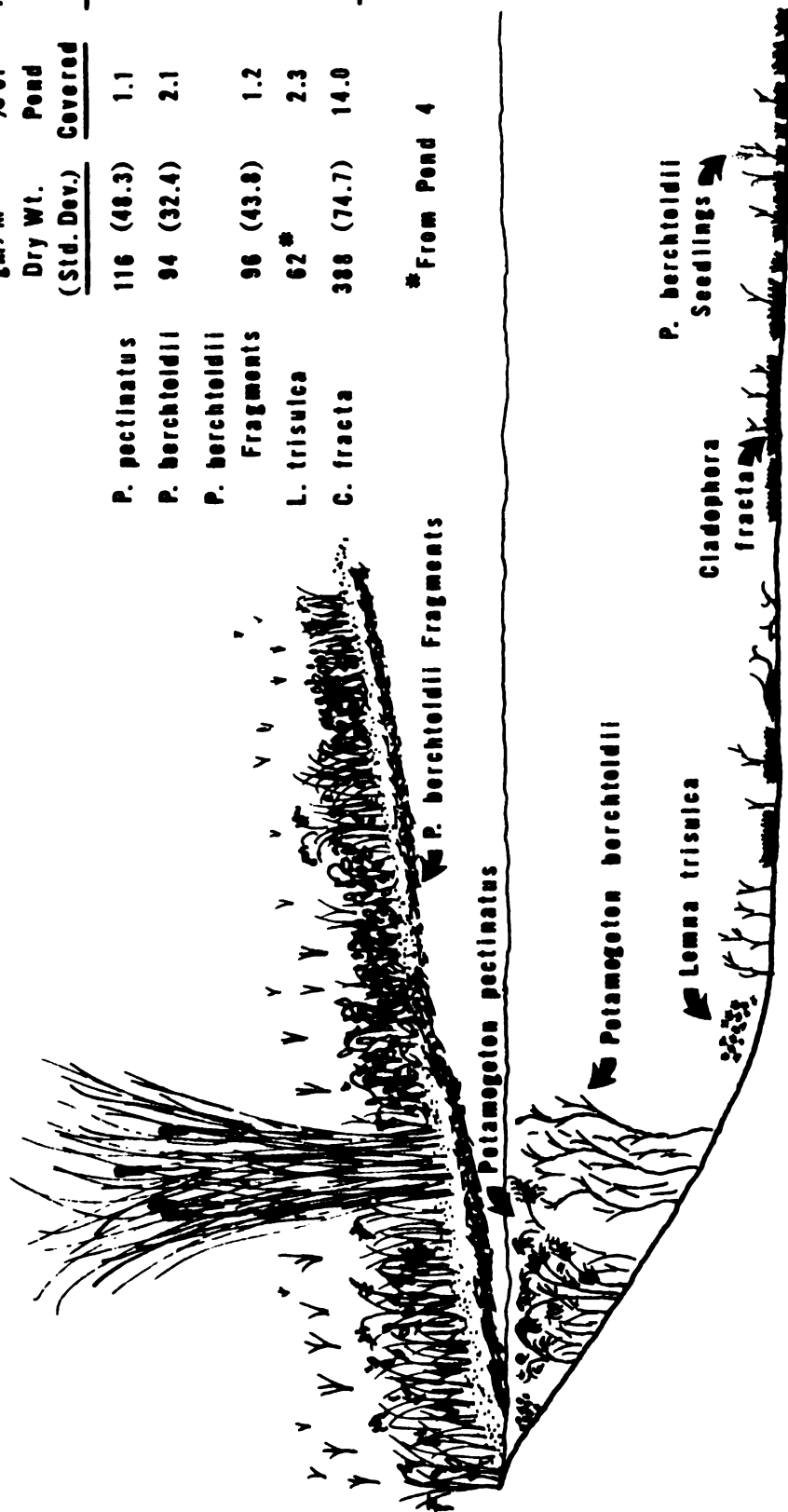


Figure 5. The submersed hydrophyte vegetation of Pond 5 in the Belding, Michigan, sewage stabilization system in September, 1972.

communities in Ponds 4 and 5 in early September when transects of the plant communities were made.

Combining the volumes of flow (Figure 2) with the trace metal concentrations in the water and plants, budgets were constructed showing the amount of metal accumulated in the various components of the plant dominated ponds over the growing season. The biomass estimates for the macrophyte communities, given in Figures 3, 4 and 5, were used to obtain the total amount of each metal held in the plant community.

