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THE USE OF TREATMENT WETLANDS FOR PETROLEUM INDUSTRY EFFLUENTS

HEALTH AND ENVIRONMENTAL SCIENCES DEPARTMENT
PUBLICATION NUMBER 4672
OCTOBER 1998

STEP
Strategies for Today's Environmental Partnership

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The Use of Treatment Wetlands for Petroleum Industry Effluents

Health and Environmental Sciences Department

API PUBLICATION NUMBER 4672

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Executive Summary

Treatment wetlands are becoming widely used for cleansing some classes of wastewater effluents. Although the use of treatment wetlands is well established for wastewater categories such as municipal waste, stormwater, agricultural wastewater, and acid mine drainage water, their use in treating a variety of industrial wastewaters is less well developed. Constructed treatment wetlands hold considerable promise for managing some wastewaters generated by the petroleum industry. Several large-scale wetland projects currently exist at oil refineries, and numerous pilot studies of constructed treatment wetlands have been conducted at terminals, gas and oil extraction and pumping stations, and refineries. This report summarizes current information about the use of treatment wetlands for managing petroleum industry wastewaters and also presents background information on the general performance, design, and operation of treatment wetlands based on experience with a variety of wastewater types.

Performance

Simplistic models of pollutant reductions based on first-order disappearance kinetics provide a reasonable first approximation of overall wetland behavior. These first-order processes are unlike many conventional treatment-tank processes in that they are highly dependent on wetland area rather than wetland water volume. Moreover, they are limited to non-zero residual pollutant levels for many parameters because of natural water quality background properties of wetlands. A first-order, two-parameter, area-based model with a background concentration (k-C* model) is used in this report and in reviewed literature to compare the performance of a variety of treatment wetlands.

This report reviews in detail treatment wetland performance for the following parameters:

- Chemical oxygen demand
- Biochemical oxygen demand
- Trace organics
- Metals
- Total suspended solids
- Forms of nitrogen
- Phosphorus

All of these parameters can be reliably removed from wastewater and returned to background levels by treatment wetlands. Pollutant removal is highly dependent on hydraulic loading and

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influent concentration, and to a lesser extent on internal plant communities, water depth, and hydraulic efficiency. In most cases, data from petroleum industry wetland studies indicate that treatment wetlands are equally or more effective at removing pollutants from petroleum industry wastewaters than from other types of wastewater. Until industry-specific data are more complete, this finding can be used along with published rate constants from other treatment wetlands to provide conservative estimates for treatment wetland sizing.

Reduction of whole effluent toxicity is an important issue for the petroleum industry and has been studied in a relatively small number of treatment wetlands. Current results indicate consistent reductions in whole effluent toxicity in treatment wetlands. These reductions are thought to be pollutant-specific, and the magnitude of reduction is dependent on the same factors that control reduction efficiencies for other pollutants.

Design Considerations

Treatment wetland systems are land intensive and their design focuses on three primary factors:

- Determining the appropriate level of pretreatment
- Selecting adequate wetland area
- Establishing effective effluent flow distribution over that area

Water depths in treatment wetlands are typically about 30 centimeters or less, except in transverse deep zones used for flow redistribution, solids retention, and wildlife habitat. Flow control structures, embankment design, lining, and use of subsurface flow substrates are all important issues during treatment wetland design. Plant selection and plant species diversity are typically dependent on project goals other than treatment performance.

Operation and Maintenance

Wetland operation and maintenance efforts can be reduced through conservative design. Treatment wetlands have few controls and respond relatively slowly to operational changes. Routine monitoring is essential for detecting changes in system performance quickly enough to respond with effective operational changes. Compared with other treatment technologies, treatment wetlands require little operation and maintenance and have low energy requirements.

Case Histories

Treatment wetland case histories from projects in the petroleum industry provide a convenient summary of experience that can be used when considering new projects. Case histories are

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presented at the end of this report for six pilot-scale and four full-scale treatment wetlands receiving petroleum industry wastewaters. These studies include wastes from oil sands mining and extraction, oil and gas wells, handling and transferring facilities, refineries, and tank farms. Treatment wetland types that have been studied in the petroleum industry include surface flow and subsurface flow constructed marshes, a pond/marsh combination, and one floating aquatic plant system.

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SECTION 1

Introduction

Wetlands have been engineered for water quality treatment in the United States since the early 1970s (Table 1-1). Considerable information on the design and operation of these treatment wetlands has accumulated since that time. As a result, a rapidly growing body of literature is available to individuals interested in applying this technology for water quality treatment.

Several efforts have assessed the effectiveness of treatment wetlands and summarized information from diverse data sources into coherent and predictive descriptions of performance. One of the most comprehensive summarization efforts to date was the development of the North American Treatment Wetland Database (NADB) funded by the U.S. Environmental Protection Agency (EPA) (Knight *et al.*, 1993a; NADB, 1993).

A comprehensive book that builds on the NADB and hundreds of published papers to describe the performance and design of treatment wetland has been published (Kadlec and Knight, 1996). Another ongoing compilation effort is a review of wetlands treating concentrated livestock wastewaters (CH2M HILL and Payne Engineering, 1997). This has resulted in an electronic database of design and performance information known as the Livestock Wastewater Wetland Database (LWDB). An earlier effort reviewed design and operational data from wetlands receiving wastewaters from the pulp and paper industry (CH2M HILL, 1994a).

This report continues this synthesis by providing the first review of treatment wetland research and full-scale projects in the petroleum industry worldwide. Over the past 10 years, journal articles and symposia proceedings have indicated the petroleum industry's interest in using constructed wetlands to manage process wastewater and stormwater at a variety of installations, including refineries, oil and gas wells, and pumping stations. These publications report that constructed wetlands provide water quality benefits when properly designed and maintained. However, published data have been scarce and unavailable for broad review within or outside of the industry.

In 1995, the Biomonitoring Task Force of the American Petroleum Institute (API) funded a review and summary of available (published and company confidential) treatment wetland data from the petroleum industry. The summary was intended to present the information in the much broader context of the role of wetlands for treating wastewaters from other sources. This report presents the results of this review and technology assessment.

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TABLE 1-1
Timeline of Selected Events in Treatment Wetland Technology

Date	Location	Description
Selected Research Efforts		
1952-late 1970s	Plon, Germany	Removal of phenols and treatment of dairy wastewater with bulrush plants
1967-1972	Morehead City, North Carolina	Constructed estuarine ponds and natural salt marsh for municipal effluent recycling
1971-1975	Woods Hole, Massachusetts	Potential of natural salt marshes to remove nutrients, heavy metals, and organics
1972-1977	Houghton Lake, Michigan	Natural wetland treatment of municipal wastewater
1973-1974	Dulac, Louisiana	Discharge of fish processing waste to a freshwater marsh
1973-1975	Seymour, Wisconsin	Pollutant removal in constructed marshes planted with bulrush
1973-1976	Brookhaven, New York	Meadow/marsh/pond systems
1973-1977	Gainesville, Florida	Cypress wetlands for recycling of municipal wastewaters
1974-1975	Brillion, Wisconsin	Phosphorus removal in constructed and natural marsh wetlands
1974-1988	NSTL Station, Mississippi	Gravel-based, subsurface flow wetlands tested for recycling municipal wastewaters and priority pollutants
1975-1977	Trenton, New Jersey	Irrigation of small enclosures in the Hamilton Marshes (freshwater tidal) with treated sewage
1976-1979	Eagle Lake, Iowa	Assimilation of agricultural drainage and municipal wastewater nutrients in a natural marsh wetland
1976-1982	Southeast Florida	Nutrient removal in natural marsh wetlands receiving agricultural drainage waters
1979-1982	Humboldt, Saskatchewan	Batch treatment of raw municipal sewage in lagoons and wetland trenches
1979-1982	Arcata, California	Pilot wetland treatment system for municipal wastewater treatment
1980-1984	Listowel, Ontario	Testing of constructed marsh wetlands for treatment of municipal wastewater under a variety of design and operating conditions
1981-1984	Santee, California	Testing of subsurface flow wetlands for treatment of municipal wastewaters
1985-1990	Columbus, Mississippi	Testing of subsurface flow marshes for treatment of pulp mill effluent
1989-1995	Leaf River, Mississippi	Testing of surface flow marshes for treatment of pulp mill effluent
1992-1994	Hemet, California	Testing of surface flow marshes for treatment of reuse wastewater and reject brine

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TABLE 1-1 (CONTINUED)
Timeline of Selected Events in Treatment Wetland Technology

Date	Location	Description
Selected Full-Scale Projects		
1972	Bellaire, Michigan	Natural forested wetland receiving municipal wastewaters
1973	Mt. View, California	Constructed wetlands for municipal wastewater treatment
1974	Othfresen, West Germany	Full-scale reed marsh facility treating municipal wastewater in an old quarry
1975	Mandan, North Dakota	Constructed ponds and marshes to treat runoff and pretreated process wastewater from an oil refinery
1977	Lake Buena Vista, Florida	Use of a natural forested wetland for year-round advanced treatment and disposal of up to 27,700 m^3/d of municipal wastewater
1978	Houghton Lake, Michigan	Natural peatland receiving summer flows of municipal wastewater
1979	Drummond, Wisconsin	Sphagnum bog receiving summer flows from a facultative lagoon
1979	Show Low, Arizona	Constructed wetland ponds for municipal wastewater treatment and wildlife enhancement
1984	Incline Village, Nevada	Constructed wetlands for total assimilation (zero discharge) of municipal effluent
1986	Arcata, California	Constructed marsh wetlands for municipal wastewater treatment
1987	Orlando and Lakeland, Florida	Two large (> 480 ha) constructed wetlands for municipal treatment
1987	Myrtle Beach, South Carolina	Natural Carolina bay wetlands for municipal wastewater treatment
1987-1988	Benton, Hardin, and Pembroke, Kentucky	Constructed wetlands for municipal wastewater treatment designed by the Tennessee Valley Authority
1988	Orange County, Florida	Hybrid treatment system combining constructed and natural wetland units
1989	Richmond, California	Full-scale treatment marshes for petroleum refinery wastewater and stormwater treatment
1991	Columbus, Mississippi	First full-scale constructed wetland for advanced treatment of pulp and paper mill wastewater
1991	Minot, North Dakota	Northern surface flow wetland system (51.2 ha) for municipal treatment during a 180-day discharge season
1993	Everglades, Florida	Treatment of phosphorus in agricultural runoff in a 1,380 ha constructed filtering marsh
1993	Beaumont, Texas	Large (263 ha) constructed marsh for municipal wastewater polishing and public use

m^3/d cubic meters per day
ha hectare
NSTL National Space Testing Laboratory

Source: Adapted from Kadlec and Knight, 1996.

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This section provides a general overview of constructed treatment wetlands and their possible importance to the petroleum industry and summarizes the NADB and other relevant databases. The contents of the rest of the document are summarized as follows:

- Section 2 provides methods for estimating the water quality enhancement capability of treatment wetlands receiving petroleum industry contaminants. Specific wetland sizing methods are provided for the major pollutants commonly treated in constructed wetlands. When possible, these methods are based on data from petroleum industry wetland systems.
- Section 3 describes the other important aspects of treatment wetland design, including site selection, pretreatment, system sizing, hydraulic design, and vegetation selection.
- Section 4 describes current information important in operating treatment wetlands. It focuses on minimizing operational requirements and using monitoring to anticipate operational changes.
- Section 5 discusses treatment wetland design considerations related to providing secondary benefits for wildlife enhancement and for public use. It also examines the potential for bioaccumulation of toxics and how nuisance conditions can be avoided in treatment wetlands.
- Section 6 provides biblographic citations for technical publications referenced in preparing this report.

The appendices, which appear at the end of this document, include a glossary of important technical terms relating to treatment wetlands and petroleum industry case histories for six pilot and four full-scale projects.

Overview of Constructed Treatment Wetlands

Wetlands are ecosystems in areas where water conditions are intermediate between uplands and deep-water aquatic systems. Technical and regulatory definitions of wetlands focus on wetland ecosystems' dependence on shallow water conditions, which result in saturated soils, low dissolved oxygen (DO) levels or anaerobiosis in soils, and colonization by adapted plant and animal communities (Cowardin *et al.*, 1979; Mitsch and Gosselink, 1993). The natural ability of wetland ecosystems to improve water quality has been recognized for more than 25 years. During this period, the use of engineered wetlands has evolved from a research concept to an accepted pollution control technology.

Three general types of shallow vegetated ecosystems are being used for water quality treatment: (1) free water surface (surface flow), (2) subsurface flow (vegetated submerged bed), and (3) floating aquatic plant treatment systems (Figure 1-1). All three of these vegetated system types are used in the United States for engineered water quality improvement. EPA has prepared a design manual summarizing early performance information for all three system types (EPA, 1988a), as well as a subsurface flow technology assessment (EPA, 1993a). A technology assessment report focusing only on the free water surface treatment wetland technology is currently in preparation for EPA (CH2M HILL, in preparation).

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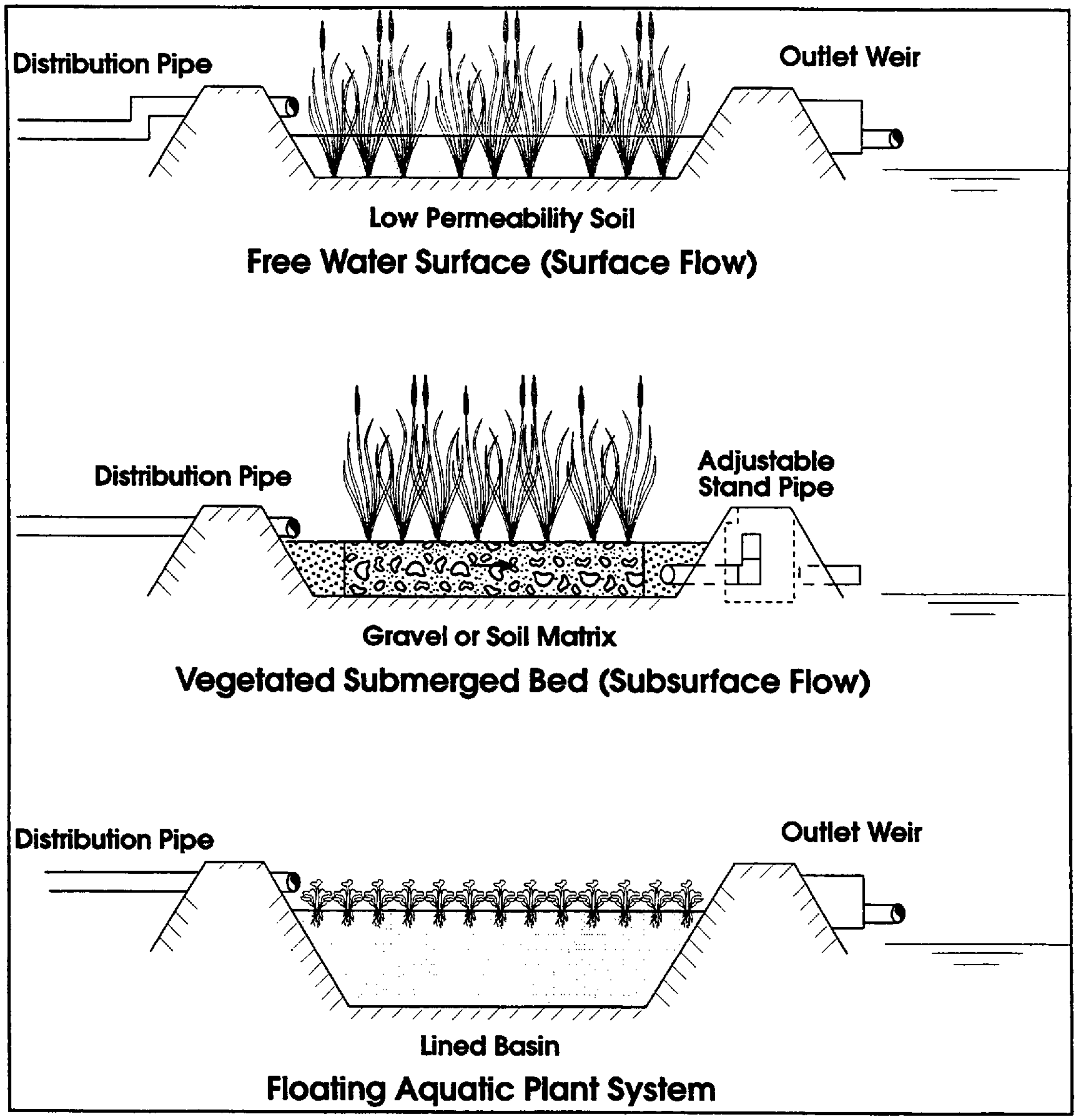

FIGURE 1-1
Schematic of Wetland and Floating Aquatic Plant Treatment Systems
Source: Adapted from Kadlec and Knight, 1996.

Treatment wetland technology started when natural wetlands were incorporated as components of wastewater treatment systems (Ewel and Odum,1984; Kadlec and Tilton, 1979). Constructed free water surface treatment wetlands mimic the hydrologic regime of natural wetlands. In surface flow wetlands, water flows over the soil surface from an inlet point to an outlet point or, in a few cases, is totally lost to evapotranspiration and infiltration within the wetland. In subsurface flow wetlands, wastewater flows through a constructed media bed planted with wetland plants which eliminates the potential for direct

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exposure of humans or wildlife to the wastewater. Floating aquatic plant systems are analagous to ponds and are not treated in this review.

The analysis of performance data from natural and constructed free water surface wetlands indicates that these systems are similar in overall function in many cases. The principal differences between natural and constructed treatment wetlands are structural. Mature natural wetlands are more likely to have a forested plant community than constructed wetlands and are more likely to include a well-developed organic soil component. They are also more likely to have variable water depths and stagnant water areas outside the flow path that reduce treatment efficiency. This reduced efficiency for some parameters may be reflected in lower pollutant removal rate constants in some natural treatment wetlands. Thus, constructed wetlands offer greater opportunity to optimize hydraulic efficiency and to achieve maximum treatment within a fixed wetland area.

Natural wetlands are considered to be waters of the United States and can be permitted only as receiving waters, not as part of treatment systems. While a number of natural wetlands have been permitted to receive secondary or high-quality municipal wastewater effluents, their widespread use for treatment of industrial wastewaters is unlikely. Consequently, this report does not discuss the design and performance of natural treatment wetlands in relation to petroleum industry wastewater. However, since much of the existing performance data for municipal treatment wetlands are from natural wetlands, those data have been included in the general performance summaries that follow.

Treatment wetlands function as land-intensive biological treatment systems (Figure 1-2). In these systems, inflow water containing particulate and dissolved pollutants slows and spreads through a large area of shallow water and emergent vegetation. Particulates (typically measured as total suspended solids [TSS]) tend to settle and are trapped in the sediment due to lowered flow velocities and sheltering from wind. These particulates contain biochemical and chemical oxygen demanding (BOD and COD) components, hydrocarbons and other organics, trace metals, and fixed forms of total nitrogen (TN) and total phosphorus (TP). Particulate-based pollutants enter the biogeochemical element cycles within the water column and surface soils of the wetland. At the same time, a fraction of the dissolved BOD, COD, organics, metals, TN, and TP are sorbed by soils and active microbial and plant populations throughout the wetland environment and become part of the mineral cycles of the wetland system.

Treatment wetlands have some properties in common with facultative lagoons and also have some important structural and functional differences. Water column processes in deeper water zones within surface flow treatment wetlands are nearly identical to ponds that have a surface autotrophic zone dominated by planktonic or filamentous algae, or by floating or submerged aquatic macrophytes. In the absence of light, the bottom portion of deeper zones in both treatment wetlands and facultative lagoons tends to be dominated by anaerobic microbial processes. However, shallow emergent macrophyte zones

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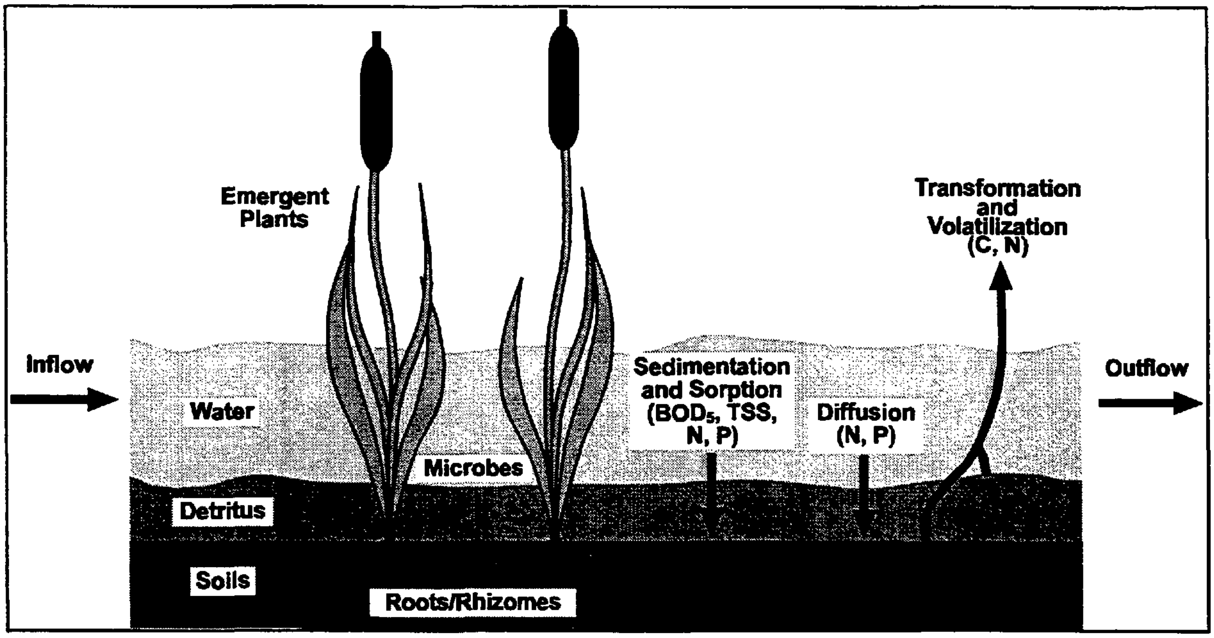

FIGURE 1-2
Wetland Processes Include Sedimentation, Chemical Sorption, and Microbial Transformations of Wastewater Source Pollutants: Adapted from ADEQ, 1995.

in treatment wetlands and aerobic lagoons can be quite dissimilar. Emergent wetland plants tend to cool and shade the water surface, reducing algae growth and concurrently reducing dissolved oxygen. Net carbon production in emergent wetlands tends to be high compared with facultative ponds, resulting in accumulation of structural carbon in the oxygen-deficient water column. This high carbon availability and the short diffusional gradients in shallow wetlands result in differences in biogeochemical cycling compared with ponds and lagoons.

