10.0 SYNTHESIS AND INTEGRATION

10.1 Critical Factors

Three factors are critical for Hg contamination to reach concentrations that can have adverse ecological and human health effects: (1) Hg source(s); (2) critical combination of environmental conditions; and (3) bioaccumulation and concentration through the food chain to top predator species. The biota, in fact, provide the integration of these three conditions. Therefore, this chapter begins with a discussion of the latter two factors: bioaccumulation of Hg through the food web; and the environmental conditions that contribute to bioaccumulation. Previous chapters discuss the conceptual model for Hg that has been revised based on the information presented in this report and supported by other scientific studies, and identifies a number of hypotheses that emerge from this discussion that can be tested in the Everglades ecosystem.

10.2 Mercury Bioaccumulation and Environmental Conditions

Differential bioaccumulation of MeHg in the Everglades ecosystem food web with latitude was evident both in periphyton and in mosquitofish. Though limited to WCA2 and WCA3, similar spatial differences in MeHg concentrations in biota were found by Cleckner et al. (1998). The generally low concentrations of MeHg in wholebody mosquitofish in the northern subareas and high concentrations in wholebody mosquitofish in the central and southern subareas requires further analyses to achieve a better understanding of the interactions of environmental factors contributing to bioaccumulation in this species. Differential Hg uptake in mosquitofish tissue existed even though high MeHg concentrations occurred in the canal and marsh waters in the northern areas, which might be expected to result in equally high concentrations in the biota. To further elucidate this relationship the database was parsed by latitude into seven subgroups running from north to south. Parsing the data by latitude unified the large scale gradient effects in water quality moving through the flowway of the ecosystem. The same biological responses (e.g., plant growth and distribution responses) occur on a broad scale across the entire system, and latitudinal parsing combines like effects into subunits with significantly large sample sizes providing a statistically powerful analytical tool. It is instructive to treat this system as a very wide shallow river rather than quiescent marsh; therefore, this analysis is limited to the central flowway omitting the samples from BCNP. Differences in water and soil quality and the differences in mosquitofish food habits indicated the BCNP subarea was different from the central Everglades and justified omission from this analysis.

10.2.1 Vegetation Responses

The randomized canal and marsh data sets were parsed into compartments for each habitat (Figures 10.1 and 10.2, Table 10.1). North EAA describes the northern EAA canal system. South EAA and LNWR describe the southern EAA canal system including points surrounding LNWR in the canal database and the LNWR marsh, which exhibits minimal change in marsh plant response. The north Alligator Alley subarea consolidates the major plant responses to TP in this system including the invasion of cattails and the growth and density responses in sawgrass, which were observed during the sampling. Sawgrass exhibited increased density and growth (increased height, Turner et al. 1995) in this subarea, which can impose a shading effect on underlying periphyton (Grimshaw et al. 1997). High TP concentrations are also known to alter the periphyton community to favor bluegreen and filamentous green algae (Browder 1994, Swift and Nicholas 1987). The central portion of WCA3 focuses on the hot spot for Hg in mosquitofish and other organisms, which was separated from the southern portion of WCA3 where Hg concentrations in mosquitofish are somewhat lower. The northern portion of ENP is exposed to higher nutrient concentrations than the southern portion of ENP, which appears least impacted by nutrients and is the reason for the demarcation of the marsh in ENP. The incidence of floating periphyton is most prevalent in central WCA3, which persists to a lesser degree downstream through the southern portion of ENP. Since there are fewer canals in the ENP, all canal data south of Tamiami Trail was consolidated into one canal subarea in order to maintain comparable sample sizes within each subarea. Water quality, periphyton, and fish tissue Hg concentrations were evaluated along this latitudinal gradient.

Table 10.1 Latitudinal divisions used to characterize canal and marsh constituent gradients.

Latitude	Canal	Marsh
>26.68	North EAA	
26.679 to 26.36	South EAA	LNWR
26.359 to 26.159	WCA-N	AA-N
26.1589 to 25.95	WCA3-C	WCA3-C
25.949 to 25.76	WCA3-S	WCA3-S
25.759 to 25.56	ENP	ENP-N
25.559 to 25.24		ENP-S

10.2.2 Water Quality

The canal median water quality values for the six latitudinal subareas with 95% distribution free confidence limits for TP, TOC, TSO_4, MeHg in water, THg in mosquitofish, and the BAF are presented in Table 10.2. The median values for each subarea are plotted for these parameters in (Figure 10.3). This plot shows an inverse relationship between TP in water and THg in mosquitofish progressing from north to south. High median TP concentrations for the canals were 94.7 μg/L in northern EAA and 103.1 μg/L in southern EAA declining to 49.3 μg/L north of Alligator Alley, 30.3 μg/L in central WCA3, 20.2 μg/L in southern WCA3, and 13.9 μg/L in ENP. In contrast, THg concentrations in mosquitofish were minimal at 27.9 μg/kg in the northern EAA and 24.6 μg/kg in the southern EAA followed downstream by rapidly increasing concentrations of 53.0 μg/kg north of Alligator Alley, 66.8 μg/kg in central WCA3, and 82.1 μg/kg in southern WCA3. However, the fish tissue Hg concentration declined to 42.2 μg/kg in ENP canals, where TP reached the lowest median canal value. The BAF was about 100,000 in the northern EAA and southern EAA and increased steadily downstream to its highest level of 820,000 in the ENP canals.