The copper budget is presented in Figure 6. It reveals a stepwise decrease in copper load as the water moves through the ponds. Pond 2 was most effective and Ponds 3 and 4 less so in reducing the copper load in the water. This reduction was reflected in the seasonal mean of 21 ppb total copper entering Pond 2 and less than 2 ppb in Pond 5 (Cf. Table 1). An entry has been made in Figure 6 to account for the amount of copper contained in the volume of water stored in each pond over the growing season. This volume is ordinarily discharged to an adjacent stream in September. The Belding system is similarly drawn down in early April to accomodate the growing season storage. Note from Figure 6 that 175 grams of copper either moved with seepage water through the bottom of Pond 5 or was adsorbed by the soil through which the water moved.

Similar budgets were constructed for the other metals studied. The elements were divisible into two groups: those

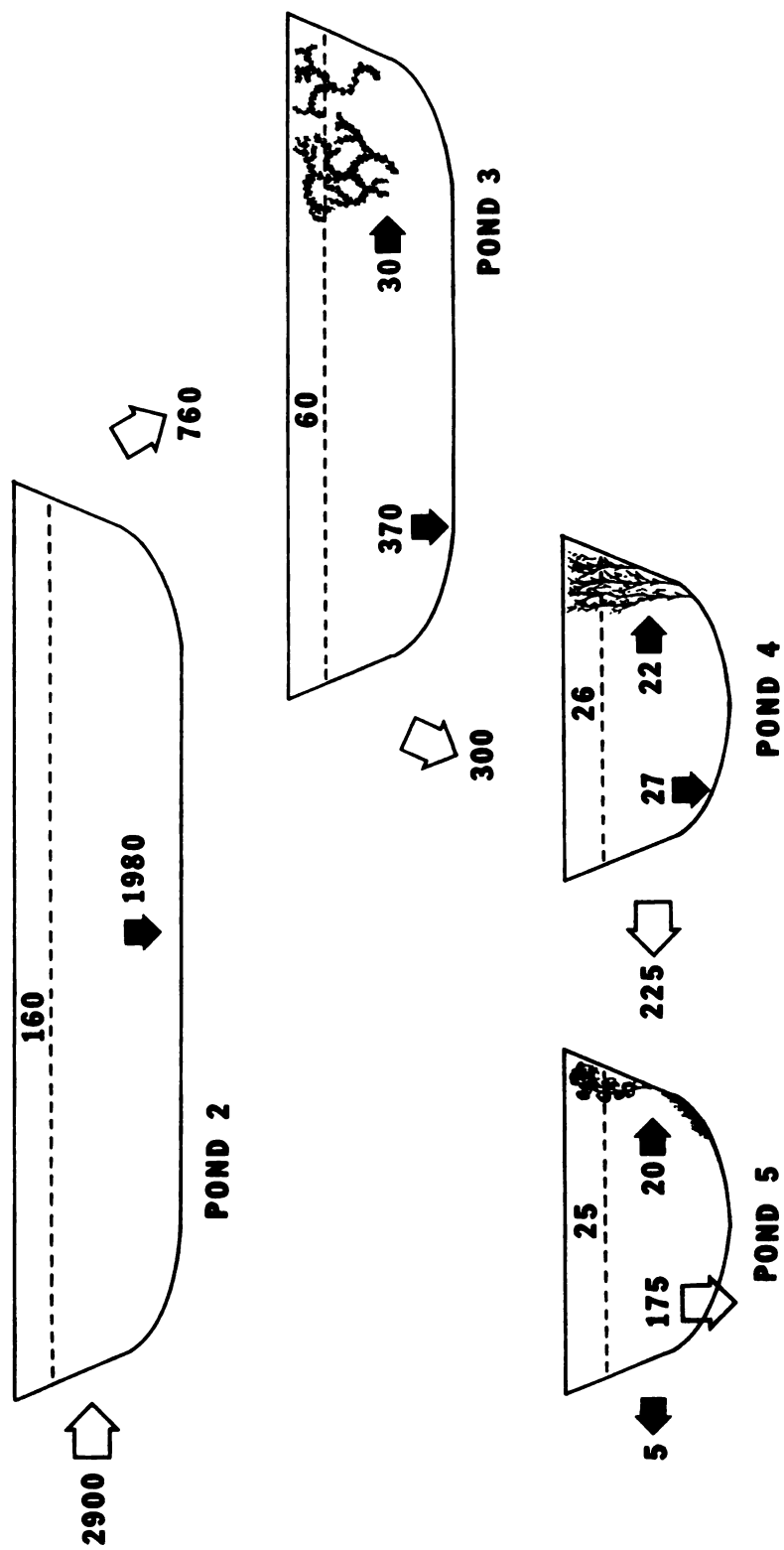


Figure 6. The copper budget of ponds in the Belding, Michigan, sewage stabilization system for the growing season of 1972 in grams.