During the process of elemental cycling within the wetland, chemical free energy is extracted by the heterotrophic biota, and fixed carbon and nitrogen are lost to the atmosphere. A portion of the phosphorus and other nonvolatile elements such as metals and nondegradable organics can be removed from the mineral cycle and buried in accreting sediments within the wetland. Wetlands are autotrophic ecosystems, and the additional fixed carbon and nitrogen concentrations from the atmosphere are processed simultaneously with the pollutants introduced from the wastewater source. The net effect of these complex processes is a general reduction of pollutant concentrations between the inlet and outlet of treatment wetlands. However, because of the internal autotrophic processes of the wetland, outflow pollutant concentrations are seldom zero; in some cases for some parameters, outflow pollutant concentrations may exceed inflow concentrations. (See Section 2 of this report for information on the magnitude of these background constituent concentrations.)

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Summary of Existing Data Sources

The use of wetlands for wastewater treatment is an emerging technology in North America and worldwide. These wetland systems have a wide variety of engineering designs, wetted areas, flow rates, inflow water qualities, plant communities, hydrologic regimes, effluent limitations, and monitoring requirements. Several handbooks provide useful syntheses of existing knowledge concerning the design of new wetlands (Kadlec and Knight, 1996; Davis, 1995; Reed *et al.*, 1995; U.S. Department of Agriculture, Soil Conservation Service [USDA NRCS], 1991; Cooper and Findlater, 1990; Water Pollution Control Federation[1] [WPCF], 1990; EPA, 1988a). Although these handbooks deal with common pollutants such as BOD, TSS, TN, and TP, they also have some information on the performance of treatment wetlands for other contaminants. Data from operational wetland treatment systems are accumulating so fast that handbooks will be outdated unless new empirical results are organized in electronic databases. Efforts are in progress to summarize and assess the surface flow treatment wetland technology (CH2M HILL, 1996) and to update the 1988 EPA constructed treatment wetland design manual.

Information on the effects of wetlands on water quality and the effects of treated wastewaters on wetland biota has been collected from many operational treatment wetland systems. Until recently, this information was widely scattered in scientific journal articles, monitoring reports to agencies, consultant reports, and private databases. A framework to record and update this expanding knowledge that would make information available to engineers and scientists nationwide was necessary to eliminate duplication of effort and to continue to refine the empirical design equations now in use. This section summarizes several treatment wetland design and performance databases developed to achieve those goals.

North American Treatment Wetland Database (NADB)

The first wetland treatment system database project was initiated in 1991 and ended in 1993. The NADB has cataloged existing information from 206 natural and constructed wetland treatment systems and available operational records for major water quality parameters. The result is a consistent, unified database. Although the NADB is the most comprehensive collection of treatment wetland data available, many data gaps exist. The NADB has been widely distributed to the engineering, scientific, and regulatory communities, and summaries of the preliminary data have been reported (Knight *et al.*, 1993a and b; Kadlec and Knight, 1996).

Types of information contained in the NADB include location, climatic factors, populations served, capital and operating costs, design considerations, operating data for water quality, biota, permit conditions, existing reports and literature, and key contact people for each system. These data are cataloged into seven linked data files using dBASE IV software.

At each wetland treatment site, either a single system with an inflow and outflow or multiple, parallel systems with discrete outflow points were included. Most of the existing wetland treatment systems in

[1] Now called the Water Environment Federation (WEF).

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North America meeting several general requirements were included in the NADB. Except for some pilot-scale systems, these systems include wetlands receiving municipal wastewater, industrial wastewater, and stormwater at flows generally exceeded 100,000 gallons per day (gpd) (378 m^3/d).

The primary purpose of the wetland treatment database effort was to develop a summary of existing information that could be expanded to accommodate additional information. To prepare the summary, operational data for inflow and outflow rates and constituent concentrations were averaged seasonally. Table 1-2 is a summary of the average surface flow and subsurface flow treatment wetland operational performance data. Design and operational data that affect assimilation rates were summarized for each system to allow regression analysis and the refinement of existing empirical design equations. Memoranda containing data quality records, anecdotal system design information, and interpretation of performance trends were included as electronic files.

A second purpose of the wetland treatment database was to serve as an academic research tool for scientific investigations of wetland ecology. Consequently, the database provides a detailed data repository for the physical, chemical, and biological processes of treatment wetlands. This knowledge may help direct new research efforts. The database has proven useful for calibration and verification of a variety of pollutant reduction models (Kadlec and Knight, 1996).

A third goal of the wetland treatment database was to help standardize monitoring and reporting in wetland treatment systems nationwide. Currently, permits vary widely in reporting requirements for wetlands receiving wastewater, and researchers frequently omit key water quality parameters from monitoring or pilot programs.

Version 2.0 of the NADB (NADB.v.2.0) is currently in preparation and will include treatment wetland data for vegetation, wildlife, metals, organics, toxicity, human use, and livestock wastewater sources. Future expansion of the database contents and additional analysis of the data collected in this format will enhance the usefulness of this product to the engineering, scientific, and regulatory communities.

Permit writers and researchers can use the operational data in the database to gain an understanding of the normal variability of water quality in wetland treatment system discharges and an appreciation of the difficulty of interpreting data from wetlands with insufficient information. Data gaps can help to focus attention on new issues and direct monitoring efforts to ensure that key information is collected.

Use of Wetlands for Treatment of Pulp and Paper Industry Wastewaters

In 1994, the National Council of the Paper Industry for Air and Stream Improvement (NCASI) funded a review of the status of treatment wetlands in the industry. A draft review report was prepared but has not yet been published in a final form (CH2M HILL, 1994a). This review describes ten pilot- or full-scale treatment wetland projects in the pulp and paper industry in the United States. These projects include four pilot-scale free water surface constructed wetlands, three constructed subsurface flow pilot

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TABLE 1-2
Summary of North American Treatment Wetland Database Operational Performance

		Average Concentration (mg/L)				Average Mass (kg/ha/d)[a]			
Parameter	Type[b]	In	Out	Eff (%)	Count (n)	Loading	Removal	Eff (%)	Count (n)
BOD_5	SF	30.3	8.0	74	182	7.2	5.1	71	133
	SSF	27.5	8.6	69	34	29.2	18.4	63	29
	All	29.8	8.1	73	216	10.9	7.5	68	162
TSS	SF	45.6	13.5	70	198	10.4	7.0	68	139
	SSF	48.2	10.3	79	34	48.1	35.3	74	29
	All	46.0	13.0	72	232	16.8	11.9	71	168
NH_4-N	SF	4.88	2.23	54	220	0.93	0.35	38	141
	SSF	5.98	4.51	25	19	7.02	0.62	9	15
	All	4.97	2.41	52	239	1.46	0.38	26	156
NO_2 + NO_3-N	SF	5.56	2.15	61	187	0.80	0.40	51	125
	SSF	4.40	1.35	69	13	3.10	1.89	61	13
	All	5.49	2.10	62	200	0.99	0.54	55	138
ORG-N	SF	3.45	1.85	46	118	0.90	0.51	56	76
	SSF	10.11	4.03	60	11	7.28	4.05	56	11
	All	4.01	2.03	49	129	1.71	0.95	56	87
TKN	SF	7.60	4.31	43	144	2.20	1.03	47	94
	SSF	14.21	7.16	50	12	9.30	3.25	35	12
	All	8.11	4.53	44	156	2.99	1.29	43	106
TN	SF	9.03	4.27	53	175	1.94	1.06	55	114
	SSF	18.92	8.41	56	12	13.19	5.85	44	12
	All	9.67	4.53	53	187	2.98	1.52	51	126
O-P	SF	1.75	1.11	37	148	0.29	0.12	41	112
	SSF	ND	ND	ND	—	ND	ND	ND	—
	All	1.75	1.11	37	148	0.29	0.12	41	112
TP	SF	3.78	1.62	57	191	0.50	0.17	34	134
	SSF	4.41	2.97	32	8	5.14	1.14	22	8
	All	3.80	1.68	56	199	0.73	0.22	31	142

[a] kg/ha/d x 0.892 = lb/ac/d

[b] BOD_5 5-day biochemical oxygen demand
Eff (%) efficiency of concentration reduction or mass removal
kg/ha/d kilograms per hectare per day
lb/ac/d pounds per acre per day
mg/L milligrams per liter
N count
ND no data
NH_4-N ammonia-nitrogen
NO_2 + NO_3-N nitrite plus nitrate nitrogen
O-P ortho phosphorus
ORG-N organic nitrogen
SF surface flow
SSF subsurface flow
TKN total kjeldahl nitrogen
TN total nitrogen
TP total phosphorus
TSS total suspended solids

Source: Kadlec and Knight, 1996.

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wetlands, one full-scale constructed free water surface treatment wetland, and two full-scale effluent discharges to natural basins.

Data from these projects were summarized by using the NADB format but with Microsoft Access software. Table 1-3 summarizes operational performance data for these systems. Wetland systems receiving pulp and paper wastewaters achieved similar pollutant removal efficiencies as the predominantly municipal wastewater wetlands in the NADB. New information for a few additional pollutants of importance for the pulp and paper industry is included in the NCASI review. These parameters include COD, color, conductivity, and total dissolved solids (TDS). According to this database, treatment wetlands were not able to significantly reduce concentrations of color or TDS.

TABLE 1-3
Summary of Operational Performance Data for Treatment Wetlands Receiving Pulp and Paper Industry Effluents

	Average HLR	Average Concentration (mg/L)				Average Mass (kg/ha/d)			
Parameter	(cm/d)	In	Out	Eff (%)	Count (n)	Loading	Removal	Eff (%)	Count (n)
BOD_5	19.9	26.1	13.6	48	30	28.6	8.3	29	19
TSS	19.9	42.5	12.5	71	30	41.6	28.5	68	19
NH_4-N	20.6	4.7	3.0	36	22	3.6	0.5	14	11
NO_2+NO_3-N	5.2	1.4	0.14	90	6	0.49	0.42	86	6
TKN	5.2	7.8	3.5	55	6	3.6	1.1	31	6
TN	9.4	12.6	6.6	48	9	4.2	1.6	38	6
TP	21.1	2.3	1.7	26	20	1.0	0.3	30	9
Color	10.7	1617	1581	2	23	2541	-115	-4	17

cm/d centimeters per day
Source: CH2M HILL, 1994a.

Livestock Wastewater Treatment Wetland Database

In 1995, the GMP Nutrient Enrichment Committee funded a review of the use of wetlands for treatment of concentrated wastes from livestock feeding operations (CH2M HILL and Payne Engineering, 1997). A total of 69 pilot- and full-scale treatment wetlands receiving wastes from dairy, cattle feeding, swine, poultry, and aquaculture operations were located in the United States and Canada. Most of these systems are small (< 1 ha) and relatively new (constructed since 1991).

Table 1-4 summarizes operational performance data from these systems. Inflow pollutant concentrations and mass loadings to these systems are significantly higher than those for municipal and industrial treatment wetlands reviewed previously. Treatment efficiencies are somewhat lower at these very high loadings.

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TABLE 1-4
Average Treatment Wetland Performance for Removal of BOD_5, TSS, NH_4-N, and TN in the Livestock Wastewater Treatment Wetland Database

Parameter Wastewater Type	Count (n)	Average Inflow Concentration (mg/L)	Average Outflow Concentration (mg/L)	Average Concentration Reduction (%)
BOD_5				
Cattle feeding	14	137	24	83
Dairy	374	442	141	68
Poultry	80	153	115	25
Swine	183	104	44	58
TSS				
Cattle feeding	12	291	55	81
Dairy	361	1111	592	47
Swine	180	128	62	52
NH_4-N				
Cattle feeding	12	5.1	2.2	57
Dairy	351	105	42	60
Poultry	80	74	59	20
Swine	183	366	221	40
TN				
Dairy	32	103	51	51
Poultry	80	89	70	22
Swine	164	407	248	39

Source: CH2M HILL and Payne Engineering, 1997.

The database format used for the GMP constructed wetland project is patterned after that of the NADB, with slight modifications to reflect the applicability of the database to the agriculture industry. These data will be added to the NADB.v.2.0. Additional fields that were developed to input data include types of livestock; numbers of animals; agricultural category (dairy, cattle, swine, poultry, and aquaculture); and additional monitoring and mass balance parameters, including conductivity, TDS, volatile suspended solids, COD, temperature, and pH (see Section 4 for details).

Specific Needs of the Petroleum Industry

Differing wastewater sources generate different types and concentrations of pollutants. These diverse pollutants might result in varying needs for pretreatment and treatment wetland design. For example, municipal wastewaters typically contain elevated levels of particulate and dissolved degradable organic

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matter and nutrients. Stormwaters generally are characterized by high suspended solids (both mineral and organic), metals, and oil and grease. Pulp and paper mill wastewaters are dominated by pollutants characterized by COD, particulate materials (lignins), and salts resulting from pulping processes. Untreated petroleum industry wastewaters share many of these same pollutants and will also contain oil and grease, various hydrocarbons, and other associated compounds and metals.

Table 1-5 characterizes the major pollutants of importance for the petroleum industry. The relative dominance and concentration of these substances varies considerably among industrial sites. In all cases, some conventional treatment practices are in use before these wastewaters are delivered to a constructed wetland for further treatment or polishing. Specific pollutants that remain in pretreated petroleum industry wastewaters include COD, oil and grease, phenolics, trace metals, sulfides, and a range of organic compounds. Toxicity is also of concern to the petroleum industry. Thus, biological assays or toxicity tests are also used to quantify the overall acute or chronic toxic effect of these wastewaters.

This report focuses on the effectiveness of constructed treatment wetlands for reducing the pollutants of primary concern to the petroleum industry. Other potential pollutants, including the nutrients nitrogen and phosphorus, are only discussed briefly. Existing treatment wetland performance data are synthesized and discussed with respect to current knowledge and data gaps on the use of treatment wetlands specifically for the petroleum industry. This report also describes relevant constructed wetland design and operation issues of importance to the petroleum industry.

TABLE 1-5
Typical Pollutant Concentrations in Untreated Petroleum Refinery Wastewaters

Constituent	Units	Concentration
BOD_5	mg/L	10-800
COD	mg/L	50-600
TSS	mg/L	10-300
TDS	mg/L	1,500-3,000
NH_4-N	mg/L	0.05-300
TP	mg/L	1-10
PH	Standard Units	8.5-9.5
Sulfate/sulfide	mg/L	ND-400
Total Organic Carbon (TOC)	mg/L	10-500
Chromium	mg/L	ND-3
Oil and grease	mg/L	10-700
Phenols	mg/L	0.5-100

ND not detected

Sources: Adams *et al.*, 1981; ANL, 1990.

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SECTION 2

Water Quality Improvement Performance in Treatment Wetlands

The primary design goal of most treatment wetlands is the improvement of effluent quality. This improvement is generally measured as a reduction in mass and concentration of one or more pollutants.

Arguably, the most important step in wetland design is selecting the appropriate wetland area that will consistently achieve pollutant reduction goals. A wetland area that is too small for a specific pollutant will result in permit violations. A wetland that is larger than necessary to deal with the given design flow and mass loading variability results in unnecessary expenditure of resources. The art of this innovative design process is to be free from violations without being excessively conservative.

This section provides a review of state-of-the-art methods to summarize wetland treatment performance using simple first-order mass balance models, and reviews current knowledge about wetland performance for many of the pollutants of primary importance to the petroleum industry. These constituents of interest include BOD_5, COD, specific organic pollutants, metals, whole effluent toxicity, TSS, various forms of nitrogen, and TP. When available, the reader is provided general treatment wetland performance information for each pollutant and petroleum industry data.

Modeling Treatment Wetland Water Quality Changes

Like other water quality treatment processes, treatment wetlands perform within definable limits. These limits must be summarized so the designer can size a treatment wetland to consistently reduce pollutant concentrations from some inflow value to some desired outflow concentration. Regression equations and relatively simple first-order models are used most commonly to summarize wetland performance because data to support more complex deterministic models are insufficient. The designer has the ability to determine the actual treatment efficiency to some extent by using general knowledge of performance expectations for internal design features such as wetland area, water depth, cell configuration, and plant selection.

Because treatment wetlands are living, autotrophic ecosystems, the designer should also consider certain constraints associated with natural systems. The natural processes that occur in surface flow wetlands result in background concentrations of various chemicals that may, at higher concentrations, be the same constituents requiring treatment. Knowledge of these background concentrations is important to avoid overly optimistic expectations for treatment wetlands. Also, a certain amount of statistical variability is inherent in wetland outflow constituent concentrations, some of which is due to environmental factors (such

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as seasonal temperature changes) outside the control of the wetland designer and operator. The inevitability of this "chatter" should be factored into the design to avoid permit violations.

Wetland Performance Equations

A vast quantity of operational performance data have been gathered from treatment wetlands. These data were collected over wide ranges of inlet concentrations, mass loadings, flow and hydraulic loading rates, hydraulic residence times, water depths, vegetation types, and water temperatures. The advancement of treatment wetland technology and the ability of designers to harness wetland processes in predictable treatment systems hinges on the ability to summarize these diverse data sets into a small number of defining relationships. Types of descriptors that have been successfully applied to treatment wetland data include loading rates and removal efficiencies, regression equations, and first-order mass balance equations. Each of these methods of summarizing performance are briefly described below.

The fundamental descriptors of wetland performance are inlet (C_i) and outlet (C_o) concentrations, volumetric flow rate (Q), wetland area (A), and water depth (h). Wetland water volume is defined as wetland area times depth times porosity (M):

$$V = Ah\varepsilon \tag{2-1}$$

One measure of relative flow rate is the nominal wetland detention time, τ:

$$\tau = \frac{Ah\varepsilon}{Q} = \frac{h\varepsilon}{q} \tag{2-2}$$

where q = Q/A is the hydraulic loading rate.

Detention time is also equal to the free water depth, Mh, divided by the flow rate per unit surface area, q. Nominal detention to an interior point in the wetland is the overall travel time (τ) multiplied by the fractional distance through the wetland (y).

Loading Rates and Efficiencies

The pollutant loading rate (LR) at the wetland inlet is defined as:

$$LR_i = qC_i \tag{2-3}$$

The percent concentration reduction efficiency is:

$$EFF = 100\frac{C_i - C_o}{C_i} \tag{2-4}$$

The mass removal efficiency is:

$$RED = 100\frac{LR_i - LR_o}{LR_i} \tag{2-5}$$

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RED embodies the overall water mass balance and explains the fate of the mass of entering pollutant. When inlet concentrations and loadings are close to zero, both EFF and RED can be misleading and result in high positive (or negative) percentages. Both are sensitive to wetland background concentrations as well as the speed of reduction processes. These variables may be used in either regression equations or mass balance equations to describe a performance data set.

Regression Equations

Regression equations (linear or log-linear equations) are the most convenient choice to represent intersystem data sets. They must be accompanied by the ranges of the variables because regressions are unreliable outside the range of data that produced them. The correlation coefficient is another useful adjunct because it reveals the fraction of variability that is described by the regression equation. Regression equations do not directly account for factors in the water mass balance or the pollutant mass balance.

Mass Balance Equations for Plug Flow

Many pollutants decline exponentially to a background concentration (C*) on passage through a wetland. At the same time, some substances are returned to the wetland water column through the complex chemical processes occurring in wetland soils, decomposing litter, and living plants and wildlife. Most removal and return processes involve solid surfaces, such as roots, litter, and algal mats. The simplest removal equation that embodies a steep curved decline is first-order; the simplest return rate equation that embodies a nonzero background concentration is zero order.

For first-order pollutant uptake (J_U):

$$J_U = kC \tag{2-6}$$

For zero-order pollutant return (J_R) from the ecosystem to the water column:

$$J_R = \text{constant} = kC^* \tag{2-7}$$

The net pollutant reduction rate (J) is the difference:

$$J = k(C - C^*) \tag{2-8}$$

When $C = C^*$, no net removal of the pollutant occurs, although both destruction and production processes continue. The net pollutant reduction rate (J) is the mass removal per unit wetland surface area (grams per square meter per year [$g/m^2/yr$]). Therefore, the global rate constant (k) is proportional to the amount of active area (biofilms, plants, algae, etc.) per unit wetland area.

In many treatment wetland cases, infiltration is prevented and no significant atmospheric deposition or precipitation (P) occurs. Under this special set of conditions, Q = constant along the length of the wetland (y) and:

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$$-Q\frac{dC}{dy} = JA = kA(C - C^*) \tag{2-9}$$

For a specified inlet concentration (C_i), this integrates to:

$$\frac{(C_o - C^*)}{(C_i - C^*)} = \exp\left(-\frac{kA}{Q}\right) = \exp\left(-\frac{k}{q}\right) \tag{2-10}$$

Equation 2-10 is the historically well known first-order plug flow concentration profile for the case of a nonzero background concentration. It relates concentrations within the wetland, including C_o (the concentration at the outlet point), to loading rate (q).

For those pollutants that have C* values close to zero, namely nitrate and ammonia nitrogen, Equation 2-10 reduces to:

$$\frac{C_o}{C_i} = \exp\left(-\frac{kA}{Q}\right) = \exp\left(-\frac{k}{q}\right) \tag{2-11}$$

Equation 2-10 can be rearranged to provide an estimate of the wetland surface area necessary to reduce an inflow pollutant concentration C_i to a target outflow concentration C_o:

$$A = -\frac{Q}{k}\ln\left(\frac{C_o - C^*}{C_i - C^*}\right) \tag{2-12}$$

The two calibration parameters are k and C*; therefore, this description is termed the k-C* model. Figure 2-1 illustrates a typical fit to data. Some pollutants, notably nitrogen (see the *Nitrogen* discussion under *Nutrients*), are linked by a sequential reaction pathway. In that case, the k-C* concept is applied to each step, and production rates are included in the mass balances. For cases where seepage and atmospheric losses/gains are significant, a more complex equation is required.

The exponent in Equation 2-12 is often regrouped to define a volumetric rate constant:

$$k_V = \frac{k}{\varepsilon h} \tag{2-13}$$

For the volumetric case, Equation 2-10 can be modified as:

$$\frac{C_o - C^*}{C_i - C^*} = \exp(-k_v \tau) \tag{2-14}$$

For those substances where C* ≈ zero, Equation 2-14 reduces to:

$$\frac{C_o}{C_i} = \exp(-k_v \tau) \tag{2-15}$$

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Temperature effects on k or k_V can be summarized by use of the modified Arrehnius equation:

$$k_T = k_{20}\,\theta^{(T-20)} \qquad (2\text{-}16)$$

where k_T is the rate constant at temperature (T) = T °C and k_{20} is the rate constant at 20°C. Values of the temperature correction factor (θ) have been estimated for data sets with adequate operational temperature data (Kadlec and Knight, 1996).

