CHAPTER 2 WATER QUALITY AND SOILS

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INTRODUCTION

This chapter emphasizes water and soil quality in wetlands without significant urbanization in their watersheds. Like other chapters in this section, its purpose is to characterize particular elements of Puget Sound Basin freshwater wetland ecology in a state relatively unaffected by human activity. The wetlands profiled in this group were those with < 4% impervious surface and ≥ 40% forested area in their watersheds. It is recognized that human influence is not entirely absent in these cases, but truly pristine examples do not exist in the lowlands of the Puget Sound Basin. While there are palustrine wetlands in the Pacific Northwest that are not directly affected by urbanization, it is difficult to locate wetlands that are completely unaffected by humans. Indeed, even where there is no human activity in a wetland's watershed, atmospheric pollutants from distant sources could still reach these "pristine" wetlands through rainfall. The wetlands considered here are regarded as representative of the closest to a natural state attainable in the ecoregion. Chapter 9 concentrates on water and soil quality in wetlands with watersheds that are moderately and highly urbanized, as well as those with watersheds that had new development during the years of the study.

It is important to reiterate that the research program concentrated on palustrine wetlands of the general type most prevalent in the lower elevations of the central Puget Sound Basin. The results and conclusions presented here are probably applicable to similar wetlands somewhat to the north and south of the study area, but may not be representative of higher, drier, or more specialized systems, like true bogs and “poor” (low nutrition) fens.

WATER QUALITY

Collection and Methods

Collection of samples for water quality analysis was performed in 1988-1990, 1993, and 1995. Sampling was concentrated during the wet and dry seasons, with fewer samples taken in the transition seasons between those periods. The reason for this scheduling was to concentrate effort when the most pollutants enter wetlands, during the runoff season, and when the decrease in surface water due to relatively low inflow and high evapotranspiration is expected to concentrate pollutants most.

In the last four of the five years' samples were collected in 19 wetlands on the following schedule: November 1-March 31--4 samples, April 1-May 31--1 sample, June 1-August 31--2 samples, and September 1-October 31--1 sample. Sampling occurred at about the same times each year in order to get a consistent view of seasonal water quality variation. The same general pattern was observed in 1988; but there were only 14 wetlands in the program at that time, sampling did not begin until May, and a total of seven instead of eight samples was taken. Some of the wetlands, in most years nine of the 19, had no surface water for varying lengths of time in the late spring, summer, and/or early fall and could not be sampled during those times.

Samples were taken from the largest open water pool in each wetland, if there was one. If not, they were collected near the outlet if surface water existed there or, otherwise downstream of the inlet. The standard grab method was generally used to collect the samples manually. A hand-pump-operated device (Horner and Raedeke 1989) was employed to take samples intended for dissolved oxygen analysis and in cases where shallow water prevented conventional grab sampling without entraining material from the bottom.

Temperature and pH were measured in the field, temperature either by mercury thermometer or electronic meter. The pH was determined with the electronic meter, in latter years a Beckman Model φ 11 instrument. Dissolved oxygen samples were stabilized in the field and transported on ice, along with samples for other analyses, to one of several laboratories used in the different years.

Water quality analyses varied somewhat from the beginning to the end of the program. Some analyses that did not produce much usable information in the early years were dropped. Analyses that were performed in all years and are the focus of this chapter are:

Temperature	Soluble reactive phosphorus (SRP)
pH	Total phosphorus (TP)
Dissolved oxygen (DO)	Fecal coliforms (FC)
Conductivity (Cond)	Total lead (Pb)
Total suspended solids (TSS)	Total copper (Cu)
Ammonia-nitrogen (NH3-N)	Total zinc (Zn)
Nitrate + nitrite-nitrogen (NO3+NO2-N)	

Among the analyses deleted after the early years were dissolved metals, which were usually below detection limits. It is probable that the use of exceptional methods would detect these constituents, but doing so was outside the objectives of this research. Enterococcus was dropped as a bacteriological measure because it did not yield the hoped for reduced variability often prevalent with fecal coliforms, and was never widely adopted as a standard analyte as had been anticipated 10 years ago. Oil and grease and total petroleum hydrocarbons were measured in a relatively small number of samples but were always present in the wetland water column in very small concentrations, with the exception of an isolated incident when an oil spill was suspected. In the final two years of sampling data became available on a number of metals in addition to the three of most interest since they were run routinely on the inductively coupled plasma-mass spectrometer (ICP-MS) used by the laboratory handling those samples.

Horner and Ludwa (1993) prepared a monitoring and quality assurance/quality control (QA/QC) plan that specifies in detail the sampling and analytical methods and QA/QC provisions for the last two years of the program, which were typical of all years. A report by Reinelt and Horner (1990) is the best source of detail on methods for the initial years. Water quality methods and results were also reported by King County Resource Planning Section (1988); Azous (1991); Reinelt and Horner (1991); Platin (1994); Ludwa (1994): Taylor, Ludwa, and Horner(1995); and Chin (1996).

Research Findings: A Portrait of Puget Sound Basin Wetland Water Quality

The main objective of this section is to develop a water quality profile of the least developed wetlands in the data set as presumably representative of the “best attainable” condition in the Puget Sound Basin lowlands. In developing this profile companion data are also presented for more urbanized cases, in part to allow some comparisons now and also for more extensive discussion of those cases in Chapter 9. Later in this chapter wetlands in the data set are classified according to morphological characteristics and again compared. These comparisons are performed with the use of basic summary statistics (primarily, means, standard deviations, and medians). For the most part, tests for statistical significance of differences and analyses of variance were not performed, because of lack of replication of conditions with any exactness, large natural variability, and relatively small sample sizes under any given set of conditions.

Table 2-1 gives a statistical summary of the water quality data gathered over the full project from wetlands whose watersheds did not experience significant urbanization change during that period (control wetlands) grouped by urbanization status. Chapter 9 takes up wetlands with watersheds that did change. Nonurban watersheds (N) were classed as those with both < 4% impervious land cover and ≥ 40% forest; highly urbanized watersheds (H) were considered to be those having both ≥ 20% impervious and ≤ 7% forest. Those not fitting either of the other categories were classified as moderately urbanized watersheds (M). Valentine (1994) developed this classification scheme for analysis of the probable origin of soil metals, and it is maintained here for water quality as well for consistency. Characteristics of the individual watersheds can be found in Section 1, Table 1. Indeterminate statistics (< or > a given value) are the result of some measurements being below detection or, in the case of FC, bacterial colonies too numerous to count in the dilutions analyzed in some very concentrated samples.