that decreased through the system (non-mobile) and those that remained relatively constant through the system (mobile). Those that decreased, in addition to copper, were zinc, iron, chromium and manganese. The concentrations of these metals in the different ponds are presented in Table 1.

As the water flowed through the system, a large portion (66%) of the zinc moved to the sediments in Pond 2; the zinc concentration remained the same in Pond 3, and was reduced in Pond 4 where 37% of the pond input moved to the sediments. The plant communities in cells 3, 4 and 5 accumulated 5-6% of each pond's zinc input. In Pond 5, where the concentration was the same as in Pond 3, 70% of the input either moved with the seepage water or was adsorbed by the soil through which the water moved.

Chromium was reduced regularly in each pond. Forty percent of the Pond 2 input went to the sediments, while 20% of the input of Ponds 3 and 4 went to their sediments. Very small fractions (1-2%) of the input chromium went to the plants of Ponds 3, 4 and 5. Eighty five percent of Pond 5's input moved with the seepage water or was immobilized in the bottom sediments.

Iron and manganese were reduced considerably in Pond 2 where 75% and 50% respectively were trapped in the sediments. In Pond 3, (11 kg Fe and 4.3 kg Mn entering) the plants accumulated large amounts of the metals (.96 kg Fe and 8.2 kg Mn) while the sediments released even larger amounts (1.8 kg Fe and 9.8 kg Mn). This resulted in increased

Table 1. Mean concentration (ppb) of the non-mobile metals in the unfiltered water of the Belding, Michigan, sewage stabilization system for the growing season of 1972.

	Zinc	Copper	Chromium	Iron	Manganese
Pond 1 Effluent	70	21.	8.5	340	73
Pond 2 Effluent	25	6.8	5.2	96	38
Pond 3 Effluent	25	3.3	4.3	110	59
Pond 4 Effluent	15	2.9	3.5	100	30
Pond 5	25	--	--	67	14

concentrations of iron and manganese in the Pond 3 effluent. There was a net movement of iron and manganese out of Pond 4 sediments (1.8 kg Fe and 6.3 kg Mn), but large quantities taken up by the plants (2.8 kg Fe and 9.1 kg Mn) helped to lower the water concentrations. In Pond 5 (8.1 kg Fe and 2.3 kg Mn entering) 31% of the input iron was trapped in the plants and 60% moved with the seepage water or was immobilized in the bottom sediments. The Pond 5 plant community accumulated 2.5 kg of manganese indicating a net movement of manganese out of the sediments (.36 kg).

In contrast to the non-mobile metals which had a tendency to become trapped in some portion of the system, several of the metals were not reduced or reduced very little as they moved through the ponds. This is shown in Table 2 to be the case for cadmium, cobalt and nickel. The coefficients of partitioning shown in Table 2 are fractions of the growing season input that accumulated in each component at the end of the growing season. The low coefficients to plant uptake and sedimentation indicate the low amounts being trapped in the ponds. Throughout the system total nickel averaged 13 ppb, cobalt 15 ppb and cadmium 2.1 ppb.

At the end of the growing season, a portion of the metals which entered each pond during the summer was trapped in the plant community. The tendency to concentrate these elements is shown in the compilation of Chapman, Fisher and Pratt (1968). As the plants age and decay, the metals that had been in them moves to the sediments or is released to

Table 2. Coefficients of partitioning of mobile metals in ponds of the Belding, Michigan, system. The total input to each pond for the growing season is taken as 1.00.