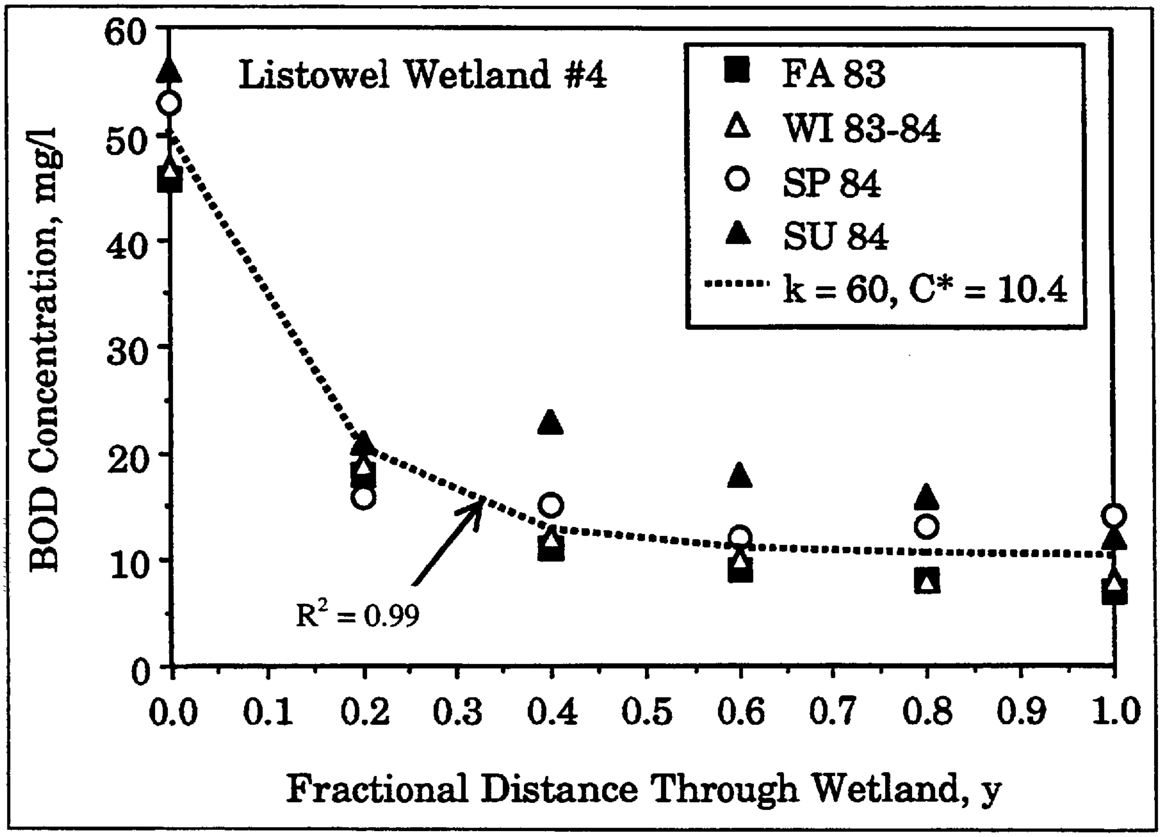

FIGURE 2-1
The k-C* Model Fit to BOD_5 Data from the Listowel Project
This site shows little seasonal effect, despite the fact that winter operation was under ice.
Source: Based on data from Herskowitz, 1986.

The dimensions of k_V are reciprocal time, typically d^{-1}, those of k are velocity in meters per day (m/d). Because of numerical magnitudes, the units of k are typically converted to meters per year (m/yr).

As described earlier, the data from many treatment wetlands indicate nonzero values of C* for some common pollutants (BOD_5, TSS, organic N, TN, and TP). However, most of the existing wetland literature makes the C* = 0 assumption and reports rate constants for the resulting one-parameter model (k_1 or k_{V1}). Rate constants determined under that assumption are always lower than the actual value by as much as a factor of 2 or 3 for light hydraulic loadings.

More importantly, if C* ≠ 0, then k_1 is not a constant and is a function of hydraulic loading rate. Theoretically, k_1 is proportional to q for low hydraulic loading rates. This relationship is also the observed

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trend of the data from a large number of free water surface wetlands. The values of k_{V1} are also nearly proportional to hydraulic loading, or inversely proportional to the detention time, for low hydraulic loadings. Because both k_1 and k_{V1} depend on hydraulic loading rate when $C^* \neq 0$, they should not be used in designing for certain pollutants.

Either k or k_V can be used to represent a data set or can be used in design. However, the use of k_V requires the accompanying information on water depth (h) because of the depth dependence indicated in Equation 2-13 (Figure 2-2). This depth dependence also means that more detention time created by deeper water is counteracted by a decrease in the volumetric rate constant. The hydraulic loading rate is not depth dependent, and data indicate that k is nearly independent of depth. Data analysis and design using volumetric coefficients require knowledge of the water depth. The use of areal coefficients does not require depth corrections. For many surface flow wetlands, especially large ones, depth is not known to a reasonable degree of accuracy. For these reasons, the parameters k, C*, and θ are used to summarize treatment wetland operational performance data for the remainder of this section.

In general, literature values of rate constants have not been corrected for water losses and gains. In some instances, water budget information was not collected; in other cases, atmospheric losses and gains were not significant. Therefore, water mass balance effects are the cause of some fraction of the variability in rate constant data.

In some instances, a supply of a limiting reactant is required; oxygen, carbon, and alkalinity are three of the most common in treatment wetlands. In this assessment, any limitations of these essential reactants are implicit in the variability of system performance.

Wetland Background Concentrations

Wetland ecosystems typically include diverse autotrophic (primary producers such as plants) and heterotrophic (consumers such as microbes and animals) components. Most wetlands are more autotrophic than heterotrophic, resulting in a net surplus of fixed carbonaceous material that is buried as peat or is exported downstream to the next system (Mitsch and Gosselink, 1993). This net production results in an internal release of particulate and dissolved biomass to the wetland water column, which is measured as BOD_5, TSS, TN, and TP. These wetland background concentrations are denoted by C*. Enriched wetland ecosystems are likely to produce higher background concentrations than pristine wetlands because of the larger biogeochemical cycles that result from the addition of nutrients and organic carbon. Surface water concentrations in closed wetland basins with inflows dominated by precipitation represent the lowest wetland effluent concentrations observed.

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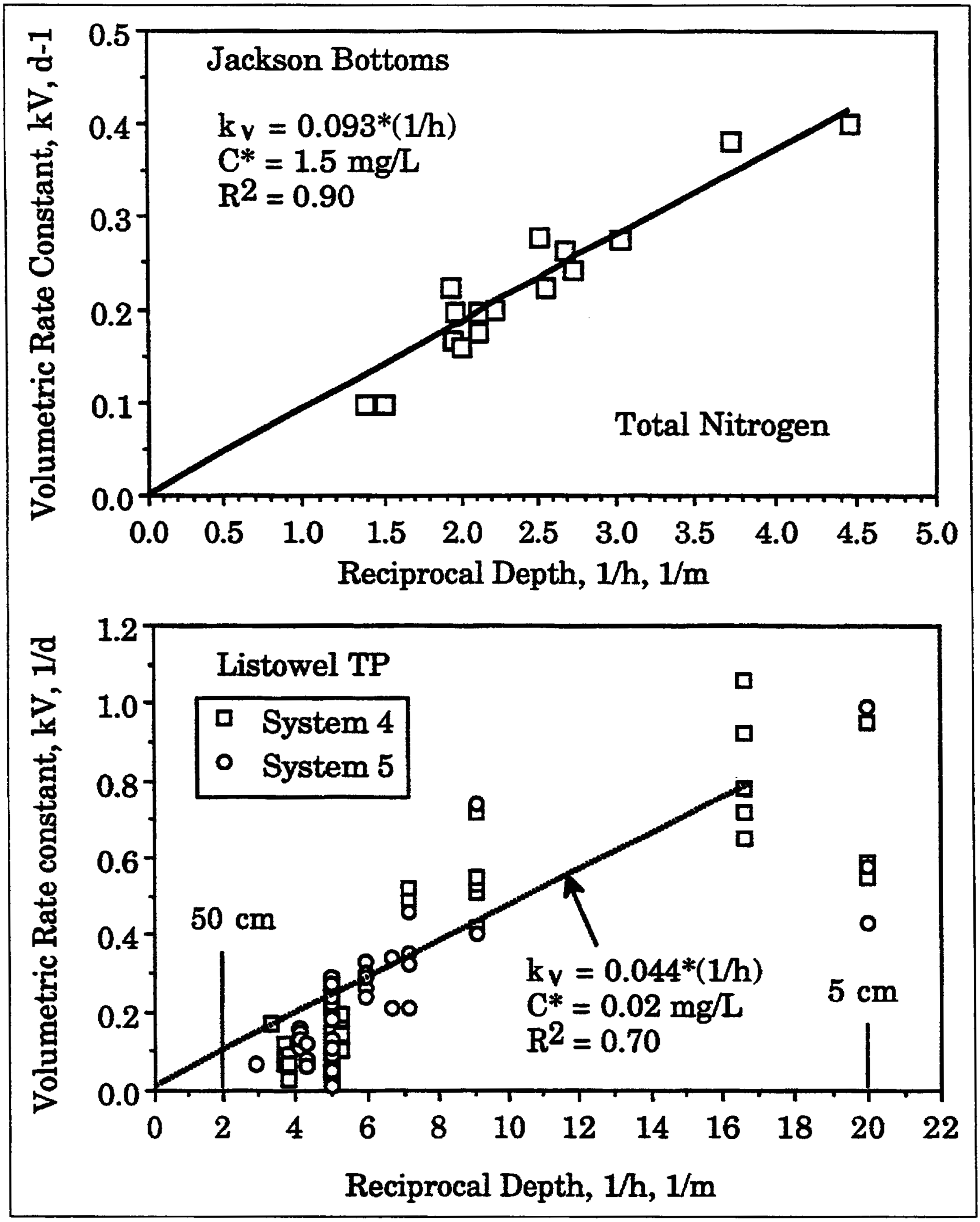

FIGURE 2-2

First-order Volumetric Rate Constants for TN and TP in Relation to Water Depth

The deeper the water, the smaller the rate constant. At very shallow depths, the rate constant again decreases as patches of the wetland are no longer immersed.

Source: Data for Jackson Bottoms from SRI, 1991; for Listowel from Herskowitz, 1986.

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Wetland systems typically have background concentrations within these ranges:

• BOD_5	1 - 10 mg/L
• TSS	1 - 6 mg/L
• Organic and total nitrogen	1 - 3 mg/L
• Fecal coliforms (FC)	50 - 500 FC/100 milliliters (mL)
• Ammonium N	< 0.1 mg/L
• Nitrate N	< 0.1 mg/L
• TP	< 0.1 mg/L

Wetland Stochastic Variability

Treatment wetlands demonstrate the same water quality variability typical of other complex biological treatment processes. While inlet concentration pulses are frequently dampened through the long hydraulic and solids residence times of the treatment wetland, there remains significant spatial and temporal variability in wetland surface water pollutant concentrations.

The stochastic character of rainfall and the periodicity and seasonal fluctuation in evapotranspiration (ET) are also responsible for a portion of the variability in effluent quality in wetlands. One index of this variability is the ratio between long-term average conditions and maximum conditions observed over shorter time intervals. Data for an analysis of average ratios between the maximum month and average annual concentrations for BOD_5, TSS, TN, and TP were available from 22 sites with a total of 53 different wetland cells in the NADB. Average ratios were 2.0 for BOD_5, 2.1 for TSS, 1.6 for TN, and 1.9 for TP. Similar ratios have not yet been summarized for discharges from wetlands treating petroleum industry wastewaters.

Carbon Processing

Biomass: Growth, Death, and Decomposition

A strong correlation exists between biomass and carbon cycling within a wetland. The proportion among the nutrient elements in the biomass is often represented as a molar proportion of C:N:P = 106:16:1, or 41:7:1 on a mass basis (the Redfield ratio). This proportion translates to a carbon content of roughly 15 percent dry weight (dw) in plant tissues.

The wetland cycle of growth, death, and partial decomposition uses atmospheric carbon, and produces gases, dissolved organics, and solids. Decomposition involves the sugars, starches, and low molecular weight celluloses in the dead plant material. Gaseous products include methane and regenerated carbon dioxide. A spectrum of soluble large organic molecules, collectively termed humic substances, are released into the water. The solid residual of plant decomposition is peat or organic sediment, which originated as celluloses and lignins in the plants. These wetland soil organics are broadly classified as fulvic material,

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humic material, or humin on the basis of their acid soluble, base soluble, or insoluble properties (Peat Testing Manual, 1979).

The internal wetland carbon cycle is large. Consideration of annual growth and decomposition patterns can provide a general idea of the magnitudes of the various carbon transfers in a northern treatment marsh. A eutrophic treatment marsh grows about 5,000 g/m^2 of above- and below-ground biomass each year, with a carbon content of about 15 percent. This translates to a requirement of 750 g/m^2/yr of carbon. Decomposition of the resultant litter returns a significant portion of that carbon to the wetland ecosystem, but residuals may accrete at rates up to 150 g/m^2/yr.

Carbon Processing in Wetland Soils

Decomposition "reactions," which can be generally described according to the following equations (Mitsch and Gosselink, 1993; Burgoon, 1993), occur in different horizons in the wetland, as shown in Figure 2-3.

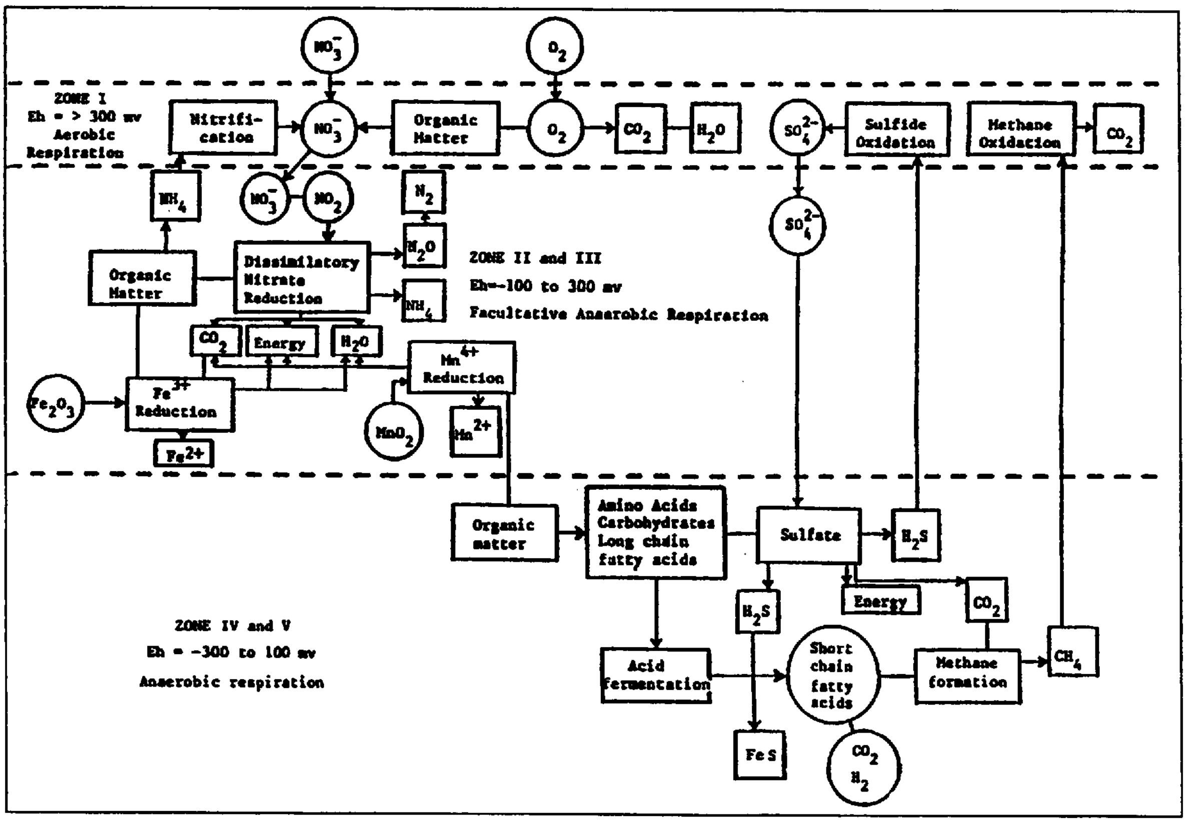

FIGURE 2-3
Pathways of Organic Carbon Decomposition in Wetland Soils
Aerobic, facultative anaerobic, and obligate anaerobic processes are typically all present at different depths in the soil.
Source: Reprinted with permission from Reddy and Graetz, 1988.

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- **Respiration** occurs in aerobic zones:

$$\underset{\text{(carbohydrates)}}{C_6H_{12}O_6} + 6\ O_2 = 6\ CO_2 + 6\ H_2O \tag{2-17}$$

- **Fermentation** occurs in anaerobic zones:

$$\underset{\text{(carbohydrates)}}{C_6H_{12}O_6} = \underset{\text{(lactic acid)}}{2\ CH_3CHOHCOOH} \tag{2-18}$$

$$\underset{\text{(carbohydrates)}}{C_6H_{12}O_6} = \underset{\text{(ethanol)}}{2\ CH_3CH_2OH} + 2\ CO_2 \tag{2-19}$$

- **Methanogenesis** occurs in anaerobic zones:

$$4H_2 + CO_2 = CH_4 + 2\ H_2O \tag{2-20}$$

$$\underset{\text{(acetate)}}{CH_3COO^-} + 4\ H_2 = 2\ CH_4 + H_2O + OH^- \tag{2-21}$$

- **Sulfate reduction** occurs in anaerobic zones:

$$\underset{\text{(lactate)}}{2\ CH_3CHOHCOO^-} + SO_4^{-} + H^+ = \underset{\text{(acetate)}}{2\ CH_3COO^-} + 2\ CO_2 + 2\ H_2O + HS^- \tag{2-22}$$

$$\underset{\text{(acetate)}}{CH_3COO^-} + SO_4^{-} + 2\ H^+ = 2\ CO_2 + 2\ H_2O + HS^- \tag{2-23}$$

- **Nitrate reduction** (denitrification) occurs in anaerobic zones:

$$\underset{\text{(carbohydrate)}}{C_6H_{12}O_6} + 4\ NO_3^- = 6\ CO_2 + 6\ H_2O + 2\ N_2 + 4\ e^- \tag{2-24}$$

- **Iron reduction** occurs in anaerobic zones:

$$\underset{\text{(acetate)}}{CH_3COO^-} + 8\ Fe^{+++} + 3\ H_2O = 8\ Fe^{++} + CO_2 + HCO_3^- + 2\ H_2O + 8\ H^+ \tag{2-25}$$

Burgoon (1993) investigated the relative percentages of these reactions in controlled subsurface flow wetland microcosms by using acetate as the carbon source. His results demonstrate that all routes can be important, depending on physical and chemical conditions (Table 2-1).

Clearly, the wetland provides a spectrum of potential pathways for the use of organic carbon compounds. Information is insufficient to quantify both the complex chemistry and the spatial distribution of chemical compounds. Therefore, the interactions must be described by correlations and rate equations that are supportable by wetland performance data.

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TABLE 2-1
Percent Acetate Oxidized via Various Pathways by *Scirpus validus* Planted in Plastic Media

Reaction	High Carbon Loading		Low Carbon Loading	
	Plants	No Plants	Plants	No Plants
Nitrate-rich environment:				
Oxidation	23.2	25.6	36.1	32.8
Nitrate reduction	70.6	69.3	51.7	56
Sulfate reduction	3.0	3.1	2.3	2.3
Ferric iron reduction	0.1	0.0	0.1	0.1
Methane formation	0.0	0.0	0	0
Bacterial biomass formation	3.1	2.0	9.8	8.8
Total	**100.0**	**100.0**	**100.0**	**100.0**
Sulfate-rich environment:				
Oxidation	40.7	31.7	44.5	13.5
Nitrate reduction	0	0	0	0
Sulfate reduction	37.8	34.1	50.6	82.7
Ferric iron reduction	0.1	0.1	0.2	0.2
Methane formation	19.6	32.1	0	0
Bacterial biomass formation	1.8	2	4.7	3.6
Total	**100.0**	**100.0**	**100.0**	**100.0**

Source: Burgoon, 1993.

Biochemical Oxygen Demand Removal Performance

The wetland carbon cycle is rapid and large. Atmospheric and dissolved carbon are fixed into new biomass during photosynthesis; leaching and decomposition return a major fraction back to the water. Therefore, natural wetland waters are rich in humic substances and other forms of carbon, which add color to the water. Some of these naturally occurring compounds are detected by the widely accepted, but imperfect, BOD_5 test.

Treatment wetlands often receive loads of BOD_5 from industrial wastewater sources. Some of these carbon compounds are dissolved; others are associated with incoming particulates. Particulate settling is one removal mechanism that would typically occur in the inlet region of the wetland (Figure 2-4). Particulate removal processes in wetlands are discussed later under *Total Suspended Solids*. Soluble, biodegradable carbon compounds are processed by microbial communities associated with solid surfaces such as floating mats, litter, and plant stems. The decomposition of litter and sediments produces a return flux of BOD_5 to the water column. The balance between removal and return processes creates the wetland background concentration.

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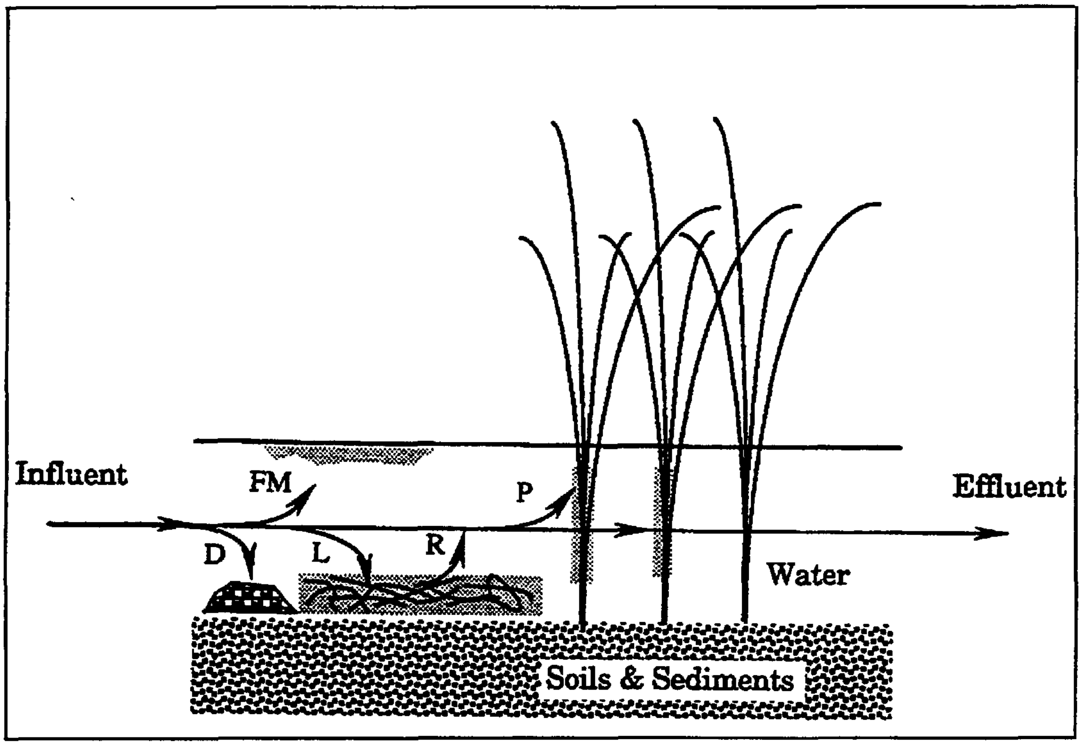

FIGURE 2-4
Simplified Portrayal of Wetland Carbon Processing
Incoming BOD_5 is reduced by deposition of particulate forms (D) and by microbial processing in floating (FM), epiphytic (P), and benthal litter (L) layers. Decomposition processes create a return flux R.