The canal median TSO_4 concentration was 35.5 mg/L in northern EAA, increased to 54.0 mg/L in southern EAA, then declined rapidly to 15 mg/L north Alligator Alley and reached background concentrations (MDL = 5 mg/L) in cental WCA3 and southern WCA3. A small increase in TSO_4 to 9.1 mg/L occurred in ENP. A maximum TOC value of 29.9 mg/L occurred in the southern EAA, which declined throughout the system to a minimum of 10.0 mg/L in ENP. Median MeHg concentrations in water ranged from 0.3 to 0.2 ng/L through the northern four subareas declining to 0.153 and 0.059 ng/L in southern WCA3 and ENP canals, respectively.

Table 10.2 Latitudinal gradients for canal constituent medians, and confidence intervals from north to south.

Parameter	EAA-N	EAA-S	AA-N	WCA3-C	WCA3-S	ENP
BAF	1.2×10^5 (n=18) ($0.5\text{-}1.7 \times 10^5$)	1.0×10^5 (n=51) ($0.7\text{-}1.2 \times 10^5$)	1.9×10^5 (n=39) ($1.4\text{-}2.4 \times 10^5$)	3.1×10^5 (n=26) ($2.4\text{-}3.9 \times 10^5$)	5.1×10^5 (n=37) ($3.7\text{-}6.5 \times 10^5$)	8.2×10^5 (n=21) ($4.7\text{-}11.6 \times 10^5$)
TP, μg/L	94.7 (n=20) (43.7-145.8)	103.1 (n=53) (83.9-122.3)	49.3 (n=41) (33.9-64.7)	30.3 (n=26) (23.7-36.9)	20.2 (n=36) (14.5-25.8)	13.9 (n=18) (10.6-17.2)
TOC, mg/L	23.0 (n=20) (16.9-29.0)	29.9 (n=53) (25.7-34.1)	22.9 (n=41) (20.1-25.7)	22.9 (n=26) (19.6-26.3)	18.1 (n=36) (15.0-21.2)	10.0 (n=18) (7.7-12.3)
TSO_4, mg/L	35.5 (n=20) (19.2-51.8)	54.0 (n=53) (39.7-68.3)	15.0 (n=41) (7.6-22.4)	5.2 (n=27) (2.3-8.1)	5.0 (n=37) (3.8-6.2)	9.1 (n=21) (5.7-12.5)
MeHg, ng/L	0.300 (n=20) (0.165-0.435)	0.205 (n=53) (0.148-0.262)	0.272 (n=41) (0.217-0.326)	0.262 (n=27) (0.174-0.350)	0.153 (n=37) (0.119-0.189)	0.059 (n=21) (0.031-0.087)
THgF, μg/kg	27.9 (n=10) (20.8-35.0)*	24.6 (n=51) (21.4-27.7)	53.0 (n=39) (36.4-69.5)	66.8 (n=26) (31.5-102.0	82.1 (n=37) (53.1-111.1)	42.2 (n=21) (26.2-58.2)

* 95% confidence interval about the median.

The marsh median water quality values with the 95% confidence intervals for six latitudinal subareas are presented for TP, TOC, TSO_4, MeHg in water, THg in mosquitofish, MeHg in floating and soil periphyton, and the BAF in Table 10.3. A plot (Figure 10.4) of these medians shows an inverse relationship of TP in water to mosquitofish THg in the upstream portion of the marsh (e.g., LNWR, north of Alligator Alley), but then shows a direct relationship with TP in the downstream portions of the marsh. Median TP concentrations were 16.7 μg/L in LNWR and 16.4 μg/L north of Alligator Alley. TP concentrations declined to

Table 10.3 Latitudinal gradients for marsh constituent medians, and confidence intervals from north to south.

Parameter	LNWR	AA-N	WCA3-C	WCA3-S	ENP-N	ENP-S
BAF	0.6×10^5 (n=57) ($0.02\text{-}1.2 \times 10^5$)*	2.2×10^5 (n=72) ($1.7\text{-}2.7 \times 10^5$)	3.0×10^5 (n=73) ($2.1\text{-}3.9 \times 10^5$)	5.6×10^5 (n=72) ($4.8\text{-}6.4 \times 10^5$)	6.9×10^5 (n=69) ($5.9\text{-}7.9 \times 10^5$)	8.5×10^5 (n=51) ($6.6\text{-}10.3 \times 10^5$)
TP, μg/L	16.7 (n=60) (13.1-20.2)	16.4 (n=86) (13.7-19.0)	12.1 (n=84) (9.1-15.2)	10.7 (n=73) (7.6-13.8)	12.3 (n=71) (9.0-15.6)	8.6 (n=67) (6.9-10.3)
TOC, mg/L	24.8 (n=60) (21.4-28.1)	27.0 (n=86) (24.6-29.3)	22.0 (n=84) (20.0-23.9)	17.9 (n=73) (15.7-20.0)	19.3 (n=71) (17.2-21.4)	12.4 (n=67) (10.5-14.4)
TSO_4, mg/L	2.0 (n=60) (1.2-2.8)	15.0 (n=86) (10.0-20.0)	2.4 (n=84) (1.0-3.7)	2.0 (n=73) (1.6-2.4)	2.0 (n=71) (1.6-2.4)	2.0 (n=67) (1.8-2.2)
MeHg, ng/L	0.538 (n=60) (0.392-0.684)	0.426 (n=85) (0.370-0.525)	0.502 (n=84) (0.370-0.634)	0.351 (n=72) (0.267-0.435)	0.274 (n=71) (0.220-0.328)	0.151 (n=67) (0.114-0.187)
THgF, μg/kg	96.5 (n=57) (68.6-124.4)	114.7 (n-72) (96.6-132.7)	208.5 (n=73) (165.1-252.0)	178.0 (n=72) (148.1-207.9)	189.3 (n=69) (156.7-221.9)	155.7 (n=51) (117.6-193.7)
Floating Periphyton MeHg, μg/kg	4.3 (n=14) (1.9-6.6)	2.4 (n=27) (1.5-3.3)	3.3 (n=52) (2.2-4.5)	2.0 (n=52) (1.5-2.4)	1.7 (n=52) (1.3-2.2)	1.8 (n=32) (1.3-2.3)
Soil Periphyton MeHg, μg/kg	5.0 (n=6) (3.2-6.9)	1.5 (n=7) (1.1-2.0)	1.2 (n=18) (-0.1-2.5)	2.1 (n=22) (1.6-2.7)	0.8 (n=21) (0.5-1.1)	0.5 (n=40) (0.3-0.6)

* 95% confidence interval about the median.