Metal	Pond	Pond Sediment	Water Stored	Plant Uptake	Output
Nickel	2	.28	.12		.60
	3	.02	.14	.02	.82
	4	.04	.10	.02	.84
	5	.78*	.17	.01	.04*
Cadmium	2	.03	.17		.80
	3	-.01	.17	.01	.83
	4	.04	.11	.01	.84
	5	.84*	.12	.005	.03*
Cobalt	2	.02	.17		.81
	3	.00	.16	.01	.83
	4	.03	.10	.01	.86
	5	.85*	.12	.005	.03*

*For Pond 5, sediment value is quantity carried into bottom by high-rate seepage flow; volume of output very low.

the water (cf. Cowgill, 1968; Kimball, 1973). Harvest of the plant community at maximum biomass could remove this fraction from the system. Using the biomass of each species in the pond with the concentration in each species and the amount of metal entering each pond, the percentage of the total metal entering the ponds over the growing season which could be harvested in the plant communities was estimated. The coefficients of partitioning to the plants in Ponds 3 and 4, given in Table 3, indicate the percentage of the input that could be harvested. Harvest of the plant crops would yield between 1 and 2% of the cadmium, chromium, cobalt and nickel entering each pond during the growing season and a slightly higher percentage of the copper and zinc (4-7%). Sediments were equally ineffective in accumulating the cadmium, cobalt and nickel. However, sedimentation removed substantially greater percentages of copper, chromium and zinc depending on the particular pond (cf. Table 3: copper-Pond 3, zinc-Pond 4, chromium-Ponds 3 and 4). The plants accumulated iron and especially manganese. In contrast there was a net movement of iron and manganese out of the sediments during the growing season as indicated by the negative values in Table 3.

Table 3. Coefficients of partitioning to the season-end communities and sediments in aerobic ponds in the Belding, Michigan, system. The total input to each pond for the growing season is taken as 1.0.

Pond	Sink	Ni	Cd	Co	Cr	Cu	Zn	Fe	Mn
3	Plants	.02	.01	.01	.01	.04	.06	.09	1.90
3	Sediments	.02	-.01	0.00	.18	.49	.02	-.16	-2.28
4	Plants	.02	.01	.01	.02	.07	.05	.28	1.69
4	Sediments	.04	.04	.03	.20	.09	.37	-.18	-1.17

DISCUSSION

The hypotheses to which this study was addressed have been rejected on the basis of the data that were obtained. Regarding the first of these (that the metal concentrations would be reduced), the concentration of certain metals was reduced as the wastewater moved through the series of ponds at Belding, Michigan. Copper, zinc, chromium, iron and manganese were all immobilized such that mean seasonal concentrations were reduced from the higher values observed at the input to Pond 2 to the lower values observed in Pond 5 (Table 1). However, contrary to the first hypothesis, cadmium, cobalt and nickel were not immobilized in this system. This mobility might be expected of nickel and cobalt because of their relatively soluble salts (Kopp and Kroner, 1970), but cadmium, which in this series was mobile, is usually reported as having chemistry similar to zinc (Hem, 1972; Leeper, 1972), which in this series was immobilized. Apparently these mobile metals are not being precipitated with iron or manganese oxides, nor being removed through adsorption on settling organic matter. Their mobility may be due to chelation by soluble organics.

The literature concerning the movement of metals in aquatic systems with concentrations of suspended and soluble

organics and inorganic compounds of the quality, quantity and ratios encountered in stabilization pond systems is scant. For rivers and other bodies of natural water Jenne (1968) proposes that precipitation and dissolution of hydrous oxides of iron and manganese are often the controlling mechanism of the concentration of many of the heavy metals. Adsorption to suspended organics which slowly settle is another potential controlling mechanism. If a single driving mechanism were controlling the concentration of all of the heavy metals in stabilization ponds, manipulation of the ponds for removal of all the heavy metals could center on that mechanism. When several mechanisms are operative, manipulation of the system to optimize immobilization of all the heavy metals becomes complex. The reduction of the metals that were immobilized was not uniform for all metals; each metal exhibited unique characteristics in its budget. As an example, in Pond 3, 49% of the input copper was deposited in the sediments and only 2% of the input zinc. There was the reverse relationship in Pond 4 where 9% of the input copper and 37% of the input zinc was deposited in the sediments. This dissimilarity in response indicates more than one mechanism controlling the reduction of these metals. Copper may be reduced by adsorption to suspended organics in Pond 3 with primarily chelated copper entering Pond 4. If the copper were chelated with soluble organics very little of the copper entering Pond 4 would be expected to settle to the sediments. Zinc is not as tightly bound

to organic material as copper (Krauskopf, 1972) which might explain zinc's mobility in Pond 3. The plant community in Pond 4 may be raising the pH higher than in Pond 3 and precipitating zinc compounds which have a minimum solubility around a pH of 9.5.