Examination of Table 2-1 reveals several general points about wetland water quality. First, excepting pH, concentrations were very variable, as indicated by the relatively high coefficients of variation (CV). The principal sources of water quality variability are examined later in the chapter. Fecal coliform was the most variable of the analytes overall, followed by TSS and NH3-N. Other than for pH, DO, and conductivity, medians were usually lower than arithmetic means, signifying the influence on means, but not on medians, exerted by a relatively few high values. This trend is consistent with a log-normal probability distribution of values, a distribution frequently observed in environmental data (Gilbert 1987).

Nonurban wetlands are the main focus of this chapter, and Chapter 9 further discusses the other categories. With a cursory comparison of the Table 2-1 medians, it can be seen that pH rose slightly and DO marginally declined with increasing urbanization. Conductivity and NH3-N increased substantially from nonurban to moderately urban wetlands but actually were a bit lower in highly urbanized cases. NO3+NO2-N and TP increased from N to M status but not further with H status. Cu showed little difference among categories, but many values were below detection. The remaining variables (TSS, SRP, FC, Pb, and Zn) all increased with each step up in urbanization level.

Table 2-1. Water quality statistics for wetlands not experiencing significant urbanization change (1988-1995).

Status	Statistic	pH		DO	Cond.		TSS		NH3-N		NO3+NO2-N		SRP	TP		FC		Cu		Pb		Zn
				(mg/L)	(µS/cm)		(mg/L)		(µg/L)		(µg/L)		(µg/L)	(µg/L)		(CFU/100 mL)		(µg/L)		(µg/L)		(µg/L)
N	Mean	6.38		5.7	72.5	<	4.6	<	59.9	<	368.2	<	17.6	52.3	>	271.3	<	3.3	<	2.7	<	8.4
	Maximum	7.65		11.3	230.0		73.0		1373.0		3200.0		414.0	850.0		6240.0		15.0		21.0		49.0
	Std. Dev.	0.53		2.6	63.8	>	8.5	>	129.3	>	484.6	>	47.6	86.6	>	1000.4	>	2.7	>	2.8	>	8.3
	CV	8%		45%	88%	>	185%	>	216%	>	132%	>	271%	166%	>	369%	>	80%	>	105%	>	99%
	Median	6.36		5.9	46.0		2.0		21.0		111.5		6.0	29.0		9.0	<	5.0		1.0		5.0
	n	162		205	190		204		205		206		200	206		206		93		136		136.0
M	Mean	6.54	<	5.5	142.4	<	9.2	<	125.7	<	598.2	<	31.5	92.5	>	2664.8	<	3.7	<	3.4	<	9.8
	Maximum	7.88		14.8	275.0		180.0		2270.0		7210.0		280.0	780.0		359550.0		7.0		13.0		33.0
	Std. Dev.	0.82	>	3.6	72.8	>	21.6	>	266.8	>	847.2	>	37.9	91.8	>	27341.7	>	1.9	>	2.7	>	7.2
	CV	13%	>	66%	51%	>	235%	>	212%	>	142%	>	120%	99%	>	1026%	>	51%	>	79%	>	73%
	Median	6.72		5.1	160.0		2.8		43.0		304.0		16.0	70.0		46.0	<	5.0		3.0		8.0
	n	132		173	161		175		177		177		172	177		173		78		122		122.0
H	Mean	6.73	<	5.4	150.9	<	9.2	<	68.3	<	395.4		31.2	109.5	>	968.6	<	4.1	<	4.5	<	20.2
	Maximum	7.51		10.5	271.0		87.0		516.8		1100.0		79.0	1940.0		38000.0		12.0		22.0		73.0
	Std. Dev.	0.57	>	2.9	85.5	>	15.1	>	104.4	>	239.4		15.7	233.5	>	4752.8	>	2.5	>	4.0	>	16.7
	CV	9%	>	53%	57%	>	164%	>	153%	>	61%		50%	213%	>	491%	>	62%	>	89%	>	83%
	Median	6.88		6.3	132.2		4.0		32.0		376.0		28.2	69.0		61.0	<	5.0		5.0		20.0
	n	52		67	61		66		67		67		65	67		66		29		44		44.0

N = wetlands with nonurban watersheds; M = wetlands with moderately urbanized watersheds;
H = wetlands with highly urbanized watersheds; OW = open water wetland; FT = flow-through wetland

A water quality portrait of Puget Sound Basin lowland palustrine wetlands relatively unaffected by humans, then, shows slightly acidic (median pH = 6.4) systems with DO often well below saturation, and in fact sometimes quite low (< 4 mg/L). Dissolved substances are relatively low (most conductivity readings < 50 µS/cm) but somewhat variable. Suspended solids are routinely low but quite variable, reflecting the strong influence of storm runoff events on TSS. Median total dissolved nitrogen concentrations (the sum of ammonia, nitrate, and nitrite) are more than 20 times as high as dissolved phosphorus, suggesting general limitation of plant and algal growth by P. Some of the fairly abundant TP would become available over time to support photosynthesis, but probably not enough to modify the general picture. The low median fecal coliform indicates that most readings are very low (< 10 CFU/100 mL), but a small number is so high that the mean is 30 times the median. Both mean and median heavy metals concentrations are in the low parts per billion range, with standard deviations just about identical to the means.

Wetland Water Quality in Context

To proceed with a descriptive picture of regional wetland water quality, it is useful to provide some context for the quantitative information. This portion of the chapter discusses the statistical data with respect to informal criteria for separating the data into groups that can be associated with various factors that may influence the magnitudes. The account also gives a sense of how water quality compares in regional wetlands versus streams.

Reinelt and Horner (1990) first presented the informal criteria based on several considerations; they were slightly modified for this paper. Some are regulatory standards applied to other water body types (water quality standards have not yet been adopted for wetlands in Washington). Others have generally recognized biological relevance, but some are simply arbitrary breakpoints in the data distributions. In all cases professional judgment was applied in adopting a numerical informal criterion.