12.1 μg/L in central WCA3 remaining at 10.7 μg/L through the southern WCA3 and 12.3 μg/L in the northern ENP declining to 8.6 μg/L in the southern ENP. In contrast, the median THg in mosquitofish was 96.5 and 114.7 μg/kg in LNWR and north Alligator Alley. However, with the decline of TP to 12.1 μg/L in central WCA3, THg in mosquitofish doubled to a median value of 208.5 μg/kg. The THg concentrations in fish remained high at 178.0 and 189.3 μg/kg in the southern WCA3 and the northern ENP, respectively, followed by a decline to 155.7 μg/kg in the southern ENP coinciding with a decline in median TP to 8.6 μg/L. This plot also indicates higher MeHg concentrations in water occurred in the northern three subareas with medians ranging from

0.43 to 0.54 ng/L, which declined to 0.151 ng/L in the southern ENP. MeHg in floating periphyton in the northern three subunits was higher than in the southern three subunits. Maximum MeHg in soil periphyton occurred in LNWR, but remained at low concentrations throughout the remainder of the system. Maximum MeHg bioaccumulation in mosquitofish occurred in central WCA3 and successive downstream subunits into the northern ENP followed by a decline in fish in southern ENP. The decline of nearly all parameters in the southern ENP suggests this subarea might be the only remaining part of the Everglades marsh system that has TP concentrations near background levels. The minimum concentrations of TP and MeHg in water and THg in mosquitofish all occur in the southern ENP. A latitudinal comparison of the BAFs for floating and soil periphyton found higher values for the former in all areas (Figure 10.5). The BAF for mosquitofish increased from north to south, indicating increased uptake efficiency which might be due to recovery of the food chain with declining concentrations of TP.

A sharp increase in marsh TSO_4 north of Alligator Alley to 15 mg/L was followed by a sharp decline to background concentrations in central WCA3 and all downstream areas. The concentrations of TOC indicate a decline from a median of 23 mg/L north of Alligator Alley to 10.0 mg/L in the southern ENP, which indicates there were relatively high concentrations of TOC throughout the entire system.

The natural Everglades is an oligotrophic food limited system. TP creates a series of plant responses from north to south in single celled algae to emergent macrophytes, which can alter periphyton communities downstream through the system. One of the most obvious plant responses to increased TP in this system is the proliferation of plant biomass. The increase in cattail presence and sawgrass density and height was evident in north of Alligator Alley and the northern part of central WCA3 with greatest occurrence in WCA3 north of Alligator Alley. Median TP concentrations in water above 16 μg/L were associated with low mosquitofish THg concentrations. When TP concentrations declined from 16 to 12 μg/L, there was a doubling in MeHg bioaccumulation in mosquitofish, which might indicate a change in the structure of the food chain. However, the highest concentrations of MeHg in water and periphyton were in the three northern subareas receiving the highest TP concentrations. TP could directly or indirectly have a stimulatory effect on the methylating microbes in the system. The methylation process is very likely enhanced by the anaerobic conditions evident in the soil in WCA2. This stimulatory effect could result in high concentrations of MeHg in the water, which declines downstream reaching minimum levels in the southern ENP, where TP is the lowest and the fertilizer effect on the microbes may decline to background. It might also indicate there is a threshold TP concentration where significant system responses begin to occur, which could have important management implications. Where TP concentrations are between 10 and 12 μg/L in central WCA3 and downstream, the presence of floating and soil periphyton appears to be greater. The presence of large amounts of thick floating and soil periphyton may provide a convenient substrate in which inorganic Hg can be methylated (Gilmour, personal communication).

Comparison of the canal and marsh datasets indicates most of the MeHg is generated in the marsh system, where abundant periphyton occurs and not in the canals. The marshes are the primary areas of Hg contamination, both in area and in magnitude.

10.2.3 Food Habits

The oligotrophic, food limited nature of the Everglades also is indicated by the small maximum sizes obtained by the mosquitofish in this system. In comparative studies with other systems, Trexler (personal communication) and Loftus (personal communication) have found Everglades mosquitofish to be smaller than those found in other parts of their natural range. A food habits analysis of mosquitofish from the September 1996 marsh cycle (Appendix E) showed periphyton composed 36% of the diet of mosquitofish based on biomass in gut contents, with insect, crustacean, arachnid, and piscine prey accounting for the remaining 64%. Adult midges gleaned from the water surface accounted for 33.5% of the biomass of the diet, and midge larvae, probably taken from floating, epiphytic, and benthic periphyton mats, accounted for an additional 9.6%. Only two fish and an assortment of spiders, ants, and beetles were found accounting for 15% of the diet by biomass. About 50% of the individual fish had plant matter present in their guts, and about 45% had adult midges. Chironomid larvae and “other” prey were both found in about 10% of the fish, while mites were present in around 8% and cladocerans in only 3% of the fish examined. Very few empty stomachs were found.