Microbial removal processes include oxidation in the aerobic regions of the wetland and methanogenesis in the anaerobic regions. The active microorganisms are almost exclusively associated with solid surfaces such as litter, sediments, and submerged plant parts. Likewise, the generation and return of BOD_5 is also associated with the microorganisms attached to the submerged solids.

As a result of these combined processes, BOD_5 declines along the flow path from inlet to outlet, down to the background level (Figure 2-5). The k-C* model provides a highly simplified description of the complex wetland carbon interactions and typically represents this progression quite well, accounting for about 90 percent of the intrasystem variability ($R^2 \approx 0.9$). The central tendency of rate constants from a variety of municipal wastewater treatment wetlands is k = 34 m/yr (Table 2-2). Seventy-three Danish soil-based wetlands receiving domestic wastewaters had values of k = 47.5 m/yr and C* = 3.0 mg/L (Brix, 1994). A review of performance data from subsurface flow treatment wetlands yielded average values of k = 180 m/yr and C* = 3.5 + 0.053 C_i mg/L (Kadlec and Knight, 1996).

No published petroleum wastewater datasets are currently available to fully calibrate the k-C* model for BOD_5 reduction. However, petroleum industry operating data collected for this report indicate that k_1 is typically between 11 and 75 m/yr (Table 2-3). Reductions in BOD_5 are significant for high incoming

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concentrations, but less when the inlet concentration is near background. The k_1 rate constant does not reflect the wetland background value C* and, therefore, is lower than the value for k.

BOD_5 rate constants can also be expressed with units d^{-1}; however, wetland volumetric rate constants (k_{v1}) are known to vary directly with mass loading (Reed *et al.*, 1995) and inversely with depth (see table 2-4 and Kadlec and Knight, 1996).

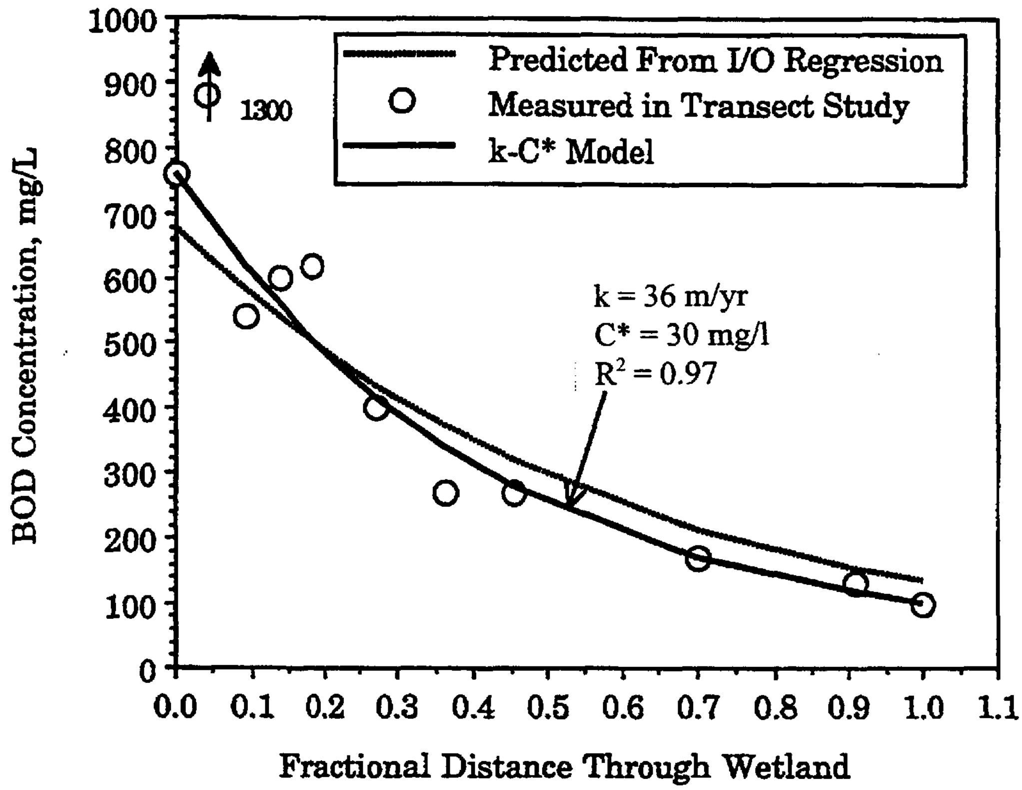

FIGURE 2-5

Transect Data for Gustine Wetland Treatment System 1D

The k-C model (solid line) explains the decline in BOD_5. The outlier at 1,300 mg/L was excluded from regression. Input-output data for seven test wetlands at the site, including 1D, were also regressed to the k-C* model (dashed line). The input/output data were fit with k = 27 m/yr and C* = 30 mg/L and provide a reasonable description of the 1D transect data.*

The decrease in BOD_5 is slower than the decline in TSS along transects or in batch mesocosm tests. Soluble BOD_5 decreases at the same value of the rate constant, as evidenced by the fit (Kadlec and Knight, 1996) of data from a sugar refinery (Gambrell *et al.*, 1987). Other individual hydrocarbons follow a similar pattern (Kadlec and Knight, 1996). No evidence exists of the instantaneous drop in BOD_5 at the wetland inlet described by some literature models (Reed *et al.*, 1995).

The wetland background concentration for BOD_5 typically ranges from 3 to 15 mg/L but depends on the strength of the wetland carbon cycle. High nutrient levels stimulate growth and, hence, accentuate the

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return flux and increase the resultant background concentration. Therefore, C* is elevated for strong influents. The possibility of irreducible components in the incoming BOD_5 also exists. The incoming BOD_5 concentration can be used as a surrogate for incoming nutrient load in many cases and is also reflective of possible residuals. Recognizing this strength dependence, the background concentration can be approximated as a function of inlet BOD_5 (Kadlec and Knight, 1996):

$$C^* = 3.5 + 0.053C_i \qquad (2\text{-}26)$$

$$R^2 = 0.67$$

$$0 < C_i < 200 \text{ mg/L}$$

TABLE 2-2
Rate Constants for BOD_5 Reduction for Some Surface Flow Wetland Systems

Site	System	k Value (m/yr)	Background C* (mg/L)
Listowel, Ontario	System 1	14	4.3
	System 2	7	3.3
	System 3	12	4.6
	System 4	37	10.4
	System 5	43	13.9
Gustine, California	Marsh 1A	18	11.6
	Marsh 1B	14	6.4
	Marsh 1C	9	13.0
	Marsh 1D	29	5.9
	Marsh 2A	22	7.8
	Marsh 2B	42	5.5
	Marsh 6A	33	3.5
	Pilot Marsh	22	4.7
Cobalt, Ontario	Marsh	54	4.7
Iron Bridge, Florida	Marsh	23	2.1
Benton, Kentucky	Marsh 1	94	5.4
	Marsh 2	60	7.9
Pembroke, Kentucky	Marsh	51	3.3
West Jackson County, Mississippi	Marsh	54	4.7
Lakeland, Florida	Marsh 1	48	1.1
Wetwang, United Kingdom	Marsh 2	52	3.9
	Marsh 3	51	5.2
Cannon Beach, Oregon	Forested	18	3.8
Bear Bay, South Carolina	Forested	7	1.9
Reedy Creek, Florida	Forested	34	1.7
Average		**34**	**5.6**
Standard Deviation		**21**	**3.4**

Source: NADB, 1993.

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TABLE 2-3
Petroleum Industry Treatment Wetland Operating Data for BOD_5

Site	Size	Type	Inlet BOD_5 (mg/L)	Outlet BOD_5 (mg/L)	Reduction (%)	k_1 (m/yr)	Reference
Amoco, Mandan, North Dakota	16.6 ha	FWS	79.4	12.4	84	11	Litchfield and Schatz, 1989
Texaco A	400 m^2	FWS	103.7	2.1	98	71	Hall, 1996
Texaco B	400 m^2	FWS	1.9	1.8	5	1	Hall, 1996
Chevron, Richmond 1989-91	36 ha	FWS	12.5	7.6	39	5	Duda, 1992
1992-95	36 ha	FWS	11.3	5.1	55		Chevron, 1996
Non-USA Oil Terminal	600 m^2	SSF	75	15	80		Farmer, 1996
Mobil/DGMK Germany		SSF	700	20	97	71	Altmann *et al.*, 1989
Tisza Petrochemical, Hungary		FWS			30		Kiss and Lakatos, 1996
Nyirbogdany Petrochemical, Hungary		FWS			25		Kiss and Lakatos, 1996
Yanshan Pond/Wetland, P.R. China	25 ha	FWS	38	15.3	60	75	Dong and Lin, 1994

FWS free water surface (surface flow)
SSF subsurface free flow system

TABLE 2-4
BOD_5 Rate "Constants" vs. Depth and Loading at the Arcata, California, Treatment Wetlands

Flow (m^3/d)	Depth (m)	Increase in HRT (%)	BOD_5 Rate Constant (1/d)	Decrease in kv (%)
93	0.40		0.29	
94	0.55	37	0.17	42
86	0.36		0.25	
83	0.61	76	0.13	49
45	0.30		0.28	
49	0.49	49	0.14	48
29	0.33		0.14	
29	0.53	78	0.08	40
23	0.35		0.14	
24	0.50	39	0.09	36

Source: Gearheart and Higley, 1993

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Intersystem performance follows the expected pattern of better performance at lower loading rates, within the constraints of the wetland carbon cycle. Data from several sites show a trend of increasing outlet concentration with increasing inlet loading rate (Figure 2-6). The format used in Figure 2-6 and other figures in this report illustrates the relationship between mass loading (the product of inlet concentration and hydraulic loading) and outlet concentration. Use of Figure 2-6 allows estimation of wetland outflow BOD_5 concentration based on any design loading rate. Input-output behavior is strongly influenced by background and inlet concentrations, which are masked in simple graphical representations. However, the k-C* model spans the intersystem scatter in input/output data.

Temperature apparently plays a minor role in the net removal of BOD_5 in treatment wetlands. Temperature coefficients are close to, but slightly less than, unity. For 10 wetlands analyzed by Kadlec (1996 [unpublished data]), $\theta = 0.974 \pm 0.029$. However, the use of a temperature correction for the rate constant is not warranted, since only about 6 percent of the variability is explained by temperature ($R^2 \approx 0.066$ for 9 of the 10 systems).

If the BOD_5 in the incoming water is above wetland background, reduction occurs, and the wetland effluent is at a lower concentration. Stochastic processes cause periods of better and poorer performance than the long-term average. Temporary spikes and valleys are the result of many factors; some are related to inflow concentration and flow rate, whereas others are related to wetland events such as animal activity. The maximum monthly outlet BOD_5 concentration is typically 2.0 times higher than the long-term mean (Kadlec and Knight, 1996).

The regression of input and output data provides a simple performance description, but at the price of a relatively low correlation coefficient (Kadlec and Knight, 1996):

$$C_o = 0.173C_i + 4.70 \qquad (2\text{-}27)$$

$$R^2 = 0.62, N = 440$$

$$\text{Standard Error in } C_o = 13.6$$

$$0.27 < HLR < 25.4 \text{ cm/d}$$

$$10 < C_i < 680 \text{ mg/L}$$

$$0.5 < C_o < 227 \text{ mg/L}$$

A similar relationship was found for seventy-three Danish wetlands (Brix, 1994). This regression equation does not contain the hydraulic loading rate, and the R^2 is not improved if it is added. The cause is related to the fact that many wetlands achieve near-background BOD_5. Consequently, Equation 2-27 cannot be used to size treatment wetlands.

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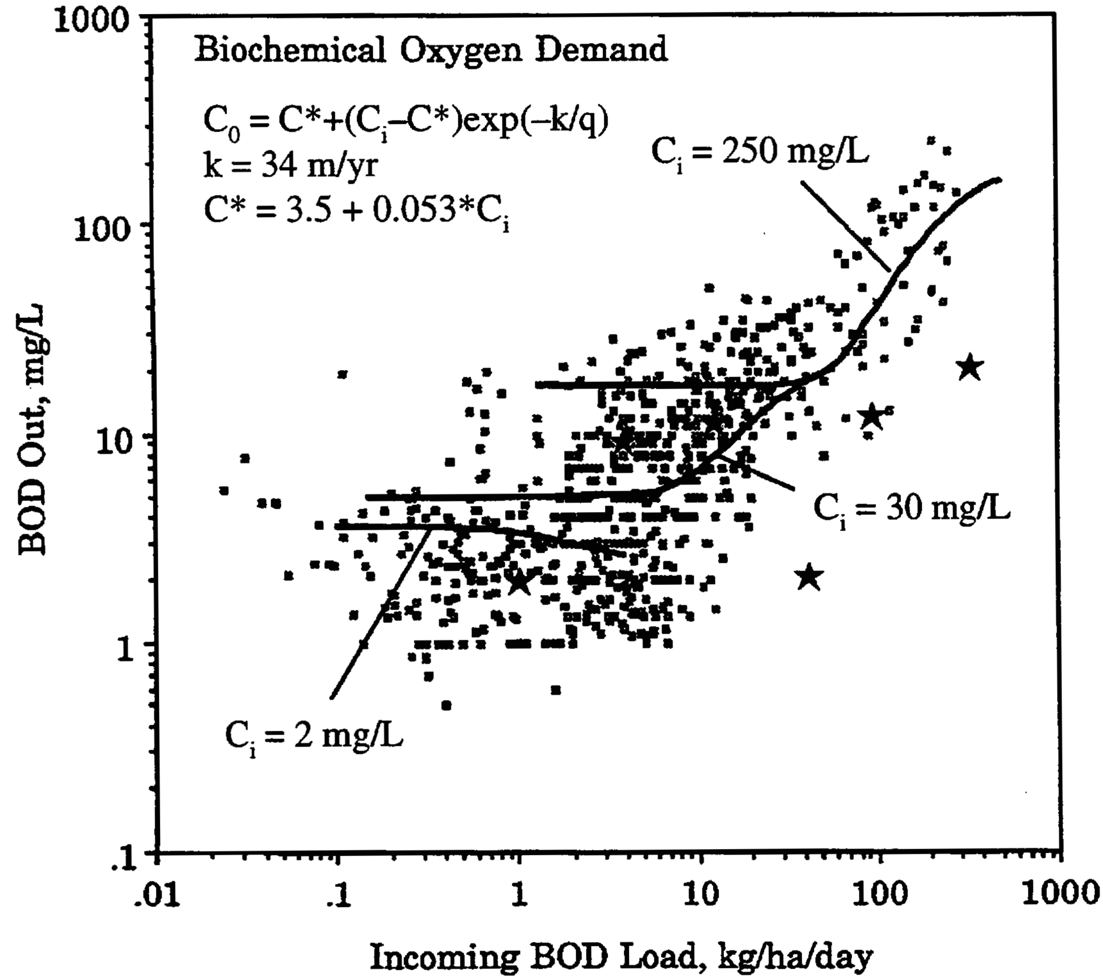

FIGURE 2-6
Intersystem Performance for BOD_5 Reduction
Data points are from 48 wetland cells at 22 sites. Petroleum industry data are highlighted (★). The k-C model is shown for different inlet concentrations. It spans the data set and accounts for increasing BOD_5 in lightly loaded wetlands with very low inlet concentrations, as depicted by the C_i = 2 mg/L curve.*

COD Reduction in Treatment Wetlands

BOD_5 represents the class of organic compounds that are susceptible to biological oxidation; COD represents the class of organic compounds that are susceptible to oxidation by a strong chemical oxidant (potassium dichromate) under acidic conditions. COD is numerically higher than BOD_5 because more organic compounds can be chemically oxidized than are degraded biologically. Often BOD_5 and COD are highly correlated for a specific wastewater.

In the wetland environment, the presence of humic materials leads to COD values that are much higher than BOD_5 values. In Northern peatlands, the BOD_5 : COD (mg/L) ratio is approximately 5 : 100 (Kadlec, unpublished data). In untreated municipal wastewaters, the ratio is 0.4 : 0.8 (Metcalf and Eddy, 1991).

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Natural wetland waters contain significant COD, often in the range of 30 to 100 mg/L. When wastewater with lower than background COD is added to a natural wetland, the COD concentration increases to the background COD value as the wastewater passes through the wetland. For example, lagoon water of 30 mg/L COD was added to the Houghton Lake peatland and left the treatment area with 100 mg/L COD (Kadlec and Tilton, 1979). Similarly, when low-COD wastewater is added to a constructed wetland, the COD concentration will increase as the wastewater passes through the system. For example, in 1990, the water entering the Jackson Bottoms wetlands was at 40 mg/L COD; the water leaving the 17 parallel cells averaged 51 ± 7 mg/L COD (SRI, 1990).

No treatment wetland project has yielded COD data that can be used to calibrate the k-C* model. Either transect data or data over variable loading rates are required to determine the value of k and C*, and such data are lacking. Accordingly, only a one-parameter model can be fit to data (C* = 0), with the knowledge that this model produces loading-variable k values (see Section 2). Equation 2-11 has been used to generate the k_1 values in Table 2-5, where the subscript "1" denotes the fact that the value of C* has unavoidably been set to zero. This initial value leads to lower k values than those for the k-C* model with nonzero C*.

The sparse information on petroleum wastewater systems indicates that COD is reduced at rates comparable to those found for other types of wastewater (Table 2-5). The mean COD k_1 rate constant for all systems is 36 m/yr; that for BOD_5 from the NADB marsh systems is 13 m/yr. However, for paired data (COD and BOD_5 for the same wetlands), the $k_1COD:k_1BOD_5$ ratio is 0.81 ± 0.33; the ratio was 0.65 for the Amoco Mandan data in 1987 (Litchfield and Schatz, 1989). This information indicates that on average, COD is reduced less effectively than BOD_5 in treatment wetlands.

Temperature effects on BOD_5 reduction are typically minimal (see the previous subsection, *Biochemical Oxygen Demand Removal Performance*), and the same is true for COD rate constants, although data are sparse. Kadlec and Tilton (1979) report $\theta = 1.023$ for COD reduction in potato processing waters; data from Saurer (1994) for the Mühlen, Austria, domestic wastewater treatment wetland indicate $\theta = 1.030$ for COD. BOD_5 reduction for the Mühlen study was $\theta = 1.009$.

Clearly, more COD data are needed, especially for petrochemical wastewater treatment in wetlands. Internal transect data and data for varying loading rates and depths are required to quantify even the simplistic k-C* model.

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TABLE 2-5
Reduction of COD for Various Wastewaters in a Variety of Wetland Types

Project Site	Wetland Area		Inlet COD (mg/L)	Outlet COD (mg/L)	Reduction (%)	k_1 (m/yr)	Reference
Petroleum Industry							
Amoco, Mandan, North Dakota	16.6 ha	FWS	131	40	69	7	Litchfield and Schatz, 1989
Yanshan Pilot, P.R. China	Spring	FWS			38.9		Dong and Lin, 1994a
	Summer	FWS			47.7		
	Fall	FWS			30.9		
	Winter	FWS			32.5		
Yanshan Pond/Wetland, P.R. China	Full Scale	FWS	170	47.5	72	104	Dong and Lin, 1994b
Non-USA Oil Terminal	600 m^2	SSF	101	47	53		Farmer, 1996
Mobil/DGMK Germany		SSF	1,800	250	86	40	Altmann *et al.*, 1989
Tisza Petrochemical, Hungary		FWS			30		Kiss and Lakatos, 1996
Nyírbogdány Petrochemical, Hungary		FWS			25		Kiss and Lakatos, 1996
General Industrial							
Mixed, Stavropol, Russia Federation	3,980 m^2	SSF			65 - 85		Magmedov, 1996
Mixed, Tenth Ramadan City, Egypt	200 m^2	SSF			0 - 86		Addleton *et al.*, 1996
Leachate, Slovenia	450 m^2	SSF	1,264	404	51 - 94	6	Bulc *et al.*, 1996
Lower Saxony, Germany	69 m^2	VF	467	37	92	62	von Felde and Kunst, 1996
Lower Saxony, Germany	40 m^2	VF	275	15	95	51	Bahlo and Wach, 1990
Oaklands Park, United Kingdom	20 m^2	VF	266	142	47	149	Burka and Lawrence, 1990
New Zealand (Meat)	250 m^2	FWS	1,531	330	78	25.8	Van Oostrom and Cooper, 1990
			247	124	50	14.6	
			161	112	30	7.7	
Belgium (Sewage)	19 m^2	FWS	240			23.8	Radoux and Kemp, 1990
Hermiston (Potato)	40 m^2	FWS	2,100	714	66	37	Kadlec *et al.*, 1996
Connell (Potato)	2,685 m^2	FWS/SSF	3,150	224	93	55	Kadlec *et al.*, 1996
American Crystal Sugar, North Dakota	64.8 ha	FWS	103	4	96	6	Anderson, 1996
Australia (Piggery)	36 m^2	SSF	630	246	61	13.7	Finlayson *et al.*, 1990
	36 m^2	SSF	630	347	45	8.7	
Czech Republic (Sewage)	1.1 m^2	SSF	380	64	83	37.1	Vymazal, 1990
	1,248 m^2	SSF	550	100	82	38.3	
Czech Republic (Chicken Waste)	1.1 m^2	SSF	2,420	395	84	16.8	Vymazal, 1990
Netherlands (Potato)	230 m^2	SSF	1,200	96	92	9.2	de Zeeuw *et al.*, 1990
					Mean	36	
					Maximum	149	
					Minimum	6	

m^2 square meter
FWS free water surface (surface flow)
SSF subsurface flow
VF vertical flow

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Organics Removal from Petroleum Wastewaters

General Results

Information on the effectiveness of constructed wetlands to remove organic compounds from wetland waters is derived from general reports on wetland processes and from preliminary reports from pilot- or full-scale wetlands associated with petroleum industry waste streams. Organic chemicals from waste streams that include petroleum products are potentially problematic for treatment wetlands for two reasons. First, if organic compounds are present at high concentrations, they may be potentially toxic to plants and microorganisms. Second, the various organic compounds found in the waste streams have differing susceptibilities to aerobic and anaerobic degradation processes (Kadlec and Knight, 1996). However, most hydrocarbons are natural products and are biodegradable. Many hydrocarbons are not toxic to organisms except at high doses, and some are used as growth enhancers at low concentrations.