Table 2-2 gives the distribution of wetlands, using median values, among the three urbanization categories relative to the informal criteria. It also repeats the medians and means for each category from Table 2-1.

Some water quality variables did not appear to depend on urbanization. One site in each category had median pH < 6, apparently as a consequence of some presence of peat in soils and peat-forming vegetation. Each group also had DO distributed among the three criteria ranges. As discussed later, it seems that DO depends more heavily on wetland morphology than on urbanization.

Several variables exhibited rising medians with urbanization; but when viewed in terms of the criteria, low concentrations predominated, suggesting relatively light pollutant loading from stormwater runoff. Most NH3-N median values were in the lowest range in all categories. Wetlands produce ammonia in decomposing the abundant organic matter internally produced (Mitsch and Gosselink 1993); and, absent an elevated source, concentrations would not necessarily be expected to follow urbanization. Most NO3+NO2-N medians were also in the lowest range in the N and M wetlands but not in the most highly urbanized. For zinc, the most frequently detected metal, no median in any urbanization class approached the chronic criterion for the protection of aquatic life. In fact, the chronic criterion was violated in only one of these wetlands, a highly urbanized one, in individual samples during the entire program. Although not shown in the table, the same general situation prevailed for copper but not for lead, which has a very low chronic criterion in these generally soft waters (3.2 µg/L). As can be seen in Table 2-1, H wetlands had Pb medians above that concentration, and M wetlands fell close to it.

TSS, conductivity, TP, and fecal coliforms exhibited a general tendency toward more sites in the higher criteria ranges with increasing urbanization. Still, TSS medians were very low. A total phosphorus concentration > 20 µg/L is often recognized as one sign that a lake is eutrophic, and > 50 µg/L as an indication of a hypertrophic state (Welch 1980). No wetland had a median below 20 µg/L, and the majority of M and H wetlands fell above 50 µg/L. Wetlands are recognized as systems more prone to eutrophication than lakes for a number of reasons (e. g., rapid nutrient cycling, often having the entire water column in the photic zone). Even those subject to little or no urbanization appear to have a rather high trophic state, and more urbanized systems are even higher. However, since wetlands flush more rapidly than lakes, these elevated TP concentrations may be a lesser concern in wetlands than they would be in lakes. All but three wetlands would meet the 50 CFU/100 mL fecal coliform standard that applies to lakes and the highest class streams in Washington on the basis of their means. Two moderately and one highly urbanized site could not meet even the least stringent standard. Of course, a number of individual values were far higher.

For the least urbanized wetlands, the following general statements can be made to characterize the water quality of Puget Sound Basin lowland palustrine wetlands in a fairly natural state:

- These wetlands are highly likely (83% of cases observed) to have median conductivity < 100 µS/cm, NH3-N < 50 µg/L, TP in the range 20-50 µg/L, fecal coliforms < 50 CFU/100 mL, and total Zn < 10 µg/L.

- These wetlands are also likely (68% of cases observed) to have median TSS in the range 2-5 mg/L and NO3+NO2-N < 100 µg/L.
- The pH and DO in these wetlands are unpredictable from consideration of urbanization status alone, being dependent on other factors.

Table 2-3 statistically summarizes water quality data from 50 locations on western King County streams collected by the Municipality of Metropolitan Seattle during 1990-1993. These data represent grab samples taken on a regular schedule, by chance most often under baseflow conditions. In these ways they are comparable to the wetland data produced by the PSWSMRP. Unlike Tables 2-1 and 2-2, though, Table 2-3 mixes results from streams with very different influences. Nevertheless, it is useful to show how regional wetland and stream water quality compare.

While most wetlands tended strongly to be slightly acidic, and some were rather more so, streams tended just as strongly to be slightly alkaline. This difference is very likely the result of organic acid production by plants that are virtually absent in lotic systems. As expected, flowing streams were observed to be better oxygenated than wetlands, with median DO about twice as high. Streams at the median level were similar to moderately and highly urbanized wetlands in conductivity, but the nonurbanized wetlands had a central tendency below even the minimum measured stream value. TSS median concentrations were generally similar in the two types of water bodies. NH3-N was generally higher in wetlands, reflecting the relatively high production rate of this species accompanying organic matter decomposition. On the other hand, NO3+NO2-N was for the most part lower in the wetlands, perhaps because of slower nitrification in the more oxygen-depleted environment. Median stream TP fell between the levels in the nonurbanized and more highly urbanized wetlands. Stream median fecal coliforms were higher than in any wetland category, but there were no extremely high values such as were measured in the wetlands. This observation suggests that coliform organisms are able to reproduce more successfully in rich, quiescent wetland environments once they enter. All in all, the two sets of results exhibit rough comparability, with most deviations mirroring the physical and biological differences in the two systems.

Table 2-2. Comparison of medians of water quality variables for wetlands not experiencing significant urbanization change (1988-1995) with informal criteria.

Variable	Criterion	Nonurbanized			Moderately Urbanized			Highly Urbanized		
		Median	Mean	%[a]	Median	Mean	%[a]	Median	Mean	%[a]
pH	5-6	6.4	6.4	16.7	6.7	6.5	14.3	6.9	6.7	50.0
	6-7			67.7			57.1			0.0
	7-8			16.7			28.6			50.0
DO	< 4	5.9	5.7	33.3	5.1	< 5.5	57.1	6.3	< 5.4	50.0
(mg/L)	4-6			33.3			14.3			0.0
	> 6			33.3			28.6			50.0
Cond	< 100	46	72	83.3	160	142	28.6	132	151	50.0
(µS/cm)	100-200			16.7			42.8			0.0
	> 200			0.0			28.6			50.0
TSS	<2	2.0	< 4.6	33.3	2.8	< 9.2	14.3	4.0	< 9.2	50.0
(mg/L)	2-5			67.7			71.4			0.0
	> 5			0.0			14.3			50.0
NH_3-N	< 50	21	< 60	83.3	43	< 126	71.4	32	< 68	100.0
(µg/L)	50-100			16.7			14.3			0.0
	>100			0.0			14.3			0.0
NO3+NO2-N	< 100	112	< 368	67.7	304	< 598	57.1	376	< 395	0.0
(µg/L)	100-500			16.7			28.6			50.0
	> 500			16.7			14.3			50.0
TP	< 20	29	52	0.0	70	92	0.0	69	110	0.0
(µg/L)	20-50			83.3			42.8			0.0
	> 50			16.7			57.1			100.0
FC	< 50	9	> 271	83.3	46	> 266	71.4	61	> 969	50.0
(CFU/100 mL	50-100			16.7			0.0			0.0
	> 100			0.0			28.6[b]			50.0[b]
Zn	< 10	5.0	< 8.4	83.3	8.0	< 9.8	85.7	20.0	< 20.2	50.0
(µg/L)	> 10[c]			16.7			14.3			50.0