When these food habits data were parsed into the six subareas the percentage of plant food was generally consistent at 31.5% except for the northern ENP, which showed a mean of 50.3%. The intake of midges was over 20% in LNWR and north of Alligator Alley when compared to all areas downstream that were less than 6.6%. The “other” prey items were lowest in LNWR with 6.7% and highest in central WCA3 and southern WCA3 with over 20.8% and declined in the two downstream areas. The analysis showed that the mosquitofish diet changed with fish size, even though the fish in this sample were very small. Both factors may confound the attempt to understand the uptake of Hg by this species and argue for additional future sampling. Another complicating factor is the likely changes in the structure of the food chain from north to south through the Everglades ecosystem as a result of the eutrophy in the north and the oligotrophy in the south and the marked changes in Hg bioaccumulation through these food chains.

The primary mechanisms controlling the accumulation of MeHg and inorganic Hg in aquatic food chains are not sufficiently understood; however, uptake most likely occurs through the food web and not directly from the water. Gaining an understanding of bioaccumulation and biomagnification is made exceedingly more difficult by the complex food chains in the Everglades, which are affected by nutrient gradients from north to south through the system. Mason et al. (1996) hypothesized that phytoplankton cell size may be an important controlling factor in the uptake of Hg and subsequent concentrations in fish with greater bioaccumulation associated with the smaller cell sizes in lakes. Proving a similar relationship exists in the Everglades periphyton communities would be much more complicated. In addition, both detrital and primary production-based food webs are important. There is probably nowhere else in the world, however, that such a nutrient gradient ranging from eutrophy to oligotrophy exists on which to test this hypothesis in a marsh environment. If periphyton cell sizes were found to be smaller and more efficient Hg bioaccumulators in the oligotrophic portion of the Everglades ecosystem, a corresponding relationship may be found with that observed in oligotrophic lakes (Lindquist et al. 1991).

10.3 Conceptual Models

Three new conceptual models have been formulated to describe the processes accounting for the methylation and bioaccumulation of Hg in the South Florida Everglades ecosystem based on this assessment. These conceptual models have been developed to correspond to the three geographic areas: (1) north of Alligator Alley, (2) between the Alley and Tamiami Trail, and (3) below Tamiami Trail in ENP. These conceptual models are based primarily on the results of this study, but are supported by other on-going Everglades studies and additional studies documented in the scientific literature.

10.3.1 North of Alligator Alley

Water quality constituent concentrations (e.g., TP, TOC, TSO_4) are high north of Alligator Alley. Elevated nutrient concentrations have resulted in a shift in the historical plant community from calcareous bluegreen algae and periphyton to filamentous algae, cattails, and dense sawgrass that shade the periphyton community and reduce the periphyton biomass. These nutrient concentrations are sufficiently high that the assimilative capacity of the natural system has been greatly exceeded, resulting in a shift in the natural community to a pollution tolerant community. MeHg concentrations in water and floating and soil periphyton are high, but concentrations in the mosquitofish are low. There are several factors contributing to low mosquitofish Hg concentrations. TOC concentrations in LNWR could complex with the MeHg and make it less biologically available for bioaccumulation. High TSO_4 concentrations in WCA2 and anoxic conditions also increase the sulfide concentrations, which may complex with inorganic Hg and reduce its availability for methylation; however, these processes are competing. In the canal system, hypoxic and anoxic conditions might result in more pollution tolerant species and an incomplete food chain. This incomplete food chain, consisting primarily of grazers and filter feeders, results in fewer links in the food chain and lower biomagnification rates. A detritus-based food web probably dominates in this area.

10.3.2 Alligator Alley to Tamiami Trail

Between Alligator Alley and Tamiami Trail, TSO_4 concentrations have declined precipitously. TOC and TP concentrations have decreased to moderate levels. In the marsh, TP concentrations are between 10 to 20 μg/L. It is our hypothesis that these concentrations might alter the periphyton community to pollution tolerant species, and these concentrations might result in the stimulation of production of the native periphyton. Although TP concentrations are currently lower, the potential for future system change is not precluded. Complexation of Hg with TOC or sulfide is reduced, and MeHg is available for bioaccumulation. Increased periphyton production, particularly floating and epiphytic periphyton, provides additional sites for increased methylation during the nocturnal period. This also results in increased bioaccumulation of MeHg within the periphyton community. More complete food webs, including both detrital and primary productivity-based pathways, provide additional links for the biomagnification of Hg through the food chain. Total system production, however, is less because of reduced nutrient concentrations, so biodilution does not decrease biotic Hg concentrations. Hg concentrations throughout the food chain, from periphyton to wading birds, are highest in this area because this long hydropattern, sustained water depth provides a sustained aquatic habitat for aquatic organisms and wading birds.

10.3.3 South of Tamiami Trail

TP concentrations have decreased below 10 μg/L to near historical background levels so periphyton community production is less and is nutrient limited, as indicated by elevated APA levels. TOC and sulfide concentrations are low, so complexation with inorganic or organic Hg is limited. Both periphyton production and methylation rates have decreased. However, because the system is ultra oligotrophic, food webs are complex, with multiple pathways. Even though productivity is lower than areas north of Tamiami Trail, Hg bioaccumulation and biomagnification continues to occur because of the increased complexity of the food webs, including both detrital and productivity-based pathways. However, THg concentrations in mosquitofish are decreasing in the southern portion of the Everglades because methylation rates and MeHg concentrations have decreased.