The mechanisms that are important in trapping metals in a facultative pond may be different than the important mechanisms in the aerobic ponds. In Pond 2, a large portion of the metals that entered were immobilized in the sediments. This movement to the sediments may be effected by the settling of the organic and suspended solids that enter the pond. Copper, chromium and zinc have all been reported to be adsorbed to these materials (Krauskopf, 1972; Leeper, 1972; Hem, 1972). The photosynthetic activity of the algae maintained a saturation of dissolved oxygen and pH in the range of 8-9 in the upper layers of the pond. Under these conditions most metal ions form precipitates or may be incorporated into or on hydrous oxides of iron and manganese (Jenne, 1968). In the lower layers of the facultative cell sulfides of iron, copper and zinc may be forming (Cowgill, 1968; Hem, 1972).

The aerobic cells were dominated by submersed macrophytes that tend to regulate the pond chemistry by contributing to a high dissolved oxygen and pH through all depths. Generally the same mechanisms of precipitation, sorption to hydrous oxides and settling solids would be operative in these cells as in the upper layers of the facultative cell. Sulfide precipitation would not be important as the bottom

of the ponds was covered with an aerobic layer of sediments. The aerobic ponds had the additional mechanism of cation uptake by the submersed macrophytes.

The iron and manganese budgets seem anomalous. In anaerobic, reducing environments, iron and manganese are usually soluble and in aerobic, oxidizing environments they tend to precipitate as oxides. However, 75% and 50% of the input iron and manganese respectively settle to the sediments in the facultative Pond 2 which is partly anaerobic and there is a net movement out of the sediments in the aerobic ponds. The high sedimentation rates in Pond 2 may be caused by a combination of settling adsorbed and suspended metals and the formation of iron sulfide which is highly insoluble. In Ponds 3 and 4 the net seasonal movement of iron and manganese out of the sediments may be explained by their uptake by the plants from the sediments of the pond.

Regarding the second hypothesis to which this study was addressed, Table 3 indicates that plants and sediments accumulate similar fractions of the input cadmium, cobalt and nickel. Neither the plants nor the sediments were effective in reducing the ambient concentration of these elements. The plants accumulated smaller fractions of the input chromium, copper and zinc than did the sediments (Table 3). The plants accumulated larger fractions of iron and manganese than did the sediments since there was a net movement of these two elements out of the sediments. The metal concentrations of the plant tissues are similar to the few

values reported in the literature for aquatic vascular plants. However, comparison of tissue concentrations between plant communities or species sampled only once during the growing season can be misleading and not representative of the seasonal means (cf. Tierney, 1972).

The terminal crop of the season has been considered as the harvestable unit in this study. A harvesting strategy that includes proper timing to achieve effects that optimize treatment in the system as a whole, presently escapes definition for lack of integrated information concerning the combined goals at the aquatic and land sites. The very low coefficients of partitioning to aquatic plants given in Table 3 suggest that harvesting of natural populations at the end of the growing season to remove metals would be impractical. The sampled crop, however, is not necessarily the maximum that could be obtained. On the other hand, manipulation of the plant community to obtain desirable levels of dissolved oxygen, pH and redox potentials may be of considerable importance.

CONCLUSIONS

The following two hypotheses regarding the dynamics of cadmium, chromium, cobalt, copper, iron, manganese, nickel and zinc were addressed:

- 1) the concentration of each of these elements is reduced in the water as it moves through facultative and aerobic cells in a series of stabilization ponds during the growing season.
- 2) during the growing season natural aquatic macrophyte communities accumulate a larger fraction of each incoming element than do the sediments of aerobic stabilization ponds.

Both hypotheses have been rejected on the basis of the data that were obtained. Regarding the first hypothesis, the Belding sewage stabilization system reduced the ambient concentrations of chromium, copper, iron, manganese and zinc during the growing season. Ambient concentrations of cadmium, cobalt and nickel were not reduced in these ponds. Regarding the second hypothesis, plant absorption was more efficient than sedimentation for removal of iron and manganese in aerobic ponds; sedimentation was more efficient for removal of chromium, copper and zinc. Plants and sediments were equally inefficient in trapping cadmium, cobalt and nickel.