[a] % of sites with this urbanization status (see Table 1 for definitions) fitting the criterion.
[b] Medians are > 200.
[c] Highest median is 21 µg/L, in comparison to the 59 µg/L chronic criterion for the protection of aquatic life with a water hardness of 50 mg/L as $CaCO_3$.

Seasonal Variation

Wetlands are highly variable systems with annual, seasonal, and diurnal variability in water chemistry. They often have several sources of water supply, each possessing a distinctive chemical blend that varies from year to year. Many water quality parameters exhibited clear seasonal fluctuations in the wetlands studied. DO concentrations were generally higher from mid-November to mid-May than during the remainder of the year

(Reinelt and Horner 1990). This pattern is not surprising considering that most precipitation and runoff and the coolest temperatures in the Pacific Northwest occur during this period, and cooler, more turbulent water absorbs more oxygen.

Conductivity and pH did not exhibit such variation in most wetlands monitored. However, some had higher conductivity from May to November, when wetland water levels drop and dissolved substances become more concentrated (Reinelt and Horner 1990). Many wetlands had substantially higher TSS concentrations during the winter and early spring, the period of greatest runoff and erosion. However, colonial algae can cause high TSS readings in the late summer as well (Reinelt and Horner 1990).

Table 2-3. Distribution of water quality data for baseflow samples from 50 stream sites (Municipality of Metropolitan Seattle 1994).

	Maximum	75th Percentile	50th Percentile	25th Percentile	Minimum
Conductivity (µmho/cm)	30,900	203	130	104	53
Suspended solids (mg/L)	12.6	4.8	3.4	2.8	1.6
Ammonia (µg/L)	190	24	15	13	5
Nitrate+nitrite (µg/L)	3,000	1,100	630	320	73
Temperature (°C)	13.5	11.1	10.6	10	8.0
Dissolved oxygen (mg/L)	11.4	11.0	10.4	9.6	5.8
Turbidity (NTU)	16.5	2.7	1.8	1.4	0.7
Fecal coliform (org/100 mL)	900	220	100	49	7
Enterococcus (org/100 mL)	410	170	53	22	5
pH	8.2	7.6	7.5	7.3	6.9
Total phosphorus (µg/L)	150	66	48	32	13

While many wetlands monitored by the program had lower concentrations of NH3-N, SRP, and TP from November to May, they had higher nutrient concentrations in the other part of year possibly as a result of greater fertilizer applications and lower water levels that concentrate nutrients. NO3+NO2-N values fluctuated greatly in the program wetlands, and tended to vary directly with DO (Reinelt and Horner 1990). This association is another sign that nitrification moderated by the degree of aerobiosis has a strong influence on how much NO3+NO2-N will be found in a wetland water column.

Medians and geometric means of fecal coliform (FC) and enterococcus bacteria were highly variable. Peak counts occurred most frequently in late August and September, and least often from mid-November through February (Reinelt and Horner 1990). The monitoring program found that while most water quality parameters varied seasonally, NH3-N, SRP, TP, FC, and enterococcus were especially changeable (Reinelt and Horner 1990).

Variation with Wetland Morphology

Wetland morphology refers to its form and physical structure and embraces its shape; perimeter length; internal horizontal dimensions; topography (also termed bathymetry), which is the pattern of elevation gradients; water inlet and outlet configurations; and water pooling and flow patterns. These factors establish zonation at early successional stages by determining the extent of inundation from place to place and the hydrodynamic characteristics of flow. From these structural zones stem vegetation composition, distribution, and productivity, and, ultimately, the same features of the animal communities. Of course, these biota in turn influence morphological development over time through detrital and sediment accretion and animal activities like burrowing and dam building by beavers. The various morphological characteristics entirely determine the flood-flow storage and alteration function of wetlands. Along with the friction produced by vegetation, they set the residence time of water within the wetland, which is a key regulator of sediment trapping, nutrient processing, and other water quality functions.

Early work in the program determined that one aspect of morphology in particular, water pooling and flow patterns, had a substantial influence on wetland water quality (Reinelt and Horner 1990, 1991). The wetlands in the study were classified as either open-water (OW) or flow-through (FT) types. The OW systems contain significant pooled areas and possess little or no flow gradient, while the FT wetlands are often channelized and have a clear flow gradient.

Using the first three years of data (Reinelt and Horner 1990), it was found, unsurprisingly, that temperatures ranged higher in wetlands characterized by relatively large open pools, especially from May to September. On an annual basis, the photosynthetic pigments chlorophyll a and phaeophytin a attained higher concentrations in wetlands characterized by large open pools, which have greater light exposure and longer residence times, and ranged much higher than in flow-through wetlands during the growing season. Dissolved oxygen tended to be significantly lower than in flow-through wetlands during these periods.

Table 2-4 summarizes statistics for the wetlands whose watersheds stayed relatively stable during the program broken down by urbanization and morphological status. Comparing open water versus flow-through wetlands in the N and M categories, it can be seen that medians were higher, often substantially so, for flow-through than for open water wetlands in both urbanization categories for pH, DO, Cond, NO3+NO2-N, SRP, FC, and Pb. In addition, the flow-through means were higher in moderately urbanized wetlands for TSS, NH3-N, TP, Cu, and Zn. Over all levels of urbanization flow-through wetland medians were higher for all water quality variables reported in the table.