Through natural processes, wetlands produce a wide range of organic compounds. Organic compounds may form complex molecules with metals (such as iron) and serve as an important mechanism to buffer redox reactions in wetlands (Wang and Peverly, 1996). The roots of wetland plants contribute to the aeration of sediments, degradation of organic compounds, and the diversity of microorganisms in the root zone (rhizosphere) (Wolverton, 1987; Wang and Peverly, 1996; Anderson and Walton, 1995). Free-floating plants, such as water hyacinth, have also been shown to reduce trace levels of organic compounds in aquatic treatment system wastewaters (Wolverton and McKnown, 1976; Wolverton and McDonald, 1981; Conn and Langworthy, 1984).

Many wetland soils have a high proportion of organic matter. The organic soil component has the ability to remove organics through adsorption and other binding mechanisms. Surfactant-modified smectitic clays (e.g., hectorite and montmorillonite) may also represent an inexpensive additive that could enhance the organic sorption potential of treatment wetlands (Srinivasan and Kadlec, 1995).

In general, the time required to break down organic compounds is linked to the relative complexity of the molecules. The breakdown time for aliphatic hydrocarbons is longer for compounds of higher molecular weight. The breakdown time for aromatic hydrocarbons (i.e., compounds with a benzene ring) is longer when more than one benzene ring is present (referred to as polycyclic aromatic hydrocarbons or PAHs). Compounds with more than three benzene rings are not capable of supporting microbial growth and are, therefore, much more difficult to degrade (Kadlec and Knight, 1996). Organic compounds with hydroxyl (OH) groups attached to a benzene ring are collectively referred to as phenols. The primary mechanism for phenol removal in wetlands occurs through sorption to various wetland components and subsequent degradation by microbial organisms (Zander, 1980).

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In wetlands, the major hydrocarbon removal pathways are (1) volatilization, (2) photochemical oxidation, (3) sedimentation, (4) sorption, and (5) biological (microbial) degradation. Relative importance of these pathways varies depending on the individual group of hydrocarbons. Microbial degradation includes fermentation and aerobic and anaerobic respiration. Treatment wetlands can be most effective if the components of the waste stream are well characterized and the conditions favorable to breakdown of those specific components (e.g., subsurface flow, free water, or open water treatment cells) are present.

Treatment wetlands have the advantage of providing treatment for a wide range of waste stream components. In addition, they provide flexibility in waste stream management by allowing additional wastewater storage capacity during high rainfall or snowmelt periods. Treatment wetlands also permit temporary diversions through different treatment cells if problems arise with wastewater quality (Litchfield and Schatz, 1990). Monitoring contaminant loading rates is critical to optimize the removal efficiency of treatment wetlands (Dong and Lin, 1994). If contaminant loadings are not carefully monitored, contaminated water, sediments, and biota may provide an exposure pathway for wildlife populations that use the treatment wetlands as habitat or food source (Rainwater *et al.*, 1995). Subsurface flow treatment wetlands provide one method to reduce direct wildlife contact with highly contaminated wastewaters.

Refinery Effluents

Many industrial facilities in the United States have either pilot- or full-scale treatment wetland projects following traditional wastewater treatment systems (such as API oil/water separators and aerated biooxidation lagoons). Constructed wetlands can be used to polish secondarily treated refinery wastewaters in order to attain more stringent water quality objectives and reduce or prevent potential National Pollutant Discharge Elimination System (NPDES) exceedances at the site discharge location (Litchfield and Schatz, 1990; Litchfield, 1993). Table 2-6 summarizes data for organic compounds removal in treatment wetlands.

A full-scale constructed wetland has been used at Amoco's Mandan, North Dakota, refinery for more than 20 years. The treatment wetland consists of an earthen canal that distributes water from the secondary treatment biooxidation lagoon into a series of cascading ponds and ditches before discharging to the Missouri River (Litchfield and Schatz, 1990). The NPDES permit for the Mandan facility requires regular monitoring of the following parameters: BOD_5, COD, NH_3-N, sulfides, phenols, oil and grease, hexavalent and total chromium, and TSS. During 1990, BOD_5 (an indicator of overall organic loading) in the secondarily treated effluent, was reduced by more than 88 percent within the treatment wetlands. Similarly, phenols and oil and grease were both reduced by 94 percent within the treatment wetlands (Litchfield, 1993). The Mandan constructed wetlands have demonstrated the ability to effect significant reductions in all of the NPDES permit parameters on a sustainable basis. In addition, the constructed wetlands constitute a valuable wildlife habitat resource for the refinery.

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TABLE 2-6
Summary of Treatment Wetland Performance for Organics Removal

Description	Concentration In	Concentration Out	Removal (%)	Reference
BOD5 (mg/L)				
SF constructed wetlands to treat refinery wastewaters, Richmond, California (1989-1995)	12.2	7.1	42	Chevron, 1996
FWS constructed wetlands to treat refinery wastewaters (1990), Mandan, North Dakota	25	3	88	Litchfield, 1993
Yanshan wetlands to treat refinery wastewaters (1992-93), Beijing, P.R. China	38	15.3	60	Dong and Lin, 1994
Primarily SSF constructed wetlands to treat wastewater from an oil terminal	75	15	80	Farmer, 1996 (personal communication)
Oil and Grease (mg/L)				
SF constructed wetlands to treat refinery wastewaters, Richmond, California (1993-1995)	2.5	1.0	60	Chevron, 1996
FWS constructed wetlands to treat refinery wastewaters (1990), Mandan, North Dakota	2.1	0.13	94	Litchfield, 1993
Yanshan wetlands to treat refinery wastewaters (1992-93), Beijing, P.R. China	0.84	0.29	65	Dong and Lin, 1994
Primarily SSF constructed wetlands to treat wastewaters from an oil terminal	24	11	54	Farmer, 1996 (personal communication)
Rock-reed wetland to treat wastewaters from a natural gas pipeline compressor station	–	–	90	Honig, 1988
SSF constructed wetland to treat runoff from a vehicle yard	–	–	54 to 92	Wass and Fox, 1993
Phenols (µg/L)				
SF constructed wetlands to treat refinery wastewaters, Richmond, California (1994-1995)	20	18	10	Chevron, 1996

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TABLE 2-6 (CONTINUED)
Summary of Treatment Wetland Performance for Removal of Organics

Description	Concentration In	Concentration Out	Removal (%)	Reference
FWS constructed wetlands to treat refinery wastewaters (1990), Mandan, North Dakota	80	5	94	Litchfield, 1993
Yanshan wetlands to treat refinery wastewaters (1992-93), Beijing, P.R. China	27	10	63	Dong and Lin, 1994
Fangshan research wetlands to treat refinery wastewaters (1991-93), Beijing, P.R. China	--	--	27.8 winter to 36.7 summer	Dong and Lin, 1994
Pilot-scale water hyacinth wetland to treat municipal wastewater, San Diego, California	6.2	1.2	81	Conn and Langworthy, 1984
Other Organics (μg/L)				
SF constructed wetlands to polish effluent from an air stripper groundwater remediation system (total VOCs - median of 5 monthly samples), Port Everglades, Florida	10 (range 5 to 20)	BDL (range BDL to 31)	--	Rogozinski *et al.*, 1992
SF constructed wetlands to polish effluent from an air stripper groundwater remediation system (total PAHs - median of 5 monthly samples), Port Everglades, Florida	BDL (range BDL to 62)	BDL (all BDL)	--	Rogozinski *et al.*, 1992
Pilot-scale water hyacinth wetland to treat municipal wastewater (total VOCs), San Diego, California	32.2	0.7	98	Conn and Langworthy, 1984
Pilot-scale water hyacinth wetland to treat municipal wastewater (total SVOCs), San Diego, California	5.0	0.8	84	Conn and Langworthy, 1984

BDL below discharge limit
μg/L microgram per liter
SVOCs semivolatile organic compounds
VOCs volatile organic compounds

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The Chevron refinery in Richmond, California, also has a full-scale surface flow treatment wetland that is used to polish wastewaters before they enter San Francisco Bay (Duda, 1992). In addition to significant reductions in other wastewater contaminants, the treatment wetlands have reduced BOD_5 by 51 percent. Toxicity tests of the wetland effluent with rainbow trout have shown 0 percent mortality.

Wetlands have been used to treat wastewaters at petroleum refineries outside of the United States. In China, the Jinling Petrochemical Company reported small reductions in several effluent quality parameters, including phenol and oil, by treatment with a floating-plant (water hyacinth) wetland (Tang and Lu, 1993). Reductions of trace levels of organic compounds by a water hyacinth wetland were also shown in a pilot-scale municipal wastewater project (Conn and Langworthy, 1984), where low-level phenol was reduced by 81 percent.

Full-scale treatment wetlands (Yanshan wetlands) and research-scale wetlands (Fangshan wetlands) in Beijing, China, were shown to reduce a number of pollutants associated with refinery wastewater. BOD_5, phenols, and oil and grease were reduced in the full-scale Yanshan wetlands by 60 percent, 63 percent, and 65 percent, respectively (Dong and Lin, 1994). Phenol reductions in the Fangshan research wetlands ranged from 27.8 percent in the winter to 36.7 percent in the summer. The research wetland studies also indicated that hydraulic loading rate had the most significant effect on contaminant reduction of the variables tested (Dong and Lin, 1994).

Spills and Washings

Tenneco, Inc., used a rock-reed wetland to treat wastewaters from a natural gas pipeline compressor station. This wetland treatment system was shown to reduce oil and grease in the effluent by about 90 percent (Honig, 1988).

A subsurface flow wetland has been used to treat runoff from a 0.8-ha vehicle yard in Surprise, Arizona. Oil and grease have been reduced between 54 percent and 92 percent by these treatment wetlands (Wass and Fox, 1993).

At an unnamed oil terminal outside the United States, a 600-m^2 constructed rock-reed wetlands (primarily subsurface flow) was established in December 1992 to treat an oily water stream and a detergent-laden truckwash effluent. Preliminary results from 1993 through 1995 indicated an 80 percent reduction in BOD_5 and a 54 percent reduction in oil and grease in addition to reductions in other contaminants of interest. Phenols were also reduced, except in several cases that may have corresponded to high loading rates. Toxicity testing with Microtox™ organisms indicated a substantial decrease in effluent toxicity (98 percent) by the constructed wetlands (Farmer, 1996).

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At an ongoing remediation project at a bulk petroleum storage terminal in Port Everglades, Florida, a 720-m^2 surface flow constructed wetlands was used to polish effluent from a conventional groundwater treatment system that consisted of an oil/water separator and air stripper. The surface flow wetlands were shown to reduce trace amounts of aromatic hydrocarbons and PAHs. Volatile organics, which were already at low levels in the air stripper effluent were reduced to trace levels in the treatment wetlands. Individual and total PAHs were all reduced to levels below analytical method detection limits by the treatment wetlands (Rogozinski *et al.*, 1992).

Oil Sand Processing Water

A pilot-scale wetland was constructed in 1991 to treat wastewater from an oil sand processing facility at Fort MacMurray, in Alberta, Canada. Naphthenic acids (NA), which are water soluble hydrocarbons, are considered to be the primary toxicants of concern in this waste stream. Results indicated that NA and other contaminants were reduced by the treatment wetland, as was toxicity to *Daphnia magna* and Microtox™. When total extractable hydrocarbons (TEH) were used as a gross organic parameter, preliminary results showed removal efficiencies ranging from 35 to 70 percent under input loads of approximately 1 kilogram (kg)/month/100 m^2 (Bishay *et al.*, 1995a). NA reduction was shown to be more effective in the summer than in the winter (Gulley and Nix, 1993).

Produced Water

The applicability of wetland treatment systems to produced waters from natural gas processing is being studied at the Argonne National Laboratory in Argonne, Illinois (Hinchman *et al.*, 1993).

A pilot-scale treatment wetland project has been conducted by the Marathon Oil Company in conjunction with the Wyoming Department of Environmental Quality (WYDEQ). The system uses bacterial ponds followed by a riffle channel flowing into a surface flow wetlands to treat produced waters. The treatment system has been shown to reduce benzene and phenolics and operates effectively all year (Caswell *et al.*, 1992).

Specific Wetland Processes

A number of operative wetland processes can be postulated as contributory to the overall removal, conversion or storage of hydrocarbons and other chemicals in treatment wetlands. Detailed research is not available to support and calibrate the mechanistic models for these individual processes for very many substances; nevertheless, the physical-chemical principles are well-known. Wetlands provide long detention time at shallow depths, which is conducive to volatilization. The water is in close proximity to a variety of organic and inorganic sediments, and other immersed surfaces such as litter. Many substances partition to these sediments and are thus bound in place for periods long enough for degradation to occur. It is common practice to describe these processes via partition coefficients, and diffusion and mass transfer coefficients.

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Kinetic mechanisms are not generally known in a complex biological environment, and thus only first-order rate constants (half lives) are typically measured or estimated. Each of these component processes are investigated in more detail in the following sections.

Volatilization from Wetlands

A surface flow wetland provides considerable opportunity for losses of volatile compounds from the water to the atmosphere. The large areal extent, coupled with relatively long detention times and shallow water depths, fosters convective and diffusional transport to the air-water interface, upward to bulk air, and laterally offsite under the influence of winds. Equilibrium typically exists between air-phase and water-phase concentrations at the interface, which separates two vertical transport zones. Subsurface flow wetlands, by definition, have a subsurface air-water interface and, hence, greater resistance to transport in the air phase.

Henry's law expresses the equilibrium ratio of the air-phase concentration to the water-phase concentration of a given soluble chemical. A variety of concentration measures may be used in both phases, thus generating several variations of Henry's Law Constants (HLCs). Here the water phase concentration is presumed to be given as mmol/L (millimoles per liter) = mol/m^3 (moles per cubic meter), and the gas phase concentration as partial pressure in air (P_a) (mole or volume fraction times total pressure), thus:

$$P_a = HC \quad (2\text{-}29)$$

C	=	water phase concentration, mol/m^3
	=	C_w (mg/L) ÷ molecular weight (MW, grams per mole [g/mol])
H	=	Henry's Law Constant, atmospheres (atm) m^3/mol
P_a	=	partial pressure in air, atm

This relationship applies to a solution confined in a closed container, so that the entire air space reaches the equilibrium partial pressure for the solution in question. In a field situation, it is typically presumed that the equilibrium vapor pressure exists immediately above the water solution, but that diffusional processes will result in different concentrations in the bulk air and bulk water, at positions away from the air-water interface (Figure 2-7).

$$P_{iF} = HC_{iF} \quad (2\text{-}30)$$

C_{iF}	=	interfacial water concentration, mol/m^3
P_{iF}	=	interfacial air partial pressure, atm

According to the laws of thermodynamics, relationships exist between the vapor pressure of the pure compound, its water solubility, and HLC (Suntio *et al.*, 1988). Complicated vapor-liquid equilibrium

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relations apply to concentrated solutions, as might exist for alcohols and ketones. However, in the dilute ranges normally encountered in water pollution situations,

$$H = P_L^S(1 - x_w) / C_L^S \quad (2\text{-}31)$$

$$H = P_S^S / C_S^S \quad (2\text{-}32)$$

C_L^S = solubility of a liquid in water, mol/m^3

C_S^S = solubility of a solid in water, mol/m^3

P_S^S = vapor pressure of a solid, atm

P_L^S = vapor pressure of a liquid, atm

x_w = solubility of water in the liquid chemical, mol fraction

Many sources of information provide HLC values. Table 2-7 gives a sampling of values for materials of interest in the petroleum industry.

Transport in both the air and water phases may involve convective currents as well as molecular diffusion; therefore, the transport flux (flow per unit area) is commonly modeled with mass transfer coefficients (Welty *et al.*, 1984):

$$J = k_w (C - C_{iF}) = k_a (P_{iF} - P_a) \quad (2\text{-}33)$$

J = loss flux, mol/m^2 hour (hr)

k_a = air-side mass transfer coefficient, (m/hr) (mol/m^3)/atm = mol/(m^2 atm hr)

k_w = water-side mass transfer coefficient, m/hr

It is common practice to eliminate the unknown interfacial concentrations between Equations 2-30 and 2-33, yielding the following expression for transfer from bulk water to bulk air:

$$J = K_w\left(C - \frac{P_a}{H}\right) \quad (2\text{-}34)$$

where:

$$\frac{1}{K_w} = \frac{1}{k_w} + \frac{1}{Hk_a} \quad (2\text{-}35)$$

K_w = overall water-side mass transfer coefficient, meters per hour (m/hr)

This form is recognizable as the k-C* model, with the background concentration $C^* = P_a/H$. In many instances, a zero bulk air concentration exists, and the transfer model reduces to:

$$J = K_w C \quad (2\text{-}36)$$

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The mass transfer coefficient on the gas side may be crudely estimated from water evaporation, which is driven by the water vapor pressure difference between the interface and the partial pressure of water in the bulk air. At 25 degrees Celsius (°C), the interfacial partial pressure is 0.0313 atm. If the ambient air is at 50 percent relative humidity, $P_i - P = 0.5 \times 0.0313 = 0.01564$ atm. The corresponding water loss rate is on the order of 8 millimeters (mm)/day = 3.33×10^{-4} m/hr, corresponding to J = 18.51 mol/(m^2 hr). Equation 2-33 then suggests k_a = 1,183 mol/(m^2 atm hr). MacKay and Leinonen (1975) used an estimate of k_a = 3,000 mol/(m^2 atm hr) for an annual average. The effect of the large value of the air-side mass transfer coefficient is to place nearly all the mass transfer resistance on the liquid side, unless the HLC is very low; for instance, MacKay and Leinonen (1975) found more than 80 percent of the transfer resistance in the water when $H > 10^{-4}$ atm m^3/mol.

Values of k_w depend upon the degree of convective mixing, as well as on the size of the molecule being transported. A large body of knowledge exists on the reaeration of lakes and streams, which is also controlled by water-side mass transfer resistance (EPA, 1985). Values of k_w range from 0.002 to 0.2 m/hr (Kadlec and Knight, 1996), with the lower values corresponding to molecular diffusion alone, unaided by convective mixing. Estimates for low to moderate weight organic molecules were reported to range from 0.05 to 0.15 m/hr (MacKay and Leinonen, 1975). Experimental studies (Peng *et al.*, 1995) verified the strong effect of mixing in the water phase and established a diffusion-only value of $k_w \approx 0.03$ m/hr for benzene, toluene, trichloroethylene (TCE), and perchloroethylene (PCE). No definitive studies have been conducted to determine k_w in wetlands, but tracer studies indicate considerable internal mixing, resulting in estimates in the upper portion of the open water range (Kadlec and Knight, 1996).

Accordingly, because of low air-side resistance, these open water ranges are also the ranges for K_w. In the context of k-C* model calibration, these rate constants are in the range of 20 to 2,000 m/yr. The half-lives of low molecular weight alkanes (<C8) and mono- and bi-cyclic aromatics (including polychlorinated biphenyls [PCBs]) have been projected to be less than 12 hours at one meter water depth (Table 2-8) (MacKay and Leinonen, 1975). Therefore, light molecules are likely to be effectively stripped in wetlands that are designed to remove other constituents with equal or lower rate constants.

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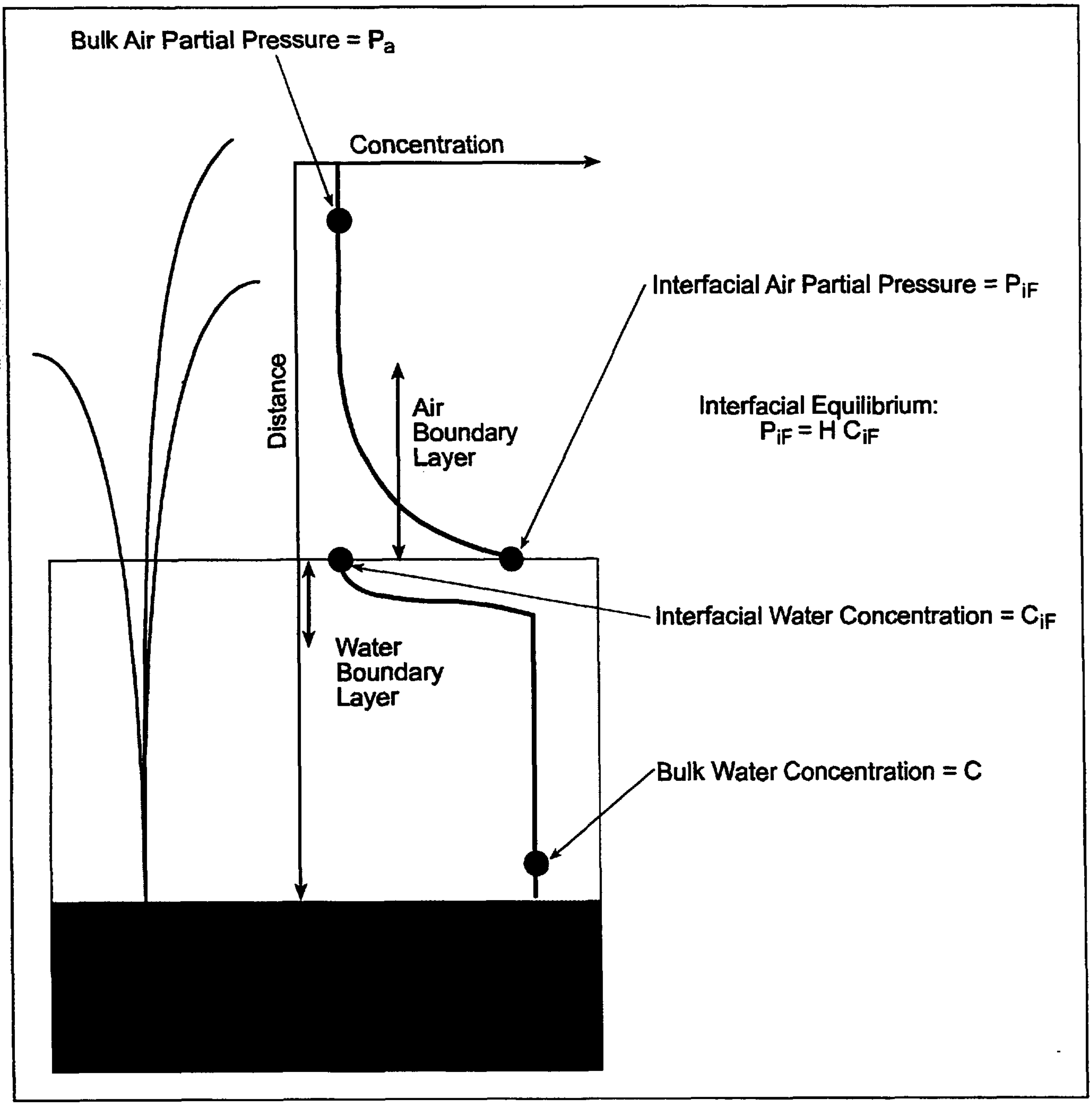

FIGURE 2-7
Volatilization of Organic Compounds to the Air
A soluble volatile organic chemical can move from bulk water to the air water interface, where it equilibrates with the air-phase chemical. Movement then occurs in the air, away from the interface out to the bulk air. Transport is typically in the turbulent range in the air and in the laminar or transition range in the water.