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APPENDIX

Table A1. The mean total concentration (ppb) of selected metals in the pond water in the Belding, Michigan, sewage stabilization system for the growing season of 1972.

Pond	Zinc	Nickel	Cadmium	Cobalt	Iron	Manganese
2	26	13	2.1	15	46	28
3	14	12	2.2	13	100	28
5	25	19	2.5	12	67	14

Table A2. Mean concentration (ppm of dry weight) of zinc, copper, iron and manganese and percent ash in each species of the season-end community of submersed hydrophytes in the Belding, Michigan, sewage stabilization system. (Mean $\pm$ S.E.).

Pond	Species	Percent Ash	Zn	Cu	Fe	Mn
3	<i>C. demersum</i>	19.0 ± 0.89	42 ± 4.6	4.9 ± 1.4	270 ± 46	2400 ± 240
3	<i>Lemna minor</i>	19.9 ± 1.44	37 ± 2.7	8.8 ± 0.93	140 ± 15	1100 ± 140
4	<i>C. demersum</i>	19.5 ± 4.10	32 ± 3.4	5.1 ± 0.77	710 ± 85	2700 ± 520
4	<i>Lemna minor</i>	21.6 ± 0.90	38 ± 3.0	4.0 ± 0.36	160 ± 26	570 ± 86
4	<i>Lemna trisulca</i>	26.4 ± 1.58	48 ± 6.4	8.2 ± 1.65	760 ± 186	3800 ± 580
4	<i>P. foliosus</i> (shallow)	11.7 ± 0.52	23 ± 1.9	5.1 ± 1.42	540 ± 152	830 ± 65
4	<i>P. foliosus</i> (deep)	20.9 ± 3.46	33 ± 4.7	6.9 ± 0.7	940 ± 225	1600 ± 170
4	<i>Cladophora</i> <i>fracta</i>	13.9 ± 0.66	43 ± 4.0	11.0 ± 1.33	3800 ± 200	400 ± 34
5	<i>C. demersum</i>	18.2 ± 1.59	34 ± 2.8	2.7 ± 0.19	240 ± 32	3700 ± 870
5	<i>Lemna minor</i>	17.7 ± 0.72	30 ± 1.2	6.0 ± 0.88	160 ± 12	1500 ± 70
5	<i>Lemna trisulca</i>	20.8 ± 0.74	50 ± 3.4	4.0 ± 0.43	440 ± 86	5400 ± 550
5	<i>P. pectinatus</i>	14.4 ± 0.90	31 ± 3.3	4.3 ± 0.94	1100 ± 500	1100 ± 110
5	<i>P. berchtoldi</i> (rooted)	15.3 ± 2.45	32 ± 2.7	4.6 ± 0.84	3600 ± 850	2100 ± 240
5	<i>P. berchtoldi</i> (mat)	13.0 ± 0.62	32 ± 1.4	4.6 ± 0.78	240 ± 29	1700 ± 190
5	<i>Cladophora</i> <i>fracta</i>	15.1 ± 2.09	40 ± 2.5	10.0 ± 1.06	1300 ± 120	1300 ± 60

Table A3. Mean concentration (ppm of dry weight) of chromium, nickel, cadmium and cobalt in each species of the season-end community of submersed hydrophytes in the Belding, Michigan, sewage stabilization system. (Mean $\pm$ S.E.).