It is clear from these results that flow-through wetlands strongly tend to be less acidic and better oxygenated than open water sites, as would be expected. Humic acid-producing vegetation thrives in an environment with low inflow, and attendant nutrient income. In these ponded systems oxygen renewal from the atmosphere is not as efficient as in flowing water, and they are warmer and hence have lower oxygen solubility. Also, more primary production and more oxygen-consuming organic decomposition occurs in the relatively long period of water residence. It is also clear that flow-through wetlands generally have higher pollutant concentrations, probably due to the greater loading of pollutants by the flow and reduced pollutant removal from the water column with the shorter hydraulic residence times.

Concentrations of NO3+NO2-N exhibited one of the greatest disparities between open water and flow-through wetlands. In addition to greater loading introduced by the flow, this phenomenon is probably partially due to higher oxygen levels in flow-through cases, which promote nitrification that converts ammonia to nitrite and then nitrate forms. In fact, ammonia differed between the two types of morphology much less than did NO3+NO2-N, suggesting that ammonia discharged to wetlands may be more effectively nitrified in flowing systems. Of course, these systems also support less decomposition by microorganisms and, thus, likely produce less ammonia internally than do open water wetlands.

Table 2-4. Water Quality Statistics for Wetlands Not Experiencing Significant Urbanization Change (1988-1995) Grouped by Urbanization and Morphological Status.

Status	Year	Stat.[a]	pH		DO	Cond.		TSS		NH_3-N		NO_3+NO_2-N		SRP		Tot P		FC		Tot Cu		Tot Pb		Tot Zn
					(mg/L)	(µS/cm)		(mg/L)		(µg/L)		(µg/L)		(µg/L)		(µg/L)		(CFU/100mL)		(µg/L)		(µg/L)		(µg/L)
N/OW	1995	Mean	33498.54		5.3	5	<	5.1	<	83	<	260	<	23		63	>	144	<	2.4	<	2.4	<	7.0
N/OW	1995	St. Dev.	935.94		2.6	3	>	7.8	>	154	>	487	>	59		103	>	702	>	3.7	>	3.1	>	8.4
N/OW	199500%	CV	3%		50%	50%	>	152%	>	186%	>	187%	>	258%		163%	>	488%	>	158%	>	131%	>	120%
N/OW	1995	Median	33092.00		5.3	5		2.4		35		49		6		31		5		0.9		1.0		2.5
N/OW	1995	n	136		135	135		109		104		107		121		136		115		23		21		65
N/FT		Mean	33443.64		6.6	7	<	6.6	<	65		672	<	11		31	<	327	<	1.6	<	5.3	<	4.4
N/FT		St. Dev.	919.99		2.3	2	>	11.7	>	133		417	>	19		27	>	855	>	2.6	>	0.0	>	5.8
N/FT		CV	3%		35%	35%	>	179%	>	206%		62%	>	165%		88%	>	262%	>	163%	>	0%	>	133%
N/FT		Median	33073.00		6.5	7		2.5		32		613		7		24		56		0.7		1.2		2.5
N/FT		n	70		70	70		54		46		70		62		70		65		8		6		29
M/OW	1995	Mean	33703.88	<	3.7	4	<	6.8	<	158	<	291	<	23		69	>	233	<	2.4	<	2.5	<	8.7
M/OW	1995	St. Dev.	851.14	>	2.7	3	>	14.7	>	371	>	401	>	41		69	>	769	>	2.0	>	2.2	>	6.7
M/OW	199500%	CV	3%	>	73%	74%	>	216%	>	235%	>	138%	>	178%		100%	>	331%	>	82%	>	88%	>	77%
M/OW	1995	Median	6.14		3.2	65		2.2		49		99		10		44		17		1.5		1.5		7.5
M/OW	1995	n	77		74	75		62		62		54		73		77		61		22		24		48
M/FT	1995	Mean	33505.61	<	7.0	7	<	12.4	<	127	<	912		39		111	>	4764	<	3.0	<	4.1	<	9.2
M/FT	1995	St. Dev.	918.20	>	3.6	4	>	26.4	>	200	>	989		35		103	>	37867	>	1.9	>	3.5	>	7.3
M/FT	199500%	CV	3%	>	51%	53%	>	214%	>	157%	>	108%		90%		93%	>	795%	>	62%	>	85%	>	79%
M/FT	1995	Median	33126.00		7.7	8		4.7		49		688		29		85		220		2.3		2.2		6.8
M/FT	1995	n	100		96	98		95		96		98		97		100		90		24		40		52
H/FT	1995	Mean	33436.94	<	5.4	5	<	10.5	<	81	<	401		31		110	>	1021	<	3.9	<	5.0	<	21.3
H/FT	1995	St. Dev.	914.79	>	2.8	3	>	15.8	>	111	>	236		16		233	>	4901.0	>	3.4	>	4.7	>	17.8
H/FT	199500%	CV	3%	>	52%	53%	>	150%	>	138%	>	59%		50%		213%	>	480%	>	88%	>	95%	>	84%
H/FT	1995	Median	33055.00		6.4	6		4.8		41		377		28		69		69		2.6		3.9		20.0
H/FT	1995	n	67		66	67		57		55		66		65		67		62		12		28		37
All		Median	6.16		4.6	39		2.3		39		70		7		35		8		1.1		1.4		5.2
OW		n	213		209	210		171		166		161		194		213		176		45		45		113
All		Median	7.00		6.9	183		4.2		42		510		21		60		110		2.3		3.0		6.9
FT		n	237		232	235		206		197		234		224	0	237		217		44		74		118

[a] See Table 1 for definitions of Status and Stat. abbreviations.

It must be noted that a preponderance of flow-through wetlands are in more urbanized areas, which certainly affects pollutant loading and may affect the strength of conclusions, although probably not the overall trends. It is possible that this skewed distribution is not just a coincidence but reflects the urban situation, in which higher peak runoff flows, wetland filling, and stream channelization favor flow-through over open water wetland conditions.

SOILS

Collection and Methods

Soil samples were collected once from each wetland during the months July-September in 1988-1990, 1993, and 1995. Soil sampling areas were selected 3 meters to the side of vegetation transect lines at every point where the soil type appeared either to be transitional or completely different. Small soil cores or signs of vegetation change were the basis for judgment. Two to five samples, most commonly four, were collected from each wetland. The number had a relationship to the size and zonal complexity of the wetlands. This coverage was considered to be adequate because a synoptic study of 73 urban and rural wetlands early in the program found that there were no significant differences among wetland zones (e.g., open pool, inlet, scrub-shrub, and emergent) with respect to soil texture, organic content, pH, phosphorus, and nitrogen (Horner at al. 1988). Because oxidation-reduction potential and one metal were significantly different near inlets as compared to other locations, the inlet zone was emphasized in as one spot in choosing sampling areas, however.