10.4 Testable Hypotheses

The conceptual model has been developed to provide a framework both for explaining current study results and for formulating hypotheses that can be tested in the field. Several of these testable hypotheses are listed in Table 10.4. While there might be agreement or disagreement on the conceptual models, the constructs can be tested in the field to support or refute the hypothesized relationships. However, it is important that comparable long-term monitoring occurs to assess the multiple interactions observed across the system because it is doubtful that the scale, magnitude, and complexity of experimental studies needed to define the interacting variables can be conducted as this dynamic system changes.

Table 10.4 Testable Hypotheses.

Ho: North of Alligator Alley
1) TOC and sulfide bind with THg in water, chelate MeHg so less is available to biota. 2) TP concentrations increase microbial activity, which results in both greater demethylation and methylation. 3) TP increases cattail and sawgrass production, which shades and reduces periphyton production and methylation. 4) TP concentrations stimulate eutrophication and significant changes in the plant community (species and density). 6) TP stimulates increased microbial peat decomposition, which increases MeHg production. 7) High TP concentrations promote high productivity, which produces biodilution of Hg in biota. 8) Impacted food web with pollution tolerant organisms, ergo minimal top predators to biomagnify Hg. 9) Elevated TP concentrations alter periphyton community composition favoring species that have low transfer efficiency of MeHg biouptake.
Ho: Alligator Alley to Tamiami Trail
1) Periphyton production stimulated by TP concentrations between 10 to 15 μg/L, which results in greater periphyton biomass. 2) Greater periphyton biomass results in anoxic interior zones in the plankton mats and significant methylation in these interior zones. 3) Elevated THgF is a function of water quality and bioavailability of MeHg. 4) Complete food chain with both detritus and primary producer base, resulting in biomagnification of THg in bass, wading birds, other top predators. 5) Moderate APA indicates TP-periphyton stimulation. 6) Water depth optimal for wading birds in dry season feeding on high THg fish. 7) BAFs are higher because of complete food chain and addition of primary producer base. 8) Drawdown (hydropattern modification) results in flushing porewater MeHg into overlying water and uptake through food chain in longer hydropattern area. 9) Chloride and pH affect MeHg uptake by algae consequently affecting periphyton BCF and fish BAF.
Ho: South of Tamiami Trail
1) Periphyton production stimulated by TP concentrations from canal extension into ENP resulting in increased methylation in localized areas. 2) TP concentrations below 10 μg/L significantly reduce productivity, biomass, and methylation, hence, bioavailability of MeHg. 3) Hydropattern has altered the habitat for fish and wading birds. 4) Fluctuating water level draws pore water MeHg into Shark River Slough and uptake by primary producers and other biota. 5) Complex food webs result in relatively high fish THg concentrations even through MeHg concentrations decreased.