Pond	Species	Cr	Ni	Cd	Co
3	<i>C. demersum</i>	0.8 ± 0.06	7.9 ± 0.20	0.58 ± 0.035	3.9 ± 0.24
3	<i>Lemna minor</i>	1.0 ± 0.06	6.6 ± 0.36	0.74 ± 0.086	4.7 ± 0.38
4	<i>C. demersum</i>	2.5 ± 0.70	6.2 ± 0.93	0.63 ± 0.040	5.0 ± 0.27
4	<i>Lemna minor</i>	1.0 ± 0.13	3.4 ± 0.44	0.62 ± 0.91	4.9 ± 0.68
4	<i>Lemna trisulca</i>	1.4 ± 0.24	7.6 ± 0.94	1.06 ± 0.030	7.0 ± 0.09
4	<i>P. foliosus</i> (shallow)	1.9 ± 0.50	5.6 ± 1.19	0.63 ± 0.097	6.5 ± 0.72
4	<i>P. foliosus</i> (deep)	2.5 ± 0.17	6.2 ± 0.66	0.69 ± 0.040	6.4 ± 0.23
4	<i>Cladophora</i> <i>fracta</i>	2.0 ± 0.22	5.9 ± 0.90	0.42 ± 0.074	4.4 ± 0.77
5	<i>C. demersum</i>	0.7 ± 0.04	4.8 ± 0.50	0.63 ± 0.049	4.0 ± 0.22
5	<i>Lemna minor</i>	0.7 ± 0.23	4.4 ± 0.47	0.60 ± 0.044	3.6 ± 0.32
5	<i>Lemna trisulca</i>	1.0 ± 0.12	6.1 ± 0.20	0.88 ± 0.120	4.6 ± 0.35
5	<i>P. pectinatus</i>	1.0 ± 0.15	4.3 ± 0.51	0.60 ± 0.084	3.5 ± 0.34
5	<i>P. berchtoldi</i> (rooted)	1.3 ± 0.16	5.0 ± 0.27	0.57 ± 0.039	4.2 ± 0.48
5	<i>P. berchtoldi</i> (mat)	1.0 ± 0.06	5.6 ± 0.22	0.84 ± 0.085	4.2 ± 0.22
5	<i>Cladophora</i> <i>fracta</i>	1.7 ± 0.07	6.6 ± 0.26	0.47 ± 0.067	3.0 ± 0.31

Table A4. The budgets of selected metals in the Belding, Michigan, sewage stabilization system for the growing season of 1972 in grams.

Metal	Pond	Input	Water Stored	Pond Sediment	Plant Uptake	Output
Zinc	2	9800	560	6440		2800
	3	2800	260	60	180	2300
	4	2300	140	840	120	1200
	5	1200	220	850*	75	50*
Copper	2	2900	160	1980		760
	3	760	60	370	30	300
	4	300	26	27	22	225
	5	225	25	175*	20	5*
Iron	2	48000	1100	36000		11000
	3	11000	1800	-1800	960	10000
	4	10000	940	-1800	2800	8100
	5	8100	600	4900*	2500	130*
Manganese	2	10200	660	5200		4300
	3	4300	520	-9800	8200	5400
	4	5400	270	-6300	9100	2300
	5	2300	130	-360*	2500	28*

* For Pond 5, sediment value is quantity carried into the bottom by high-rate seepage flow; volume of output was very low.

Table A4. (continued)

Metal	Pond	Input	Water Stored	Pond Sediment	Plant Uptake	Output
Chromium	2	1200	120	500		580
	3	580	80	106	4	390
	4	390	30	80	10	270
	5	270	30	230*	3	7*
Nickel	2	2500	310	690		1500
	3	1500	240	27	33	1200
	4	1200	120	46	24	1010
	5	1010	170	790*	12	40*
Cobalt	2	2100	350	50		1700
	3	1700	280	0	20	1400
	4	1400	140	40	20	1200
	5	1200	140	1020*	6	30*
Cadmium	2	290	50	10		230
	3	230	40	-3	3	190
	4	190	20	8	2	160
	5	160	20	135*	1	4*

* For Pond 5, sediment value is quantity carried into the bottom by high-rate seepage flow; volume of output was very low.

Table A5. Coefficients of partitioning of non-mobile metals in ponds of the Belding, Michigan, system. The total input to each pond for the growing season is taken as 1.00.

Metal	Pond	Pond Sediment	Water Stored	Plant Uptake	Output
Zinc	2	.66	.06		.28
	3	.02	.09	.06	.83
	4	.37	.06	.05	.52
	5	.71*	.18	.06	.04*
Copper	2	.68	.06		.26
	3	.49	.08	.04	.39
	4	.09	.09	.07	.75
	5	.78*	.11	.09	.02*
Chromium	2	.42	.10		.48
	3	.18	.14	.01	.67
	4	.20	.08	.02	.70
	5	.85*	.11	.01	.03*
Iron	2	.75	.02		.23
	3	-.16	.16	.09	.91
	4	-.18	.09	.28	.81
	5	.60*	.07	.31	.02*
Manganese	2	.51	.06		.42
	3	-2.28	.12	1.90	1.26
	4	-1.17	.05	1.69	.43
	5	-.16*	.06	1.09	.01*

* For Pond 5, sediment value is quantity carried into bottom by high-rate seepage flow; volume of output very low.

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