Soil samples were collected with a corer consisting of a 10-cm (4-inch) diameter ABS plastic pipe section ground to a sharp tip. The corer was twisted into the soil with a wooden rod inserted horizontally through two holes near the top. Coring depth was 15 cm (6 inches). Samples were inserted immediately into plastic bags, air was extruded, and the bags were sealed with tape. They were then transported to one of several laboratories used in the different years.

A standard 60-cm (2-ft) deep soil pit was dug at each sampling point not inundated above the surface. The pit was observed and notes were recorded for depth to water table (if within 60 cm of the surface), horizon definition (thickness of each layer and boundary type between), color (using Munsell notations), structure (grade, size, form, consistency, and moisture), and presence of roots and pores.

Soil core samples were analyzed for:

<u>General characteristics</u>	<u>Metals</u>
Particle size distribution (PSD)	Arsenic (As)
% organics as loss on ignition (LOI)	Cadmium (Cd)
pH	Copper (Cu)
Oxidation-reduction potential (redox)	Lead (Pb)
<u>Nutrients</u>	Zinc (Zn)
Total phosphorus (TP)	
Total Kjeldahl nitrogen (TKN)	

A report by King County Resource Planning Section (1988) provides detail on the general analytical methods, as well as the sampling program design. A method for PSD, also termed soil texture, was developed during this program for soils with more than 5% organics, as most wetland soils have. Texture is the measurement of the proportions of the various sizes of mineral particles in a soil, classified from largest to smallest as sand, silt, and clay (gravel, when significant, is also recognized in the texture classification). The analysis of any soil with more than 5 % organic content must include a step that removes the organic material. Failure to remove the organic component may cause clumping of particles and render the results inaccurate. The new PSD method, which is provided in Appendix A of this chapter, is considered to be accurate for soils with up to 25% organics. At higher levels it is not accurate because of sample loss during organic removal preparation, especially in the clay component.

Publications by Cooke, Richter, and Horner (1989); Richter et al. (1991); Cooke (1991); and Cooke and Azous (1993) are additional sources of detail on methods and findings from the initial years. Soils methods and results were also reported by Azous (1991), Cooke (1991), and Platin (1994).

Research Findings: A Portrait of Puget Sound Basin Wetland Soils

General Soil Characteristics and Nutrients

As with water quality, this discussion is conducted mainly with reference to descriptive statistics. Tests for statistical significance of difference and analyses of variance generally were not performed, for the same reasons stated earlier in the chapter. Table 2-5 statistically summarizes the soils data, excluding PSD, for wetlands that did not experience significant urbanization change during the program. Metals are discussed in a later subsection. Nonurban wetlands are the main focus of this chapter, and Chapter 9 further discusses the other categories, as well as wetlands with watersheds that did change.

Like water quality, soil quality exhibited extensive variability. As with most water quality variables, coefficients of variation for the majority of the soil variables were generally in the approximate range 75-150%, although in both soil and water cases some were higher. CVs for pH were considerably lower than for other analytes for both soils and water, usually about 10 $\pm$ 3%. Again like water quality variables, the quantities in Table 2-5 usually exhibited medians lower than the means, except for redox and sometimes pH. Therefore, most of these data also are far from normally distributed, and are probably log-normal.

Most wetlands had at least some pockets of peat of mainly sedge and grass origins (Cooke 1991), and their soils accordingly tended to be acidic. Among the different groupings of data in Table 2-5, median pH values were $\leq$ 6.1, except for highly urbanized cases, which were both flow-through . Overall, highly urbanized sites had the highest median pH, followed by moderately urbanized and then nonurbanized locations. Flow-through wetlands overall and in the N and M categories had higher median pH than open water types.

These wetlands frequently had anaerobic soils, as indicated by median redox values often < 250 mv, the approximate point at which oxygen is fully depleted. The median for the most highly urbanized case was lower than for the N wetlands, which themselves had lower median redox than the M cases. Open water wetlands overall had higher redox readings than flow-through ones. This result is somewhat surprising, in that open water wetlands are thought to host more oxygen-consuming decomposition and to have oxygen replenished from the atmosphere less efficiently than flow-through cases. It was found in the synoptic study of 73 wetlands at the beginning of the program that open water zones had the lowest redox readings (<100 mv) (Horner at al. 1988). Redox was below the level at which oxygen is generally depleted in the inlet, open water, and emergent zones but not in the scrub-shrub and forested zones. In another contrast with the more recent results, soils in the inlet zones of wetlands in nonurban wetlands had significantly ($P < 0.05$) lower redox than in urban wetlands.

The highest median TP occurred in moderately urbanized wetlands, and the highest TKN in nonurbanized ones. Open water systems were higher than flow-through cases in both nutrients overall, but that result was due to large differences between the two types of morphology in the M wetlands. This tendency was actually reversed in nonurbanized wetlands, which exhibited higher nutrients among the flow-through wetlands in that subset.

The N urbanization category had median organic content over 30%, although with extensive variation. The M and H sites overall had about half to two-thirds of that level. On the whole open water wetlands exceeded flow-through ones in organics, although again this tendency is due to the M wetland data. This finding is as expected, since ponded systems have more primary productivity and capability of settling solids.

Soil texture is important to the nutrition, structure, drainage, and erosion prevention characteristics of a soil. Nutrients are found in a soil attached to organic matter, clay particles, and metal oxides (especially iron oxides). Soils with a high portion of clay, organic material, or both adsorb water and nutrients much more readily than soils low in these components. Fine textured soils have a more compact structure, which may impede aeration of the soil. Clays adsorb water and if positioned lower down in the soil profile, can impede drainage, causing an impervious layer and creating a wetland. Sandy soils have very little cohesion and erode much more easily than silt- or clay-rich soils. One of the influences of urbanization on wetland ecosystems is deposition of sediments from development activities (clearing and grading).