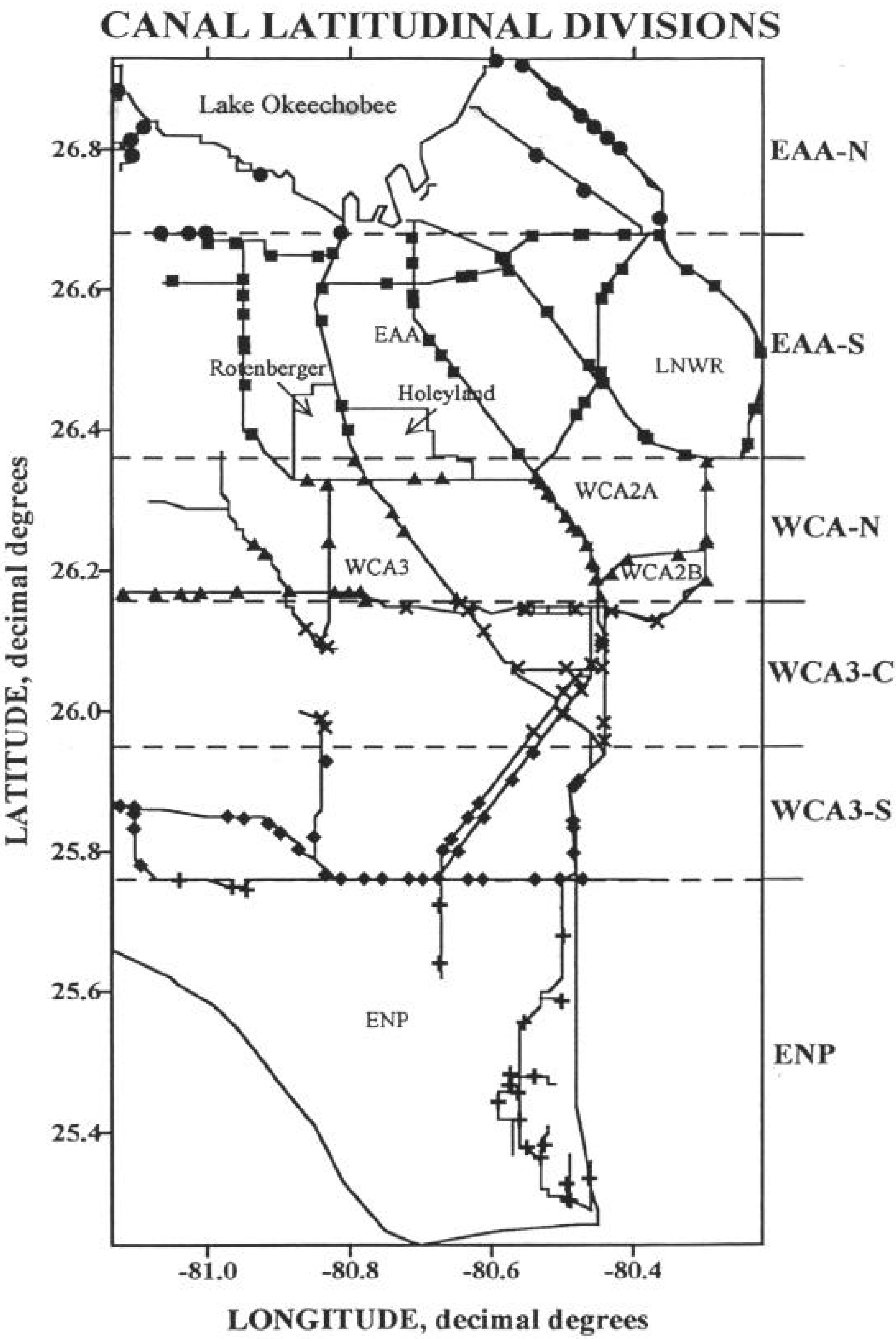

Figure 10.1 Six canal compartments with locations of sampling points contained in each.

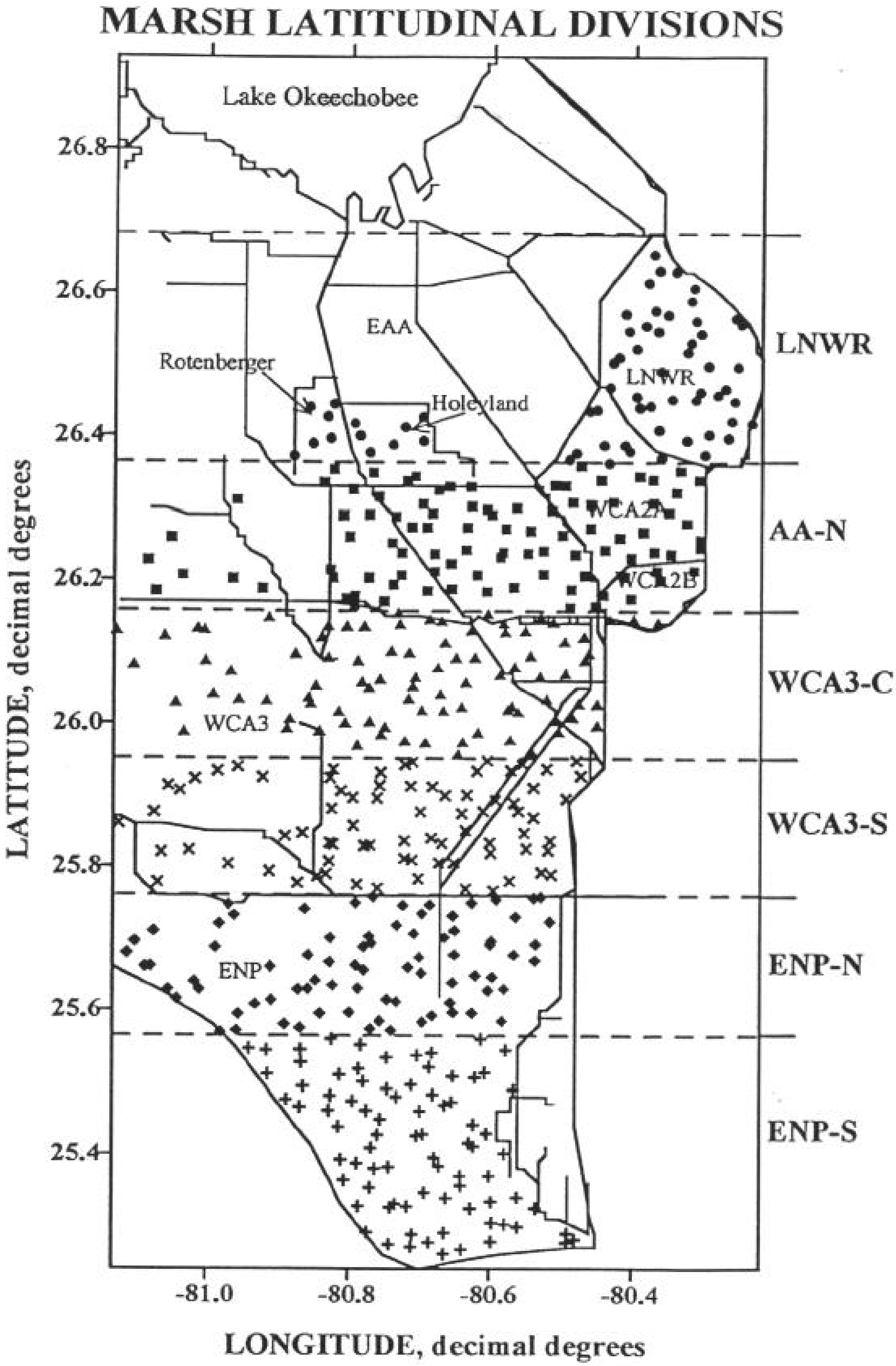

Figure 10.2 Six marsh compartments with locations of sampling points contained in each.