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TABLE 2-7
Fate and Transport Properties of Constituents of Potential Interest in Petroleum Industry Wastewaters

Chemical Name	CAS Registry No.	Molecular Weight (g/mol)	Molecular Diffusion Volume (cm^3/mol)	Henry's Law Constant (atm•m^3/mol)	Reference	K_{oc} (cm^3/gm)	Reference	K_d (mL/g) (ranges)	Reference	Air Diffusivity (cm^2/sec)	Reference	Water Solubility (mg/L)	Reference
Volatiles Organic Compounds (VOCs)													
Benzene	71-43-2	78	90.7	0.005	h	57	h	-	-	0.087	h	1,780	h
Butanone, 2-(MEK)	78-92-3	72	87.3	5.50E-05	f	33	f	-	-	0.095	l	2.68E + 05	f
Carbon disulfide	75-15-0	76	50.5	0.013	h	52	h	-	-	0.1	h	2,670	h
Chlorobenzene	108-90-7	113	108	0.004	h	204	h	-	-	0.073	h	409	h
Chloroform	67-66-3	120	77	0.004	h	56	h	-	-	0.1	h	7,960	h
Dibromoethane, 1.2-(EDB)	106-93-4	188	111	0.0007	l	44	l	-	-	0.078	k	4,300	e
Dichlorethane, 1,2-(EDC)	107-06-2	99	79.9	0.001	h	38	h	-	-	0.1	h	8,310	h
Ethylbenzene	100-41-4	106	132	0.008	h	221	h	-	-	0.075	h	173	h
Styrene	100-42-5	104	128	0.003	h	912	h	-	-	0.071	h	257	h
Toluene	108-88-3	92	11	0.006	h	131	h	-	-	0.087	h	558	h
Xylene, total	1330-20-7	106	132	0.006	g	260	g	-	-	0.076	l	186	i
Semivolatile Organic Compounds (SVOCs)													
Anthracene	120-12-7	178	190	1.11E-04	h	21,200	h	-	-	0.032	h	0.054	h
Benzo(a)anthracene	56-55-3	228	240	3.61E-06	h	3.57E + 05	h	-	-	0.051	h	0.013	h
Benzo(a)pyrene	50-32-8	252	253	8.36E-07	h	9.16E + 05	h	-	-	0.043	h	0.002	h
Benzo(b)fluoranthene	205-99-2	252	253	6.17E-06	h	8.83E + 05	h	-	-	0.023	h	0.04	h
Benzo(g,h,i)perylene	191-24-2	276	266	1.44E-07	b	1.60E + 06	b	-	-	0.052	k	2.60E-04	b
Benzo(k)fluoranthene	207-08-9	252	253	3.87F-05	b	5.50E + 05	b	-	-	0.053	k	0.004	b
Bis(2-ethylhexyl)phthalate	117-81-7	391	473	8.36E-06	h	87,400	h	-	-	0.035	h	0.4	h
Butylbenzyl phthalate, n	85-68-7	312	335	1.91E-06	h	34,100	h	-	-	0.017	h	2.58	h
Chrysene	218-01-9	228	240	1.21E-06	h	3.12E + 05	h	-	-	0.025	h	0.002	h
Di-nbutyl-phthalate	84-74-2	278	309	1.43E-06	h	1570	h	-	-	0.044	h	10.8	h
Dibenz(a,h)anthracene	53-70-3	278	290	1.12E-08	h	1.80E = 06	h	-	-	0.02	h	0.0007	h
Dichlorobenzene, 1,2-	95-50-1	147	126	0.002	h	376	h	-	-	0.069	h	125	h
Dichlorobenzene, 1,3-	541-73-1	147	126	0.004	l	1,700	i	-	-	0.075	k	123	i
Dichlorobenzene, 1,4-	106-46-7	147	126	0.003	h	516	h	-	-	0.069	l	73	h
Diethylphthalate	84-66-2	222	227	5.47E-07	h	82	h	-	-	0.026	h	883	h

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TABLE 2-7 (CONTINUED)

Fate and Transport Properties of Constituents of Potential Interest in Petroleum Industry Wastewaters

Chemical Name	CAS Registry No.	Molecular Weight (g/mol)	Molecular Diffusion Volume (cm^3/mol)	Henry's Law Constant ($atm \cdot m^3/mol$)	Reference	K_{oc} (cm^3/gm)	Reference	K_d (mL/g) (ranges)	Reference	Air Diffusivity (cm^2/sec)	Reference	Water Solubility (mg/L)	Reference
Dimethylphenol, 2,4-	105-67-9	122	137	3.25E-06	h	126	h	-	-	0.058	h	6,250	h
Dimethylphthalate	131-11-3	194	187	5.78E-07	h	46	h	-	-	0.057	h	4,190	h
Fluoranthene	206-44-0	202	203	9.33E-06	h	49,100	h	-	-	0.03	h	0.23	h
Methylnaphthalene, 1-	90-12-0	142	161	3.60E-04	e	1,584	g	-	-	0.068	k	25.8	g
Methylphenol, 2- (o-cresol)	95-48-7	108	117	1.64E-06	h	54	h	-	-	0.074	h	37,700	h
Methylphenol, 3- (m-cresol)	108-39-4	108	117	1.10E-06	j	500	j	-	-	0.08	k	31,000	j
Methylphenol, 4- (p-cresol)	106-44-5	108	117	1.10E-06	j	500	j	-	-	0.08	k	31,000	j
Naphthalene	91-20-3	128	140	4.82E-04	h	964	h	-	-	0.059	h	31.1	h
Phenanthrene	85-01-8	178	190	2.26E-04	b	14,000	b	-	-	0.062	k	1	e
Penol	108-95-2	94	96.2	5.95E-07	h	22	h	-	-	0.082	h	90,800	h
Pyrene	129-00-0	202	203	8.27E-06	h	68,200	h	-	-	0.027	h	0.14	h
Pyridine	110-86-1	79	77.9	0.007	d	6.92	c	-	-	0.098	k	1.00E + 06	l
Inorganics					-		-				-		-
Aluminum	7429-90-5	27	-	-	-	-	-	-	-	0.8	k	-	-
Arsenic	7440-38-2	75	-	-	-	-	-	(III) 1.0-8.3 or (V) 1.9-18	l	0.65	k	-	-
Barium	7440-39-3	137	-	-	-	-	-	-	-	0.61	k	-	-
Beryllium	7440-41-7	9	-	-	-	-	-	-	-	1.14	k	-	-
Cadmium	7440-43-9	112	-	-	-	-	-	1.26-26.8	l	0.62	k	-	-
Chromium (hexavalent)	18540-29-9	52	-	-	-	-	-	(VI) 1.2-1,800	l	0.69	k	-	-
Chromium (trivalent)	16065-83-1	52	-	-	-	-	-	(III) 470-150,000	l	0.69	k	-	-
Cobalt	7440-48-4	59	-	-	-	-	-	0.2-3,800	l	0.68	k	-	-
Lead	7439-92-1	207	-	-	-	-	-	4.5-7,640	l	-	-	-	-
Mercury	7439-97-6	201	-	0.011	h	-	-	-	-	0.13	h	0.056	a
Nickel, soluble salts	7440-02-0	59	-	-	-	-	-	-	-	0.68	k	-	-

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TABLE 2-7 (CONTINUED)
Fate and Transport Properties of Constituents of Potential Interest in Petroleum Industry Wastewaters

Chemical Name	CAS Registry No.	Molecular Weight (g/mol)	Molecular Diffusion Volume (cm^3/mol)	Henry's Law Constant (atm•m^3/mol)	Reference	K_{oc} (cm^3/gm)	Reference	K_d (mL/g) (ranges)	Reference	Air Diffusivity (cm^2/sec)	Reference	Water Solubility (mg/L)	Reference
Nickel, subsulfide	12035-72-2	240	-	-	-	-	-	-	-	0.68	k	-	-
Selenium	7782-49-2	79	-	-	-	-	-	(IV) 1.2-8.6	l	0.65	k	-	-
Vanadium	7440-62-2	51	-	-	-	-	-	-	-	0.69	k	-	-

Notes:

K_{oc} Organic partitioning constant; provides a measure of the extent of chemical partitioning between organic carbon and water at equilibrium. The higher the K_{oc} the more likely a chemical is to bind to soil or sediment than to remain in water.[m]

K_d Dissociation constant; provides a soil or sediment-specific measure of the extent of chemical partitioning between the soil or sediment and water. The higher the K_d the more likely a chemical is to bind to soil or sediment than to remain in water.[m]

References:

a. ATSDR, 1993.
b. ATSDR, 1992.
c. ATSDR, 1991.
d. Howard *et al.*, 1991.
e. HSDB, 1994.
f. MacKay, Shiu, and Kuo, 1995.
g. MacKay, Shiu, and Kuo, 1992.
h. EPA, 1994a.
I. EPA, 1988b.
j. EPA, 1986a.
k. CEHT, July 1995.
l. Dragun, 1988.
m. EPA, 1989a.

CAS Chemical Abstract Registry Service
cm^3/mol cubic centimeters per mole
cm^3/g cubic centimeters per gram
cm^2/sec square centimeters per second
mL/g milliliters per gram

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Partitioning to Wetland Sediments, Biofilms, and Humics

Organic contaminants partition strongly to solid organic substrates (Figure 2-8). As a result, wetland sediments are excellent sinks for organics. Subsequent to such partitioning, the organic chemical may diffuse downward, or undergo biodegradation. The first step along this pathway is transfer to the sediment-water interface, which is governed by the same convective processes as transfer to the air-water interface (Figure 2-9). Equilibrium is typically presumed to exist at the sediment-water interface, according to a linear partition equation, or a more complicated sorption isotherm, such as the Langmuir or Freundlich equations.

The wetland environment is complicated by the existence of biofilms on submerged plant parts and litter. Although small in terms of mass per unit volume, these biofilms are active in biodegradation and, consequently serve as important sinks for organics (Alvord and Kadlec, 1995a). In this aspect, wetlands resemble conventional attached growth treatment processes.

Suspended particulate matter (TSS) forms a mobile substrate for partitioned organics. Some insoluble high molecular weight organics, such as PCBs, DDT, and dichlorodiphenyldichloro-ethene (DDE), predominately travel through the environment in association with particulates.

The wetland biogeochemical cycle creates and processes large quantities of TSS and, thus, can play an important role in organic chemical cycling and removal.

The wetland environment is further complicated by the presence of large molecules of humic substances, which comprise a good share of dissolved organic carbon. Organic solutes can partition to these dissolved humic substances, thus creating two soluble forms with different chemical characteristics.

Partition Coefficients. A linear relationship between solid-phase and liquid-phase concentrations is often observed. The partition coefficient is also often proportional to the organic content of the solid phase, therefore:

$$C_{si} = KC_{wi} = f_{oc}K_{oc}C_{wi} \tag{2-37}$$

C_{si} = interfacial sediment concentration, milligrams per kilogram (mg/kg)

C_{wi} = interfacial water concentration, mg/L

f_{oc} = fraction organic carbon in sediment, unitless

K = partition coefficient, liters per kilogram (L/kg) = cm^3/g

K_{oc} = carbon-based partition coefficient, liters per kilogram (L/kg) = cm^3/g

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TABLE 2-8
Calculated Evaporation Parameters and Rates at 25°C from Ponds

Compound	Solubility (mg/L)	Vapor Pressure (mm Hg)	H (atm m^3/mol)	K_L, (m/hr)	Resistance in liquid phase (%)	Half-Life for H = 1 m (hr)
n-Octane	0.66	14.1	3.21	0.124	>99.9	5.55
2,2,4-Trimethylpentane	2.44	49.3	3.04	0.124	>99.9	5.55
Benzene	1,780	95.2	5.5×10^{-3}	0.144	95.6	4.81
Benzene at 10°C	1,750	45.5	2.67×10^{-3}	0.137	91.3	5.03
Toluene	515	28.4	6.68×10^{-3}	0.133	96.3	5.18
o-Xylene	175	6.6	5.27×10^{-3}	0.123	95.4	5.61
Cumene	50	4.6	1.46×10^{-2}	0.119	98.3	5.79
Naphthalene	33	0.23	1.18×10^{-3}	0.096	82.2	7.15
Biphenyl	7.48	0.057	1.55×10^{-3}	0.092	85.5	7.52
DDT	1.2×10^{-3}	1×10^{-7}	3.89×10^{-5}	9.34×10^{-3}	13.2	73.9
Lindane	7.3	9.4×10^{-6}	4.93×10^{-7}	1.5×10^{-4}	0.19	4,590
Dieldrin	0.25	1×10^{-7}	2.00×10^{-7}	5.33×10^{-5}	0.078	12,940
Aldrin	0.2	6×10^{-6}	1.44×10^{-5}	3.72×10^{-3}	5.4	185
Aroclor 1242	0.24	4.06×10^{-4}	5.73×10^{-4}	0.057	69.2	12.1
Aroclor 1248	5.4×10^{-2}	4.94×10^{-4}	3.51×10^{-3}	0.072	93.2	9.53
Aroclor 1254	1.2×10^{-2}	7.71×10^{-5}	2.76×10^{-3}	0.067	91.6	10.3
Aroclor 1260	2.7×10^{-3}	4.05×10^{-5}	7.13×10^{-3}	0.067	96.6	10.2
Mercury	3×10^{-2}	1.3×10^{-3}	1.14×10^{-2}	0.092	97.8	7.53

Source: MacKay and Leinonen, 1975.

DDT dichlorodiphenyltrichloro-ethane
Hg mercury

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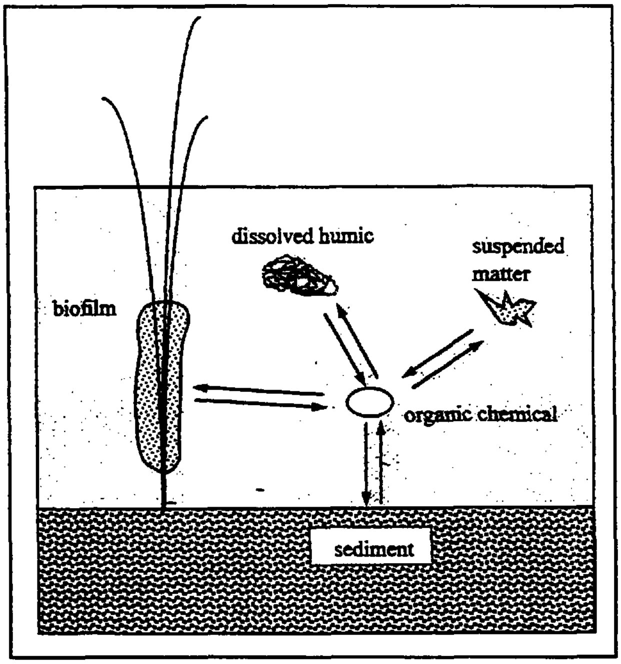

FIGURE 2-8
Partitioning of Organic Contaminants
A soluble chemical can partition to (1) biofilms on live and dead vegetation, (2) suspended particulate matter, (3) dissolved humic substances, and (4) bottom sediments.

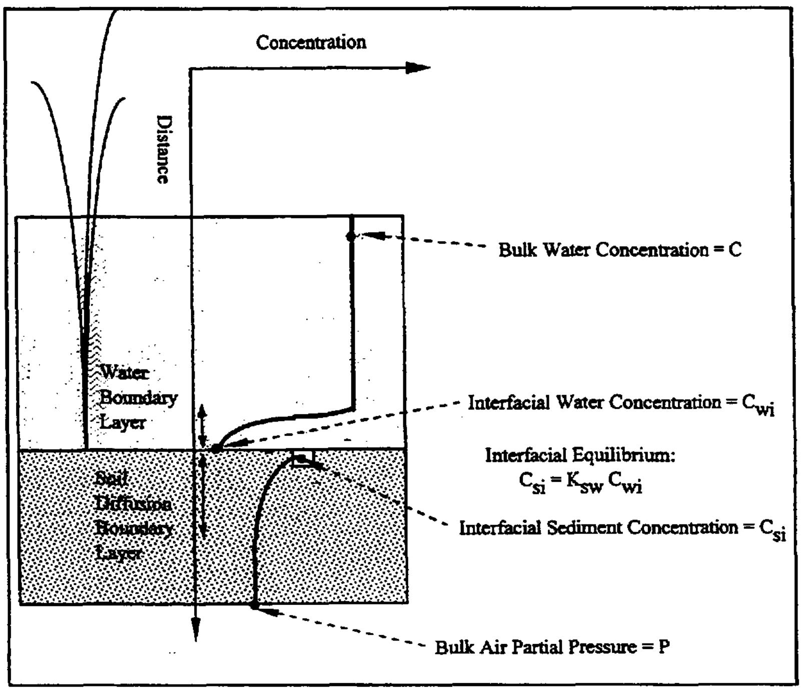

FIGURE 2-9
Chemical Transfer to the Sediment-Water Interface
A soluble chemical can move from bulk water to the sediment-water interface, where it equilibrates with the soil-phase chemical. Diffusive movement then occurs in the sediment, away from the interface down into the bulk soil.

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A similar relation is postulated to apply to the partitioning of the chemical to dissolved organic carbon (DOC):

$$C_{DOC-BOUND} = C_{DOC}M_{DOC} = C_{DOC}K_{DOC}C_w \qquad (2\text{-}38)$$

C_w = water concentration, mg/L

C_{DOC} = DOC concentration in water, mg/L

$C_{DOC-BOUND}$ = DOC concentration in solid phase, mg/L

K_{DOC} = partition coefficient, L/kg = cm^3/g

M_{DOC} = mass fraction chemical associated with DOC, mg/mg

Combining Equations 2-37 and 2-38 shows that the apparent (observed) partition coefficient will depend upon the dissolved carbon content, as follows:

$$K_{obs} = \frac{K}{1 + C_{DOC}K_{DOC}} \qquad (2\text{-}39)$$

K_{obs} = observed partition coefficient, L/kg = cm^3/g

The effect of DOC is to reduce the apparent partition coefficient, resulting from the removal of some sorbed organic from the measured solid-phase concentration. The magnitude of this effect has been measured to be a factor of 10 on the partition coefficient of hexachlorobenzene (HCB) to wetland sediments (Pardue *et al.*, 1993). These investigators also determined that the association of dosed HCB with DOC was a fast reaction that equilibrated in one hour.

Mass Transfer to Sorption/Degradation Sites. Convection and diffusion combine to transport a chemical from the bulk water to solid surfaces, including biofilms and the bottom sediments. Transport to sediments or biofilms is described by an analog of Equation 2-33:

$$J_b = k_{ws}(C - C_{wi}) \qquad (2\text{-}40)$$

J_b = flux to biofilm per unit biofilm area, mol/m^2 hr

k_{ws} = water-side mass transfer coefficient, m/hr

The mass transfer coefficient k_{ws} for transfer to bottom sediments is expected to be of the same order of magnitude as for transfer to the air-water interface, because it is driven primarily by convection currents in the water column. In contrast, k_{ws} for transfer to biofilms is related to small-scale convection in the vicinity of plant stems, which is somewhat less efficient than transfer to the air-water interface (Kadlec and Knight,

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1996). However, the surface area of biofilms in a given wetland section is much greater than the area of the air-water interface, leading to the amplification factor:

$$J = a_A J_b \qquad (2\text{-}41)$$

a_A	=	biofilm area per unit wetland area, square meters by square meters (m^2/m^2)
J	=	flux to biofilms per unit wetland area, mol/m^2 hr

Sorption, diffusion, and degradation may subsequently occur in the biofilm or sediment. These simultaneous processes have been modeled for trickling filters (Melcer *et al.*, 1995) and for wetlands (Kadlec and Knight, 1996). The resulting overall removal rate to biofilms or sediments is:

$$J = a_A k_i C_w = kC_w \qquad (2\text{-}42)$$

k	=	apparent degradation rate constant, m/yr
k_i	=	intrinsic degradation rate constant, m/yr

Within the limits of very fast reaction in the biofilm or sediment, $k_i = k_{ws}$; for very slow reactions, $k_i = \delta_b k_b$, the reaction rate in the biofilm. Under other conditions, k_i depends upon the degradation rate in the solid, as well as the biofilm thickness and the mass transfer coefficient k_{ws} (Kadlec and Knight, 1996).

$$k_i = \left[\frac{Ek_b\delta_b}{1 + M}\right] \qquad (2\text{-}43)$$

$$E = \frac{tanh(\phi)}{\phi};\ \phi = \delta_b\sqrt{\frac{k_b}{D_b}} \qquad (2\text{-}44)$$

$$M = \frac{Ek_b\delta_b}{k_{ws}} \qquad (2\text{-}45)$$

D_b	=	diffusion coefficient in biofilm, square meters per day (m^2/d)
δ_b	=	thickness of the biofilm, meters (m)
k_b	=	reaction rate constant inside biofilm, d^{-1}

Intrinsic degradation rate constants were found to vary from 0 to 95 m/yr for a variety of organics in trickling filters (Table 2-9) (Melcer *et al.*, 1995), under conditions of very fast external mass transfer, $k_i = \delta_b k_b$. Although the data in Table 2-6 are not for wetlands, they indicate an upper limit to biodegradation, under conditions of negligible mass transfer resistance, for biofilms fully activated with domestic wastewater. The data were corrected for stripping, which contributed significant additional reductions.

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TABLE 2-9
Intrinsic Degradation Rate Constants and Mass Transfer Coefficients in Trickling Filters

Compound	$D_w \times 10^5$ (m^2/d)	k_{ws} (m/d)	k_i (m/yr)
Toluene	7.8	0.78	61
o-Xylene	7.2	0.72	50
1,3,5-Trimethylbenzene	6.6	0.66	50
1,4-Dichlorobenzene	8.1	0.81	24
1,1,1-Trichloroethane	8.1	0.81	25
Trichloroethylene	8.6	0.86	18
Tetrachloroethylene	8.0	0.80	15
1,1,2,2-Tetrachloroethane	7.9	0.79	1
Chloroform	9.2	0.92	15
Bromoform	8.8	0.88	10

Notes: Assumed a water boundary layer thickness of 0.1 mm.
Values were corrected for stripping.
Means are for 5 replicate runs.
Source: Melcer *et al.*, 1995.

At the other extreme of companion technologies, wastewater stabilization ponds possess limited air-water interfaces per unit volume, and limited attached growth per unit volume. Yet, comparing the overall removal rates from ponds (Table 2-10) with biodegradation rates from trickling filters (Table 2-9) yields order-of-magnitude similarities.