Table 2-5. Soil quality statistics for wetlands not experiencing significant urbanization change (1988-1995) grouped by urbanization and morphological status.

Status [a]	Stat. [a]	pH	Redox. (mV)	TP (mg/kg)	TKN (mg/kg)	Org. (%)	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	As (mg/kg)
N/OW	Mean	5.43	143	743	5261	45.5	58	65	27	6.5
	Maximum	6.67	649	6579	27369	97.3	2221	418	154	20
	St. Dev.	0.64	322	1087	5983	34.2	300	96	29	5.4
	CV	12%	225%	146%	114%	75%	515%	147%	106%	84%
	Median	5.40	153	251	2866	47.0	16	24	18	4.4
	n	47	46	55	58	58	54	54	54	54
N/FT	Mean	5.73	113	839	3899	36.1	21	33	31	15
	Maximum	7.12	629	8882	14223	97.3	40	322	103	225
	St. Dev.	0.48	296	1698	3297	28.8	13	60	30	42
	CV	8%	262%	202%	85%	80%	61%	184%	97%	284%
	Median	5.70	184	342	3799	34.1	17	18	17	6.6
	n	27	27	27	29	29	27	27	27	27
All N	Mean	5.54	132	775	4807	42.4	46	54	28	9.3
	Maximum	7.12	649	8882	27369	97.3	2221	418	154	225
	Std. Dev.	0.60	311	1310	5261	32.6	245	87	29	25
	CV	11%	236%	169%	109%	77%	536%	159%	103%	267%
	Median	5.60	184	283	2885	35.8	16	20	17	6.0
	n	74	73	82	87	87	81	81	81	81
M/OW	Mean	5.31	317	1114	6354	35.4	12	32	22	6.2
	Maximum	6.72	656	3827	22517	92.3	24	101	92	16
	St. Dev.	0.90	227	1019	5670	29.9	7	30	24	4.4
	CV	17%	72%	91%	89%	85%	60%	95%	107%	70%
	Median	5.11	362	945	5783	23.7	14	21	15	4.8
	n	26	26	25	25	25	28	28	28	28
M/FT	Mean	5.95	165	756	3999	25.7	18	77	60	8.1
	Maximum	6.96	611	2743	27967	92.3	63	530	334	25
	St. Dev.	0.51	279	819	5942	28.1	12	89	62	5.2
	CV	9%	169%	108%	149%	109%	68%	115%	104%	65%
	Median	6.09	226	481	2021	12.6	17	57	48	7.7
	n	45	43	41	43	47	43	43	43	43
All M	Mean	5.71	222	892	4865	29.1	16	59	45	7.3
	Maximum	6.96	656	3827	27967	92.3	63	530	334	25
	Std. Dev.	0.74	269	909	5912	28.9	11	75	53	5.0
	CV	13%	121%	102%	122%	99%	69%	126%	119%	68%
	Median	5.78	306	537	2764	15.1	15	34	33	6.2
	n	71	69	66	68	72	71	71	71	71
H/FT	Mean	5.88	87	654	2703	31.6	31	89	103	13
	Maximum	6.97	640	2995	11282	80.9	63	273	456	40
	St. Dev.	1.01	291	784	2892	26.3	17	68	112	9.4
	CV	17%	335%	120%	107%	83%	56%	76%	109%	74%
	Median	6.46	91	314	2033	22.8	30	64	65	10
	n	32	32	34	36	35	32	32	32	32
All OW	Mean	5.39	206	859	5590	42.4	43	54	25	6.4
	Maximum	6.72	656	6579	27369	97.3	2221	418	154	20
	St. Dev.	0.74	302	1074	5877	33.1	244	81	27	5.1
	CV	14%	147%	125%	105%	78%	572%	151%	107%	80%
	Median	5.35	305	414	3141	34.2	15	24	16	4.5
	n	73	72	80	83	83	82	82	82	82
All FT	Mean	5.87	127	744	3540	30.3	23	69	66	11
	Maximum	7.12	640	8882	27967	97.3	63	530	456	225
	St. Dev.	0.70	286	1102	4449	27.8	15	78	80	22
	CV	12%	226%	148%	126%	92%	67%	113%	123%	199%
	Median	5.92	162	378	2274	16.1	20	46	45	7.70
	n	104	102	102	108	111	102	102	102	102

[a] See Table 1 for definitions of abbreviations.

Table 2-6 presents a comparison of soil textures in 1989 and 1995 for the wetlands that did not experience significant watershed change. As was hypothesized for these cases, little change occurred over these years regardless of urbanization or morphological status. The soils of the majority of these wetlands were dominated by silt-range particles, again irrespective of status. One N/OW and one M/FT site, located in different parts of the study area, had predominately sand. With two exceptions, the wetlands were found to have relatively little clay (≤ 20%). However, a wetland in north King County and one in south King County had about 30% and 50%, respectively. It bears noting that some of the samples contributing to these statistics had > 25% organic content, in the range where the analytical method is less accurate.

Table 2-6. Comparison changes in average particle size distributions from 1989 to 1995 in wetlands that experienced little urbanization change grouped by urbanization and morphological classifications.

Site[a]	Wetland Area (ha)	PSD 1989 (%sand/silt/clay)	PSD 1995 (%sand/silt/clay)
N/OW			
AL3	0.81	26/54/20	No data
HC13	1.62	47/47/6	45/37/18
RR5	10.52	74/15/11	68/21/11
SR24	10.12	1/89/10	6/75/19
N/FT			
LCR93	10.93	No data	30/50/20
MGR36	2.23	13/76/11	20/70/10
M/OW			
ELS39	2.02	35/49/16	15/69/16
SC84	2.83	4/81/15	11/73/16
TC13	2.06	30/41/29	38/32/30
M/FT			
ELW1	3.84	83/13/4	75/18/7
FC1	7.28	13/71/16	10/75/15
SC4	1.62	No data	No data
N/FT			
B3I	1.98	31/62/7	24/61/15
LPS9	7.69	30/16/54	32/20/48

[a]See Table 1 for definitions of abbreviations.