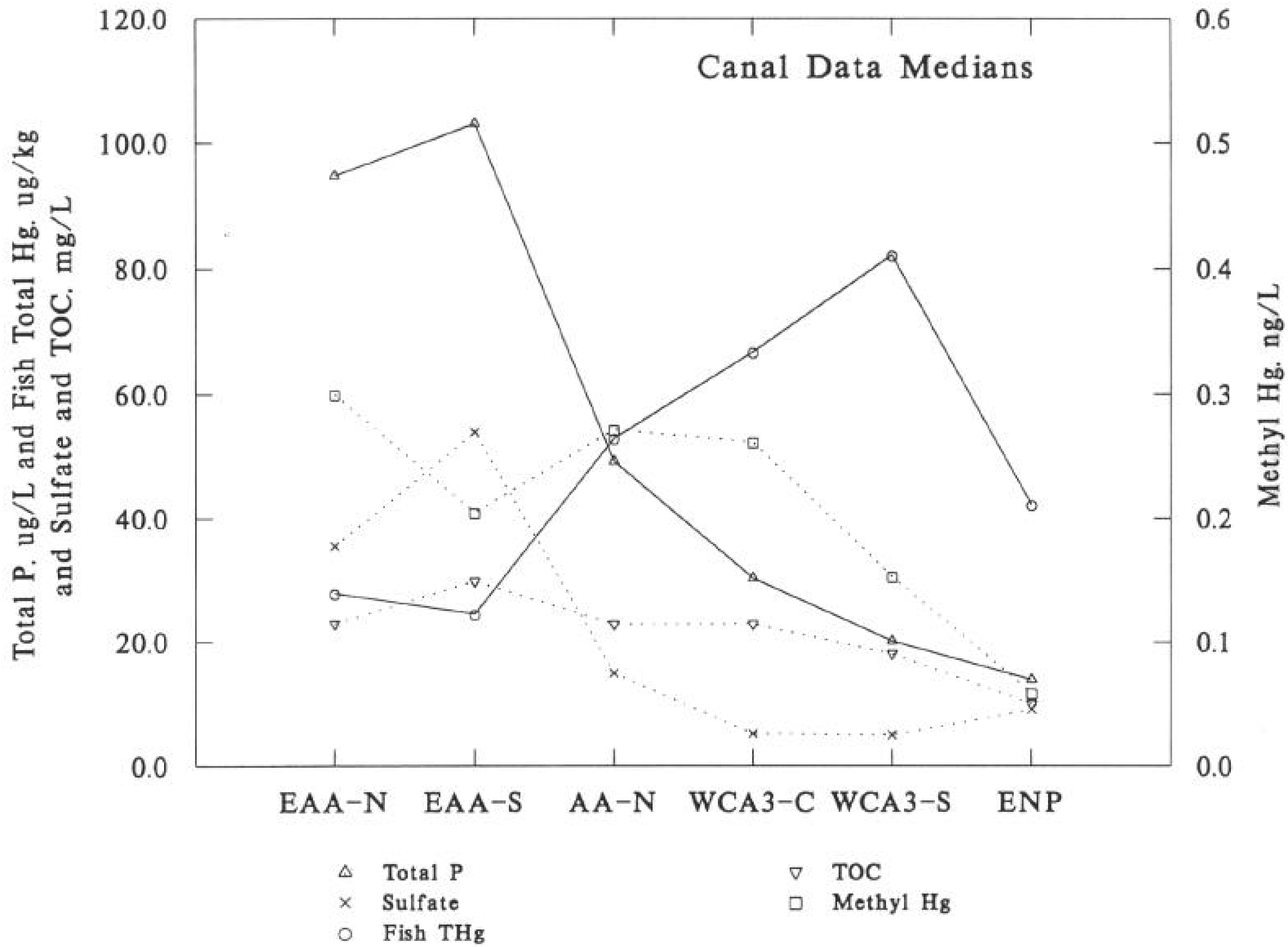

Figure 10.3 Median values of selected parameters in canal subareas.