Diffusion into the bottom sediment of a wetland can be measured by removing cores and dosing the cores with wastewater. Fickian diffusion, coupled with the appropriate retardation factor for sorption, provides a reasonable description of this process (Pardue *et al.*, 1993). These studies confirm the model (Equations 2-41 through 2-45) for the macroscopic case of diffusion into planar sediments.

The description of solid-partitioned and DOC-partitioned organic chemicals is clearly complicated by the need to describe water column TSS and DOC, as well as biofilm density. Further, the partitioned material is placed in close proximity to potential populations of degrading organisms, which are themselves selectively located on solid surfaces. At the time of this writing, no wetland study has contained sufficient detail to elucidate and calibrate the full suite of processes.

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TABLE 2-10
Removal Rate Constants in Stabilization Ponds

Compound	k_l (m/yr)
Toluene	55
o-Xylene	68
1,4-Dichlorobenzene	5
1,2,3-Trichlorobenzene	13
Hexachlorobenzene	13

Notes: Ponds are 2 m deep; 19.2 days detention occurred. Rate constants include stripping, storage, and biodegradation.
Source: Shugui *et al.*, 1994.

Biodegradation in Wetlands

Anthropogenic organic chemical additions to wetlands are modifications to an exceedingly complex background array of hydrocarbons and organic chemical reactions, as described in the preceding subsections. In some instances, natural background concentrations of a compound such as phenols need to be "treated" (Herskowitz, 1986). Indeed, wetland sediments and soils are the geological precursors to crude oil, tar sands, and coals, which, during processing, give rise to the aqueous contaminants under consideration here.

Hydrocarbon molecules are susceptible to fragmentation and chemical conversion in the wetland environment, predominately via microbially mediated pathways. Partial conversion may occur via hydrolysis, de-alkylation, and ring cleavage or through the removal of amino, nitro, halogen, hydroxyl, acid, or thio groups from the parent molecule. Oxidative processes ultimately produce carbon dioxide and water, whereas anaerobic processes may terminally result in the evolution of methane. Therefore, it is important to identify the by-products of degradation.

Measurement of carbon dioxide (CO_2) emission rates has been attempted as a measure of the degradation of added diesel fuel hydrocarbons (Nix, 1993) and oil sands processing wastewater (Nix and Gulley, 1995). However, interpretation of results was complicated by the need to subtract the background wetland CO_2 emission, for which there was no internal control. Recommended design loadings of 120 to 300 g carbon/m^2/yr are less than reported mineralization rates for constructed wetlands of 343 to 730 g carbon/m^2/yr (Gale *et al.*, 1993).

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Jackson and Pardue (1996) used radio-tagged crude oil ($\delta^{13}C$) to separate the CO_2 produced by oil and by the indigenous carbon pool in the wetland, while simultaneously monitoring decreases in alkanes and other hydrocarbons via the hopane ratio method. The crude oil dosage was 1,160 g/m^2, which was significant compared with the indigenous carbon pool. Mineralization, which did not begin for 2 weeks, represented only about 2 percent of the total CO_2 produced. This method produced statistically indistinguishable alkane removal rate constants, $k_V = 0.082$ and 0.087 d^{-1}, respectively (corresponding to k = 10 m/yr for a water depth of 30 centimeters [cm]).

A few studies have followed the kinetics of wetland degradation to intermediate byproducts. Pardue (1996) reported that hexachlorobenzene degraded to dichlorobenzene and then to chlorobenzene. Pier *et al.* (1996) report that trinitrotoluene (TNT) proceeds to 2-aminodinitrotoluene, 4-aminodintrotoluene, and trinitrobenzene, all reactions proceeding with half-lives on the order of one day in wetland microcosms planted to 10 different macrophyte species. Scale-up and kinetics measurements are in progress (Cheadle *et al.*, 1996).

Enhancement by Nutrient Addition. The degradation of hydrocarbons is apparently keyed to the magnitude of the biogeochemical cycle in a particular wetland. Sobelewski and MacKinnon (1995) found that phosphate additions stimulate naphthenic acid degrader populations. Pier *et al.* (1996) found that removal rate constants for degradation of explosives TNT, RDX, and HMX are proportional to plant biomass. Jackson *et al.* (1997) found that fertilizer amendments stimulate crude oil degradation in aerated microcosms, but no clear effect occurred in field studies.

Induction Periods. Several wetland studies have shown that removal of individual hydrocarbons does not start immediately, but requires a period of days to weeks to begin (Jackson and Pardue, 1996 [crude oil]; Pardue, 1996 [hexachlorobenzene]; Srinivasan and Kadlec, 1995 [naphthoic acid, Figure 2-10]; Polprasert and Dan, 1994 [phenol]). It is likely that an induction period is required for the development of a significant population of microorganisms adapted to the specific hydrocarbon.

Photodegradation in Wetlands

Many hydrocarbon molecules are decomposed by ultraviolet light (photolysis), and some may be degradable by aqueous photo-oxidation. However, rates of these processes are directly dependent on irradiation of the water column, which is not effective in subsurface flow wetlands or in densely vegetated surface flow wetlands. Low molecular weight molecules are not susceptible to photodegradation (Table 2-11).

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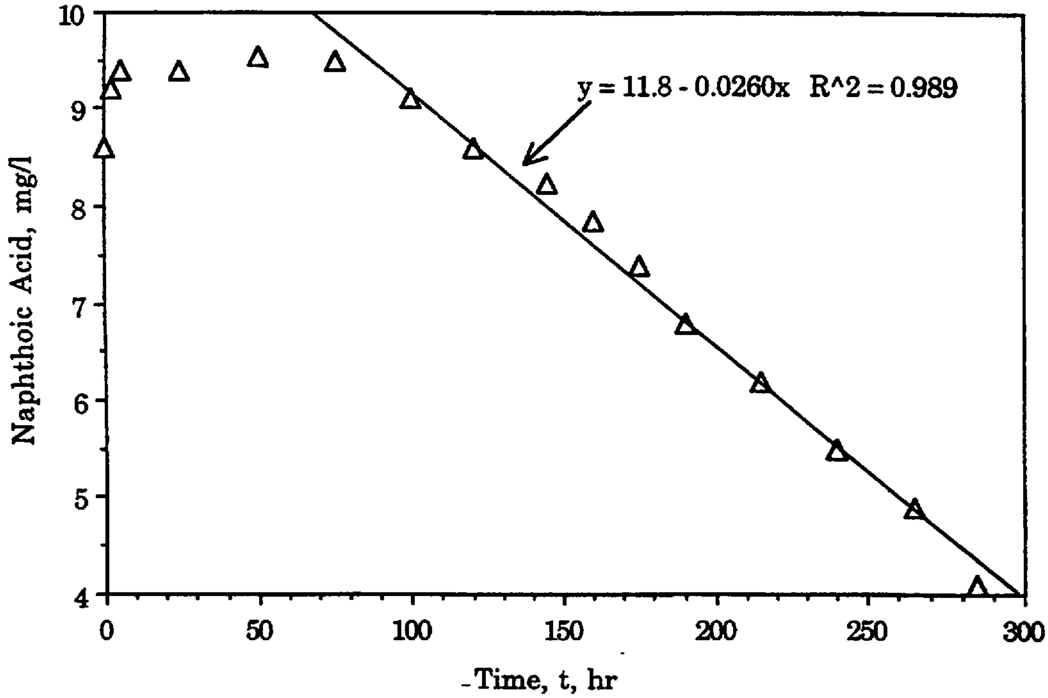

FIGURE 2-10
Disappearance of Naphthoic Acid in Cattail Microcosms
A zero order fit is appropriate after an induction period.
Source: Srinivasin and Kadlec, 1995.

Plant Uptake

Little is known about plant ingestion and translocation of specific organic chemicals. Some have speculated that plants can take up organic chemicals from their root zone, as well as from the atmosphere (Trapp and Matthies, 1995). However, these mechanisms may often be overshadowed by volatilization, partitioning to sediments, and biodegradation (Pardue, 1996). Efforts to find water-dosed, radio-tagged U-^{14}C-palmitic acid in cattail shoots produced low and erratic amounts, whereas evolved $^{14}CO_2$, sediment-bound ^{14}C, and incorporation into the food chain (chironomid larvae and fish) were clearly more important (Wood *et al.*, 1995). Early reports from EPA, Athens, Georgia, (Best, 1996) indicate that *Myriophyllum* degrades TNT and that degradation byproducts are found in plant tissues.

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TABLE 2-11

Estimated Biodegradation Rates for Selected Petroleum-Related Compounds in Soil and Surface Waters

Compound	CAS Registry No.	Unacclimated Anaerobic Half-Life (days)	Unacclimated Aerobic Half-Life (days)	Soil Half-Life (days)	Aqueous Photolytic Half-Life (days)
Acetone	67-64-1	4 - 28	1 - 7	1 - 7	
Methanol	67-56-1	1 - 5	1 - 7	1 - 7	
Ethanol	64-17-5	1 - 5	0.25 - 1	0.1 - 1	
1-Butanol	71-36-3	4 - 54	1 - 7	1 - 7	
Phenol	108-95-2	8 - 28	0.25 - 3.5	1 - 10	1.9 - 7.2
Propylene	115-07-1	28 - 112	7 - 28	7 - 28	
1,3-Butadiene	106-99-0	28 - 112	7 - 28	7 - 28	
Benzene	71-43-2	112 - 730	5 - 16	5 - 16	117 - 673
Toluene	108-88-3	56 - 210	4 - 22	4 - 22	
m-Xylene	108-38-3	28 - 112	7 - 28	7 - 28	
Biphenyl	95-52-4	6 - 28	1.5 - 7	1.5 - 7	
Naphthalene	91-20-3	25 - 258	20	16.6 - 48	71 - 550
Hexachlorobenzene	118-74-1	10.6 - 22.9 years	2.7 - 5.7 years	2.7 - 5.7 years	
1,4-Dichlorobenzene	106-46-7	112 - 730	28 - 182	28 - 182	
1,2,4-Trichlorobenzene	120-82-1	16 - 730	28 - 182	28 - 182	

Source: Howard *et al.*, 1991.

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Total Suspended Solids Removal

Processes

Total suspended solids are one result of natural wetland processes, as well as being common contaminants in feed waters. Incoming particulate matter usually has ample time to settle and become trapped in litter or dead zones. The combination of removal processes is called filtration, although stem and litter densities are not typically high enough to be considered a filter mat.

A number of wetland processes produce particulate matter: death of organisms, fragmentation of detritus from plants and algae, and the formation of chemical precipitates such as iron flocs (Figure 2-11). Bacteria and fungi can colonize these materials and add to their mass.

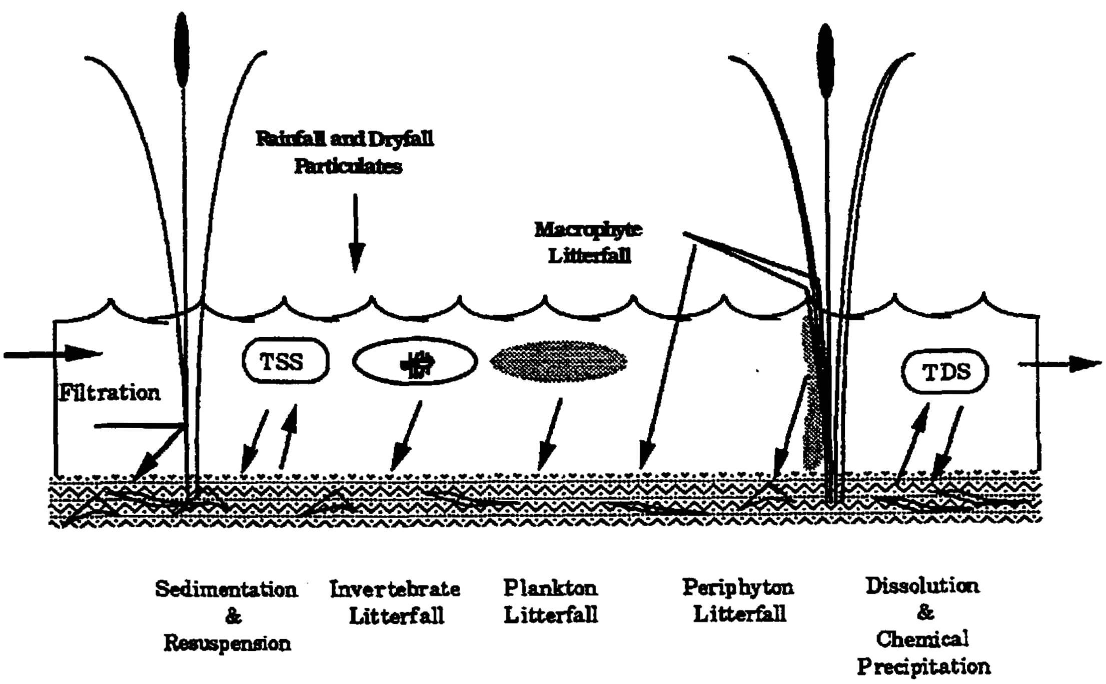

FIGURE 2-11
Sedimentation and Resuspension Processes
Wetlands are more than filters; many processes trap or create solids. The dominant removal process is often sedimentation, followed by trapping in the litter layer. Velocity-induced resuspension is minimal, but gas lift and bioturbation bring solids back into the water column.

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Wetland sediments and micro-detritus are typically near neutral buoyancy and easily disturbed. Bioturbation by fish, mammals, and birds can resuspend these materials and lead to high TSS concentrations in the wetland effluent. The oxygen generated by algal photosynthesis or methane formed in anaerobic processes can cause flotation of floc assemblages. Because of the low velocities normally used for treatment purposes, resuspension from fluid shear forces on bed solids is not usually a major process, except near a point discharge into the treatment wetland.

Wetland particulate cycling is extensive and almost always overshadows TSS additions, with high levels of gross sedimentation and resuspension (Figure 2-12). TSS background concentrations are rarely irreducible leftovers from feed water; they are often the result of the wetland processes enumerated above. If the TSS concentration in added water is lower than the background concentration, TSS concentrations increase. Many treatment wetlands are sufficiently large to approach background levels of suspendable materials. Gross deposition is measurable with high-sided cup collectors that prevent resuspension (Fennessey *et al.*, 1992). Net accretion is measurable with chemical or mechanical horizon markers (Reddy and D'Angelo, 1994). Typical accretion rates for lightly loaded wetlands are in the range of 2 to 10 millimeters per year (mm/yr) (Craft and Richardson, 1993).

High incoming TSS or high nutrient loadings that stimulate high production may eventually lead to measurable increases in bottom elevation (van Oostrom and Cooper, 1990). However, no treatment wetland has yet required maintenance because of solids accumulation, including some that have been in operation for 20 years or more. In situations of high incoming solids, a settling basin can be designed to intercept a large portion of the solids, provide for easier cleanout, and extend the life of the inlet region of the wetland.

Animals can be strong determinants of wetland TSS by virtue of their physical activity. Some known examples include stirring by the following:

- Foraging carp
- Spawning shad
- Muskrats and beavers
- Wild hogs and deer
- Foraging waterfowl

All of these resulted in the negative effect of increased effluent TSS concentrations.

Performance

Treatment wetlands are typically efficient in net reduction of TSS concentrations, with removal efficiencies often in the 80 to 90 percent range. As a result of the combined processes discussed above, TSS concentration declines along the flow path from inlet to outlet, down to the background level (Figure 2-13). The k-C* model provides a highly simplified description of the complex wetland solids interactions and, typically, represents the decreasing profile quite well, accounting for more than 90 percent of the intrasystem variability ($R^2 \approx 0.9$) (Kadlec and Knight, 1996).

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The value of k for TSS is theoretically the same as the settling velocity of the incoming particles, which can vary widely depending on the type of wastewater and its pretreatment. The reduction of TSS concentration along a transect was found to correspond to settling column data for Des Plaines river solids in Wetland EW3 (Table 2-12). Some incoming solids, such as emulsions and planktonic debris, are slow to settle. For instance, the planktonic solids in Muskego Lake (about 1 meter deep and vegetated by submerged and emergent macrophytes) remain suspended for long periods (Table 2-12). The value of k (net TSS reduction) may be substantially lower than the settling rate for some wetlands with high resuspension or highly variable hydrology, such as natural wetlands (e.g., bottomland hardwoods).

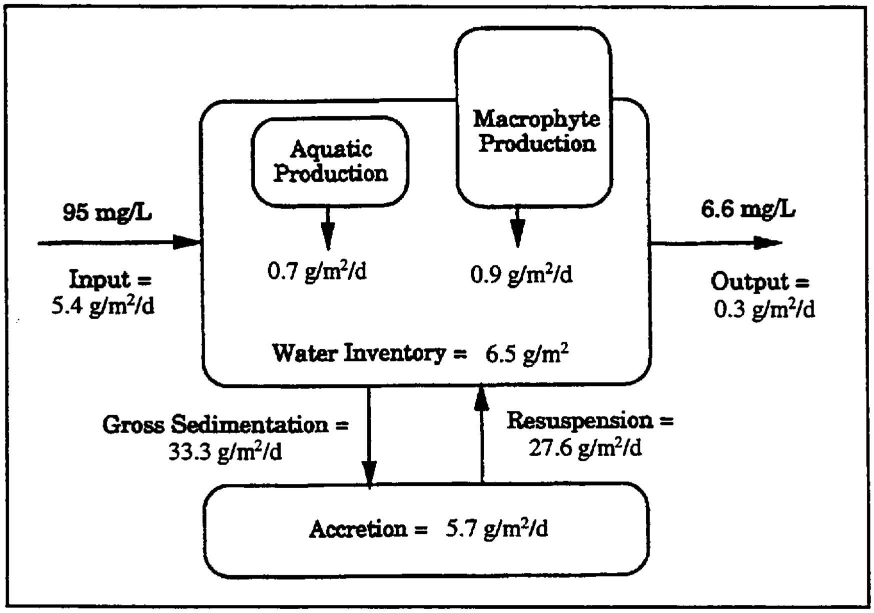

FIGURE 2-12
Components of the Sediment Mass Balance for Wetland EW3 at Des Plaines in 1991
The balance period is the 23-week pumping season.
Source: Fennessy et al., 1992.

The wetland background TSS concentration is typically in the range of 3 to 15 mg/L but depends on the size of the wetland carbon cycle. High nutrient levels stimulate growth and, hence, accentuate the return flux and increase the resultant background concentration. Therefore, C* is elevated for strong influents. The incoming TSS concentration can be used as a surrogate for incoming nutrient load in some cases and is also reflective of possible residuals.

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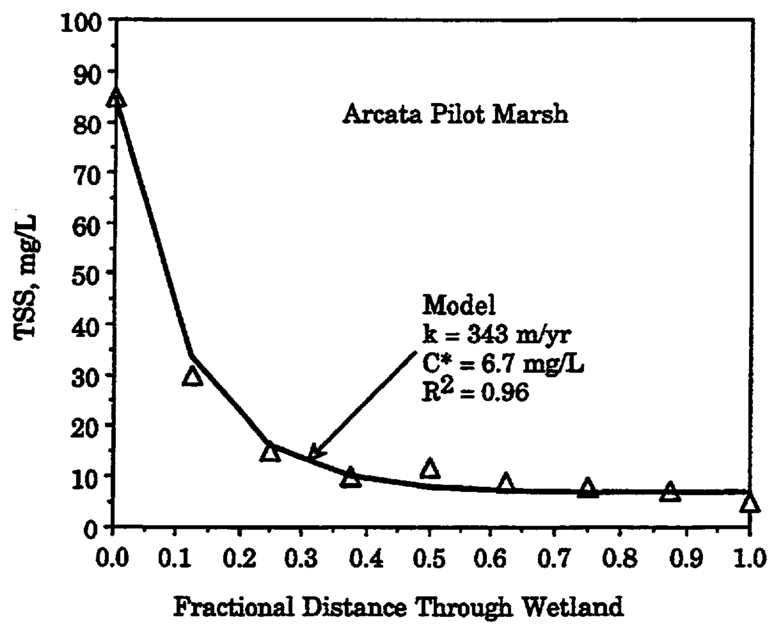

FIGURE 2-13
TSS Profile through a Compartmentalized Wetland in Arcata, California
Each data point represents the average of twice-weekly samples collected over 9 months (n = 78).
Source: Gearheart, 1992.

TABLE 2-12
Parameters for the k-C* Model of TSS Reduction

Site	Wetland	k (m/yr)	C* (mg/L)	R^2
Arcata, California	Pilot	343[a]	6.7[a]	0.96
Des Plaines, Illinois	EW3	3,543[a]	4.9[a]	0.99
	EW3	2,125[b]	7.0[c]	0.98
	EW4	3,160[b]	10.2[c]	0.98
	EW5	2,046[b]	5.4[c]	0.94
Houghton Lake, Michigan	Full Scale	726[b]	5.0[c]	0.93
Listowel, Ontario	System 3	6[a]	0.0[a]	0.53
	System 4	49[a]	7.5[a]	0.99
Sendai, Japan	Gamou Marsh	630[a]		0.86
Wind Lake, Minnesota	Muskego "Lake"	31[b]		0.99

[a] From transect data.
[b] From settling column data.
[c] From exit concentration.

Sources: Herskowitz, 1986; Gearheart, 1992; Hokosawa and Horie, 1992; Kadlec, unpublished data.