Analysis of the PSD measurements within individual wetlands indicates that PSD often varied substantially across wetlands and showed no trends with the amount of organic matter in the soil or the soil series. No association was seen between the total suspended solids in the surface water and changes in soil texture. However, soils located near the inlets of M and H wetlands were significantly ($P < 0.05$) more likely to have more sand than silt as compared to other locations.

METALS IN SOILS

Cadmium, lead, and zinc in wetland soils were observed to be highly variable from year to year, but copper and arsenic varied less. Overall, there was a declining trend in soil metal content over the years of the study. These results are somewhat surprising since the soil cores were 15 cm deep, representing soil horizons that would be expected to maintain fairly stable metals concentrations from year to year. Figure 2-1 shows that median concentrations of As, Cu, Pb, and Zn for all of the program wetlands generally declined each year. It is possible that metals enter and depart from wetland soils more easily than previously believed, permitting a rapid change in results in response to changes in inputs from the watershed. Declining metals pollution from vehicles and dissipating pollutants from industrial air pollution point sources, such as the closed ASARCO smelter in Tacoma, could explain the general decline of metals since the start of the program.

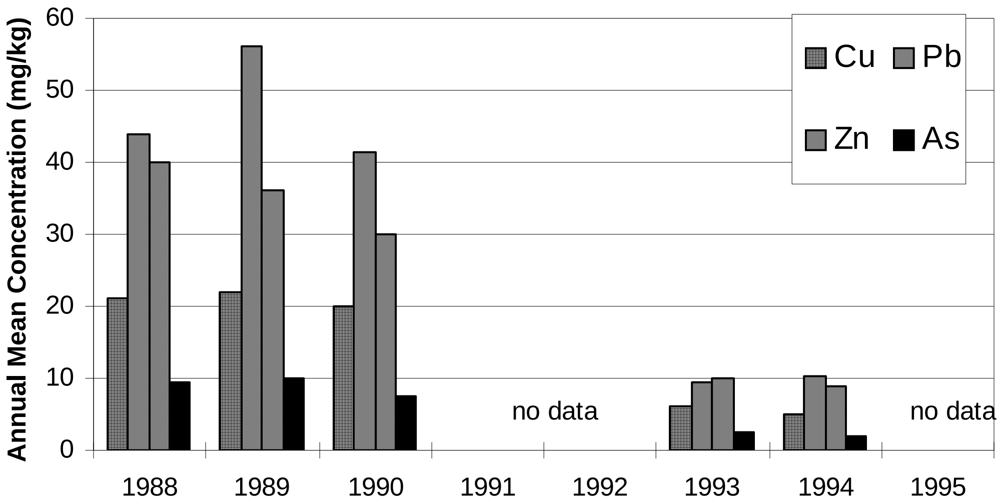

Figure 2-1. Annual mean metal concentration for all wetland samples in each year.

Cadmium was undetectable in the soils of most monitored wetlands, except in three that also had relatively high Pb. This result is consistent with the observation that metals often increase in tandem. Although the program detected substantial increases in Cd, Pb, and Zn at several wetlands between 1989 and 1990 (Richter et al. 1991), it is significant that there are no apparent common characteristics among these wetlands. They represent differing hydrology, ecology, and levels of watershed development.

It can be seen in reviewing the metals data in Table 2-5 that, like water quality and general soil characteristics, soil metals exhibited extensive variability. Again, too, medians were normally considerably less than means.

It is further apparent in Table 2-5 that median metals concentrations increased from nonurban to moderately urbanized and again from there to highly urbanized wetlands, except for a small drop in copper from N to M. Flow-through wetlands overall had higher median concentrations of all metals than did open water ones, although very marginally so for Cu. This tendency was again stronger for the moderately urbanized than the nonurbanized wetlands. For the most part, then, soils exhibited the same trend as water quality, with quantities considered to be pollutants higher in FT than in the OW wetlands. It was thought that water column contaminants might be lower in open water wetlands because of losses to the soil. However, this supposition was not borne out by the soil results. Still, having the two most developed sites in the FT group may be skewing the results.

The Washington Department of Ecology (1991) set metals criteria for freshwater sediments in terms of lowest effect and severe effect thresholds. The criteria are:

	Lowest Effect Threshold (mg/kg dry soil)	Severe Effect Threshold (mg/kg dry soil)
Copper	16	110
Lead	31	250
Zinc	120	820

No mean or median value exceeded the severe effect criteria, and very few individual readings surpassed them at any time during the program. However, lowest effect thresholds were exceeded by some Cu and Pb means and even medians. Many individual readings in wetlands in all urbanization categories were beyond these lower limits.

Even though there is a trend toward increasing soil metals with urbanization, it is a fact that soil in either urban or nonurban wetlands can have elevated metals. These contaminants could be entering wetlands outside of urban areas in a variety of ways. Possibilities include via precipitation and atmospheric dryfall, dumping of metal trash, and leaching from old constructed embankments. Roads and narrow-gage railroad beds were built using mine tailings to serve logging operations in the last century in the vicinity of some of the wetlands. This phenomenon suggests the need for site-specific inquiries into metals pollution in Pacific Northwest palustrine wetlands, rather than reliance on broad patterns.

SUMMARY OF SOILS CHARACTERISTICS OF WETLANDS WITH NONURBANIZED WATERSHEDS

A soils portrait of Puget Sound Basin lowland palustrine wetlands relatively unaffected by humans shows a somewhat acidic condition; pH is very likely to be in the range 5-6. With redox as a basis, soils at many times and places will be anaerobic, but with great variability. Phosphorus is likely to be somewhere in the vicinity of 300 mg/kg, with nitrogen (TKN) approximately an order or magnitude higher. Based on these results, most soil samples from nonurban wetlands can be expected to have > 25% organics, and > 10% is extremely likely. Texture appears to be more a function of local conditions than a function of urbanization, or lack of it.

The metals As, Cu, Pb, and Zn, can range over two orders of magnitude, from a minimum in the low parts per million (mg/kg) region, in the soils of these nonurban wetlands. Most commonly, they appear to have approximately equal amounts of Cu, Pb, and Zn, around 20 mg/kg, and about one-quarter to one-third as much As. This level and the observed variation around it is sufficiently high to exceed lowest effect threshold freshwater sediment criteria for Cu often and for Pb occasionally, but very rarely for Zn.

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