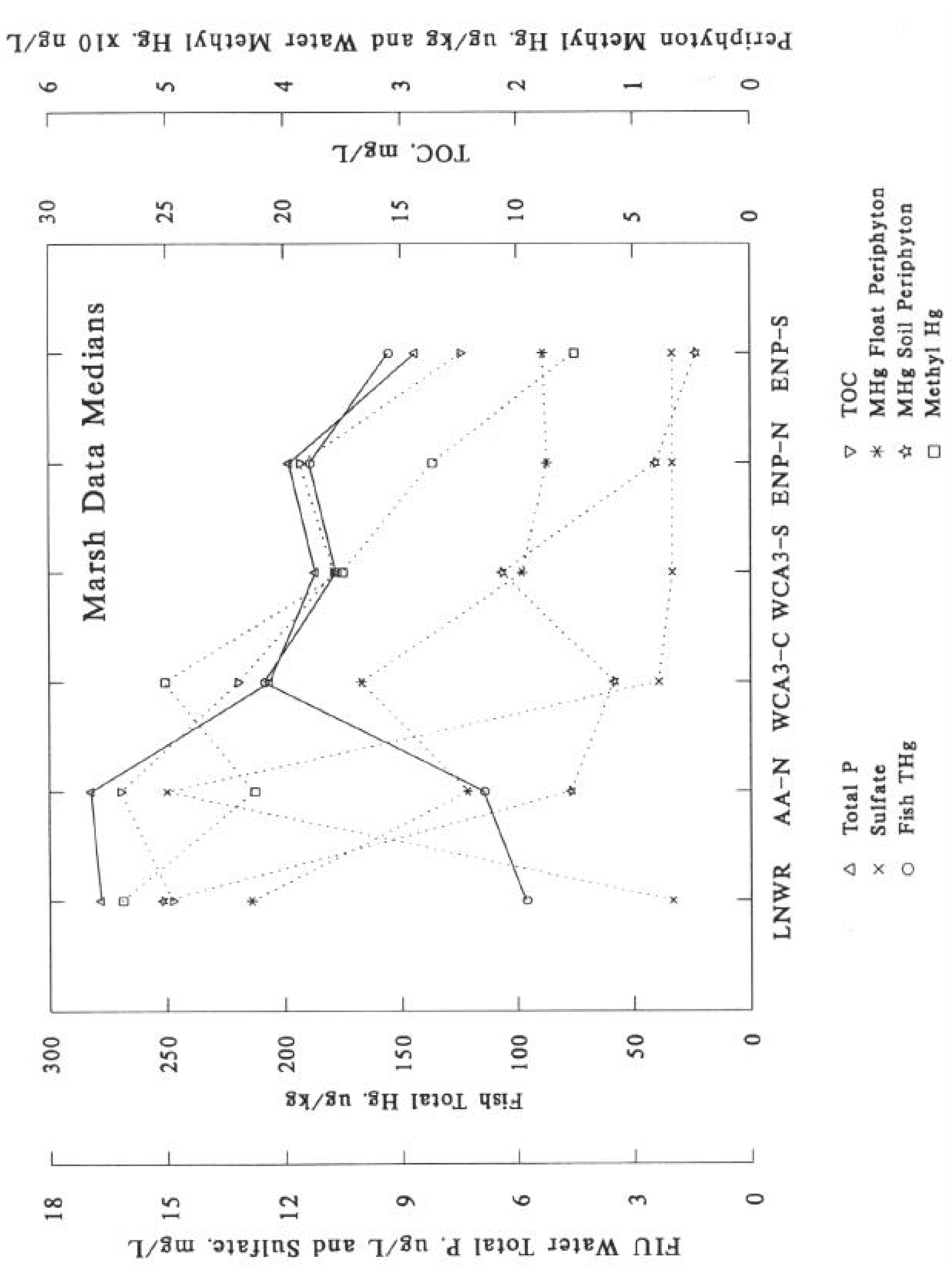

Figure 10.4 Median values of selected parameters in marsh subareas.

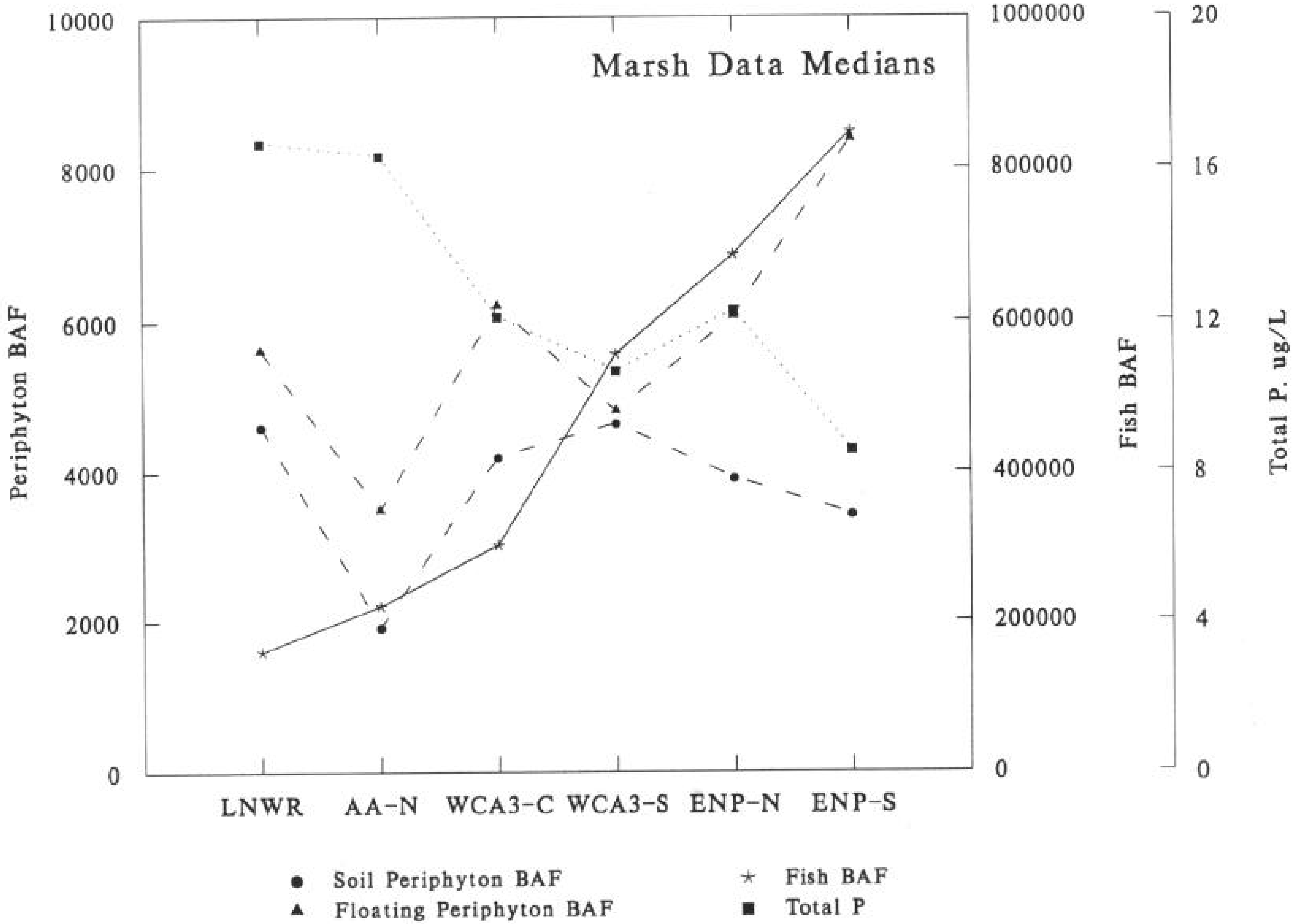

Figure 10.5 Median marsh TP and BAFs in subareas.