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Recognizing this strength dependence, the background concentration can be approximated as a function of inlet TSS (Kadlec and Knight, 1996):

$$C^* \approx C_o = 5.1 + 0.158C_i \qquad (2\text{-}46)$$

$R^2 = 0.23$, $N = 1{,}582$

Standard Error in $C_o = 15$

$0.1 < C_i < 807$ mg/L

$0.0 < C_o < 290$ mg/L

The validity of this weak correlation for petroleum wastewaters is not known. Intersystem performance is not strongly sensitive to hydraulic loading rates because many wetlands are overdesigned with respect to solids removal. Therefore, the TSS concentration in the outlet stream is characteristic of wetland background concentrations. Data from several sites show a trend of increasing outlet concentrations with increasing inlet concentrations (Figure 2-14). A simple regression model explains the general trend, but the intersystem scatter in input/output data is large, leading to a low R^2 value.

$$C_o = 1.125C_i^{0.58} \qquad (2\text{-}47)$$

$R^2 = 0.38$

$N = 460$

$1 < C_i < 800$ mg/L

$0.5 < C_o < 200$ mg/L

A regression equation, similar to Equation 2-46, was found for 77 Danish soil-based wetlands (Brix, 1994):

$$C_o = 4.7 + 0.09C_i \qquad (2\text{-}48)$$

$R^2 = 0.67$, $N = 77$

Standard Error in $C_o = 15$

$0 < C_i < 330$ mg/L

$0 < C_o < 60$ mg/L

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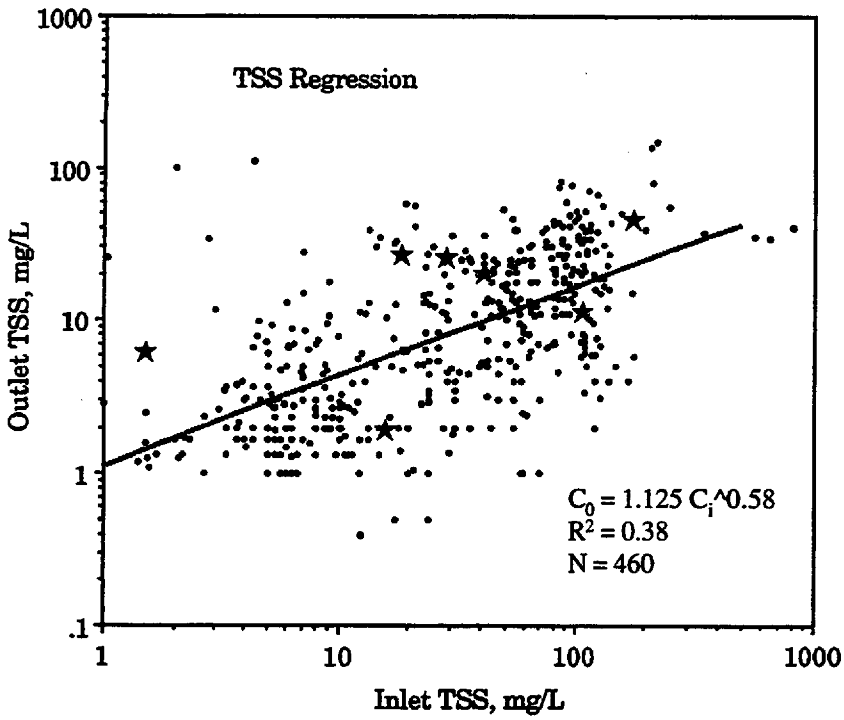

FIGURE 2-14
Regression of Monthly or Quarterly Input/Output TSS Data from 49 Wetlands at 31 Sites
Petroleum industry data are highlighted (★). The scatter indicates the importance of site-specific factors, such as the settling characteristics of the solids and vegetation density and type.

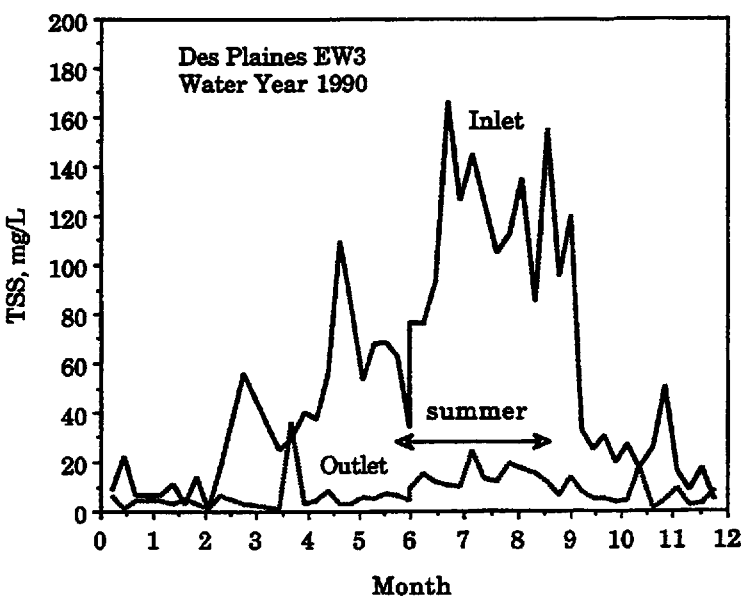

FIGURE 2-15
Input/Output TSS Performance of Des Plaines Wetland EW3
The mean annual outlet concentration was 6.1 mg/L, and the maximum monthly average value was 12.3 mg/L, corresponding to a ratio of 2.0. The outlet TSS does not track the large seasonal trend in the TSS concentration of the incoming river water.

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Because wetland processes involve a strong stochastic component, numerous and frequent excursions occur for this water quality parameter. The outlet concentrations are not reflective of inlet concentrations but of the internal wetland solids processes (Figure 2-15). The character of the variability is typified by maximum monthly TSS values that average 1.9 times the annual average values described by the regressions above.

Temperature apparently plays a minor role in TSS reduction ($\theta \approx 1.00$). The temperature coefficient for the background TSS concentration (C*) from the Listowel Wetlands 4 and 5 was $\theta = 1.065$ ($R^2 = 0.41$), indicating a seasonal increase in the background TSS concentrations from surface flow wetlands.

Petroleum Industry Data

The removal of suspended material has not been the principal focus of petroleum industry treatment wetland projects. The data in Table 2-13 indicate that reductions are possible for high entering TSS (i.e., Amoco, Yanshan), but that a clean influent may be subject to increased TSS in the outflow (Texaco B). This finding is commensurate with behavior in other treatment wetlands (Kadlec and Knight, 1996). Final pond elements create the potential for elevated TSS in the form of algal materials, which may have influenced the Yanshan data. Performance for TSS reduction in petroleum wastewaters is generally in line with other treatment wetlands (Figure 2-14).

TABLE 2-13
Petroleum Industry Treatment Wetland Operating Data for TSS

Site	Size	Type	Inlet TSS (mg/L)	Outlet TSS (mg/L)	Reduction (%)	k_1 (m/yr)	Reference
Amoco, Mandan, North Dakota	16.6 ha	FWS	106.1	11.7	89	13	Litchfield and Schatz, 1989
Texaco A	400 m^2	FWS	14.5	2.4	83	33	Hall, 1996
Texaco B	400 m^2	FWS	1.3	6	-362	-28	Hall, 1996
Chevron, Richmond, California 1989-91	36 ha	FWS	28.3	26.2	7	1	Duda, 1992
1992-95	36 ha	FWS	19.2	27	-41		Chevron, 1996
Non-USA Oil Terminal	600 m^2	SSF	38	20	47		Farmer, 1996
Yanshan Pond/Wetland, P.R. China	25 ha	FWS	181	41	77	122	Dong and Lin, 1994

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Metals Removal

General Occurrence and Processes

Metals refer to the chemical class of elements that have all or most of the following physical properties:

- High electrical and thermal conductivity (e.g., copper)
- High metallic luster or shine (e.g., silver)
- Malleability or ability to be shaped (e.g., tin)
- Ductility or ability to be drawn out to a thin wire (e.g., gold)
- High density (e.g., lead - $\delta = 11.34$ g/mL at 20°C)
- High melting point (e.g., iron - mp =1,535°C); hence, metals are solids at room temperature (except for mercury, gallium, and cesium, which are liquids)
- Hardness (e.g., iron, tungsten, and chromium; sodium and lead are relatively soft metals)

Some general chemical properties of metals are as follows:

- They do not readily combine with each other.
- They generally combine with nonmetal elements and, in nature, are usually found in combined forms.
- A few metals, such as gold, silver, copper, and platinum, are relatively unreactive and can be found in nature in a relatively pure state.

Some nonmetal elements such as silicon, arsenic, and selenium are considered metalloids because they possess both metallic and nonmetallic properties. This section discusses wetland processes for both metals and metalloids. Table 2-14 summarizes the properties of metals and metalloids of interest in treatment wetlands.

A number of metals are essential micronutrients for plants and microorganisms at trace levels because they are required for normal biochemical functioning. However, metals are common contaminants in petroleum wastewaters and can be found at concentrations that are toxic to sensitive organisms in wetland systems. Some metals can bioconcentrate from the exposure medium (such as soil or surface water) into the organisms living there. *Bioconcentration* refers to the direct uptake through the skin or gills. A few metals may not be readily eliminated or may undergo biochemical transformations that cause them to be accumulated within the organisms (referred to as bioaccumulation, which includes dietary as well as direct uptake). *Biomagnification* refers to the increasing concentration of a bioaccumulating contaminant as it passes up through different consumers in the food chain or food web (EPA, 1994b). Table 2-15 summarizes some chemical properties of metals that are significant in treatment wetlands.

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Table 2-16 summarizes the occurrence of selected metals in wetlands and related surface waters, plants, and soils. Chemical analyses of environmental media (water, sediment, or soil) may indicate the presence of a particular contaminant, but they do not indicate whether or not the contaminant is present in a form that can be taken up by a particular organism (i.e., *bioavailability*) (MacDonald and Salazar, 1994; EPA, 1992).

In wetland systems containing either iron or manganese sulfides, certain divalent metals (especially cadmium, copper, nickel, lead, and zinc), may tend to form sulfide compounds that are not bioavailable. Analysis of the ratio of the molar sum of these metals to the acid-volatile sulfides (AVS) may provide another tool for predicting bioavailability of these metals in wetland sediments (MacDonald and Salazar, 1994).

Performance

Wetlands are capable of significant metals removal as demonstrated by many studies. Three primary mechanisms for metal removal in wetlands are as follows:

- Binding to soil, sediments, particulates, and soluble organics
- Precipitation as insoluble salts such as sulfides and oxyhydroxides
- Uptake by plants, including algae, and bacteria

Metals removal through volatilization is relatively minor, except for mercury and selenium.

A number of physical and chemical properties of soils affect metal mobilization-immobilization processes. Important soil physical properties include particle size distribution (texture), and to some extent, the type of clay minerals present. Soil chemical properties affecting these processes include oxidation-reduction status (redox potential), pH, organic matter content, salinity, and the presence of inorganic components such as sulfides and carbonates (Gambrell, 1994).

Cation exchange capacity (CEC) of wetland soils and sediments tends to increase as texture becomes finer because more negatively charged binding sites are available. Silicate clay mineralogy will also affect CEC because the relative number of binding sites varies among clays with different types of crystal lattice structures. Surfactant-treated smectitic clays were shown to strongly adsorb metal ions and may represent an option to enhance sorption potential of treatment wetlands (Srinivasan and Kadlec, 1995).

Organic matter behaves similarly to mineral clays because it also has a relatively high proportion of negatively charged binding sites. Salinity and pH can influence the effectiveness of CEC in soils or sediment because the negatively charged binding sites and pore water will be occupied by a high number of sodium or hydrogen cations. Sulfides and carbonates may combine with metals to form relatively insoluble compounds.

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TABLE 2-14
Metals and Metalloids of Interest in Treatment Wetlands

Trace Element	Chemical Notation	Atomic Weight[a] (g/mol)	Average Abundance in Biosphere[b] (mg/kg)	Average Abundance in Freshwater[b] (mg/L)	Average Abundance in Earth's Crust[b] (mg/kg)	Biological Significance
Aluminum	Al	26.98	510	0.24	83,600	Nonessential; low solubility; low toxicity
Antimony	Sb	121.75	--	--	--	Nonessential; moderate toxicity
Arsenic	As	74.92	3.1	0.0004	1.8	Nonessential; high toxicity
Barium	Ba	137.33	310	0.054	390	Essential micronutrient; low toxicity
Beryllium	Be	9.01	--	<0.001	2.0	Essential micronutrient; low toxicity
Boron	B	10.81	110	0.013	9.0	Essential micronutrient; low toxicity
Cadmium	Cd	112.41	--	0.00007	0.049	Nonessential; high toxicity
Calcium	Ca	40.08	51,000	15.0	46,600	Essential macronutrient
Carbon	C	12.01	180,000	11.0	180	Essential macronutrient
Chlorine	Cl	35.45	2,100	7.8	126	Essential macronutrient; conservative; low toxicity
Chromium	Cr	52.00	--	0.0002	122	Essential macronutrient; high toxicity
Cobalt	Co	58.93	2.1	0.0009	29	Essential micronutrient; low toxicity
Copper	Cu	63.55	11	0.002	24	Essential micronutrient; variable toxicity
Fluorine	F	19.00	51	0.090	544	Essential micronutrient; low toxicity
Iodine	I	126.90	--	--	0.106	Essential micronutrient; low toxicity
Iron	Fe	55.85	1,100	0.67	62,200	Essential macronutrient; low to moderate toxicity
Lead	Pb	207.2	5.1	0.005	13	Nonessential; high toxicity

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TABLE 2-14 (CONTINUED)
Metals and Metalloids of Interest in Treatment Wetlands

Trace Element	Chemical Notation	Atomic Weight[a] (g/mol)	Average Abundance in Biosphere[b] (mg/kg)	Average Abundance in Freshwater[b] (mg/L)	Average Abundance in Earth's Crust[b] (mg/kg)	Biological Significance
Lithium	Li	6.94	1.1	0.0011	18	Nonessential; low toxicity; conservative
Magnesium	Mg	24.30	4,100	4.1	27,640	Essential micronutrient; low toxicity
Manganese	Mn	54.94	110	0.012	1,060	Essential micronutrient; low toxicity
Mercury	Hg	200.59	--	0.00008	0.086	Nonessential; high toxicity
Molybdenum	Mo	95.94	--	--	0.44	Essential micronutrient; low toxicity
Nickel	Ni	58.69	5	0.01	99	Essential micronutrient; high toxicity
Oxygen	O	16.00	780,000	889,000	456,000	Essential macronutrient
Potassium	K	39.10	31,000	2.3	18,400	Essential macronutrient
Selenium	Se	78.96	--	0.0001	0.017	Essential micronutrient; moderate toxicity
Silicon	Si	28.09	21,000	6.5	273,000	Essential micronutrient; low toxicity
Silver	Ag	107.87	1.7	0.0003	0.1	Nonessential; high toxicity
Sodium	Na	22.99	2,100	6.3	22,700	Essential macronutrient; conservative; low toxicity
Sulfur	S	32.06	5,100	3.7	340	Essential macronutrient
Zinc	Zn	65.38	51	0.01	76	Essential micronutrient; moderate toxicity

[a] One mole is equal to 6.02×10^{23} atoms.
[b] Sources: Fortescue (1980); Brownlow (1979); Stephenson (1987); Fowler (1983).

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TABLE 2-15
Summary of Certain Aspects of Metal Chemistry Important in Wetland Treatment Systems

Metal	Common Valence States in Natural Waters[a]	Common Forms in Surface Water[a]	Insoluble Compounds[a]	Partition Coefficients: Soil/Water[b] (L/kg)	Partition Coefficients: Plant/Soil [c]	Partition Coefficients: Fish/Water[d] (L/kg)
Arsenic	As (III), As (V)	Inorganic arsenate and arsenite	Sulfides	1.0-8.3	--	44
Cadmium	Cd (II)	Ionic hydrate, complexes with humics, carbonate, etc.	Carbonate, sulfide, hydroxide	1.26-26.8	1-10	64
Chromium	Cr (III), Cr (VI)		Hydroxide, chloride	1.2-1,800	0.01-01	16
Copper	Cu (II)	Complexes with carbonate, hydroxide, and organics	Carbonate, sulfide, and hydroxide	1.4-333	0.1-1.0	36
Iron	Fe (II), Fe (III)	Hydroxide, organic complexes, sulfides	Sulfide			
Lead	Pb (II)	Ionic hydrate adsorbed on particulates	Sulfides, carbonates	4.5-7,640	0.01-0.1	49
Manganese	Mn (II)	Ionic hydrate adsorbed on particulates	Hydroxide, sulfide	0.2-10,000	--	--
Mercury	Hg (0), Hg (I), Hg (II)	Ionic hydrate complexed with humics; elemental	Sulfide carbonate	--	0.01-0.1	5,500
Nickel	Ni (II)	Ionic hydrate	Sulfide, hydroxide			47
Selenium		Selenite; selenate	Elemental selenium			6(566-4,000[e,f])
Silver	Ag (I)		Sulfide	10-1,000	--	0.5
Zinc	Zn (II)	Ionic hydrate, carbonate, organic complexes	Sulfide, hydroxide	10-8,000	1-10	47

[a] Rudd (1987).
[b] Dragun (1988).
[c] Bolt *et al.* (1991).
[d] EPA (1993b).
[e] Schuler *et al.* (1990).
[f] Ohlendorf *et al.* (1986).

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TABLE 2-16
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Action Levels: Soils and Sludge (mg/kg dry weight)															
USDA NOAEL	--	100	18	2,000	1,200	--	300	--	15	500	--	--	2,700	--	Chaney, proposed no observable adverse effect limit
Nonagricultural land maximum	--	36	385	11,000	3,300	--	1,622	--	17	988	--	--	8,600	503 Sludge Regulations	EPA, 1989b
U.K. annual loading limits (kg/ha)	--	0.33	0.17	33.3	9.33	--	33.3	--	0.07	2.33	0.17	--	18.7	--	Lake, 1987
U.S. cumulative loading (kg/ha)	--	14	18	530	46	--	125	--	15	78	--	--	170	503 Sludge Regulations	EPA, 1989b
Soils and Sludge (mg/kg dry weight)															
Average upland soils	--	5	0.06	100	30	38,000	10	800	0.03	40	8	0.05	80	--	Lindsay, 1979; Lake, 1987
Average U.S. upland soils	72,000	7.2	--	54	25	26,000	19	600	0.089	19	0.39	--	60	--	Shacklette and Boerngen, 1984
Average Arizona upland soils	10,650	9.4	0.4	17.5	16.6	--	7.7	--	0.05	18.2	0.6	0.5	38.9	--	The Earth Technology Corporation (TETC), 1991
Average China upland soils	66,000	11	0.097	61	23	30,000	27	582	0.065	27	0.29	0.13	74	--	Chen *et al.*, 1991
Average sludge	18,300	14	110	2,620	1,210	31,000	1,360	380	9	320	3	225	2,790	--	Lake, 1987
Unpolluted wetland, United Kingdom	--	--	2	--	20	--	40	--	--	--	--	--	35	--	Zhang *et al.*, 1990

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Polluted wetland, United Kingdom	--	--	12	--	220	--	841	--	--	--	--	--	779	Stormwater municipal effluent	Zhang *et al.*, 1990
Control wetland, China	--	85.6	1.85	--	20.2	--	55.2	0.17	--	--	--	--	119.8	--	Lan *et al.*, 1990
Lead-zinc mine wetland, China	--	365	20.9	--	68.9	--	5,980	6.28	--	--	--	--	5,796	Mine wastewater	Lan *et al.*, 1990
Carolina Bay baseline-1986, South Carolina	--	--	0.11	3.29	0.93	1,409	--	--	<0.02	1.30	--	0.020	2.87	--	CH2M HILL, 1988
Carolina Bay operational-1991, South Carolina	--	--	<0.04	8.6	2.28	2,024	9.6	--	<0.05	3.07	--	<.12	2.94	Municipal effluent	CH2M HILL, 1992
Alaska salt marsh	--	--	--	--	--	--	--	95-120	--	--	--	--	45-55	Unpolluted	Nixon and Lee, 1986
Oregon salt marsh	--	--	0.1-0.5	--	9-94	--	8-13	--	--	--	--	--	39-101	Unpolluted	Nixon and Lee, 1986
Everglades peat soils, Florida	--	--	<2-5	<7-71	<5-36	437-28,400	<16-95	--	--	<5-23	--	--	<1-69	Unpolluted	Delfino *et al.*, 1993
Pond cypress wetland, Florida	--	--	<1.9	--	1.2	689	5.2	--	<0.07	<5.6	--	<1.9	<1.9	Municipal effluent (8 years)	CH2M HILL, 1994b
Riverine swamp forest, South Carolina	--	<5	<5	9.5	23.2	1,535	24	--	0.30	<16	<25	<5	18	Unpolluted	CH2M HILL, 1988
Okeefenokee Swamp, Georgia	--	--	--	--	15	--	20	6.5	0.54	--	--	--	23.5	Unpolluted	Nixon and Lee, 1986
Reed marsh, Nanokita River, Japan	--	--	0.1-0.14	--	8-9	--	4-6	--	--	2-2.5	--	--	45-50	Unpolluted	Suzuki *et al.* 1989

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Southeast U.S. salt marshes	--	--	0.1-5.0	--	2-30	--	4-49	30-366	0.01-1.7	--	--	--	6-70	37 sites	Nixon and Lee, 1986
Freshwater tidal marsh, Camden, New Jersey	--	--	5.5	--	117	--	1,025	--	--	64.4	--	--	452	Delaware River wetlands urban runoff	Simpson *et al.*, 1983
Freshwater marsh, Orlando, Florida, inlet area	--	--	7	30	92	1,300	1,300	--	--	--	--	--	410	Urban runoff	Schiffer, 1989
Freshwater marsh, Orlando, Florida, outlet area	--	--	1	9	4	15,000	40	--	--	--	--	--	23	Background	Schiffer, 1989
Swamp forest, Sanford, Florida	--	--	2.2	--	8.5	--	48	--	--	--	--	--	40	Urban runoff	Harper and Livingston, 1985
Shallow lake with emergent wetland vegetation, Tacoma, Washington	--	--	5.9	300	160	--	3,000	1,000	--	100	--	--	900	Urban runoff	Wisseman and Cook, 1977
Freshwater tidal marsh, Hudson River, New York	--	--	2-42,000	--	--	--	--	--	--	--	--	--	--	Nickel-cadmium battery factory	Hazen and Kneip, 1980
Action Levels: Surface Waters (µg/L)															
Freshwater (Gold Book) standards	--	190	0.66	Cr(VI): 11 Cr(III): 117	6.54	1,000	1.32	--	0.012	87.71	5	1.23	58.91	Hardness = 50 mg/L as $CaCO_2$	EPA, 1986a, b

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
California inland surface water (4-day average)	--	190	0.66	11	6.5	--	1.3	--	--	88	5	--	59		
Florida Class III Criteria	1,500	50	0.8-1.2	50	30	1,000	30	100	0.2	100	25	0.07	30		Florida Administrative Code (F.A.C.), 1989
Raw wastewater	--	7	8	167	117	2,250	148	117	1	--	6	22	419	Municipal	Williams, 1982
U.S. limits for agricultural irrigation	5,000	100	10	100	200	5,000	5,000	200	--	200	20	--	2,000		Kirk, 1987
U.K. limits for agricultural irrigation	--	400	--	2,000	500	--	2,000	--	--	150	--	--	1,000		Kirk, 1987
U.S.S.R. limits for hygenic and domestic purposes	--	50	10	500	100	500	100	--	5	100	1	--	1,000		Kirk, 1987
Suggested discharge limits for waterfowl wetlands	10	100	10	50	1,000	1,000	150	50	7	400	50	3	200		Kaczynski, 1985
Surface Waters (μg/L)															
World rivers	--	2	0.07	0.5	2	35	0.2	<5	0.01	0.3	0.1	0.3	10		Stephenson, 1987
Swamp forest, Sanford, Florida	176	--	3.92	2.78	19.9	105	24.7	3.10	--	2.71	--	--	3.90	Urban runoff	Harper and Livingston, 1985 (unpublished)
Riverine swamp, South Carolina	--	<5	<5	<6	6.2	936	<2	--	<0.2	<15	<15	<5	6.8	Predischarge baseline	CH2M HILL, 1995
Rural rainfall, Sweden	--	--	0.03-0.7	--	0.04-5.4	15-160	2-9	1.3-22	--	--	--	--	4.2-150	Rural locations in Sweden	Ross, 1987

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Action Levels: Biota - Plants (mg/kg dry weight)															
Phytotoxic levels	--	20	10	10	20	--	35	--	3	11	30	4	200	Agricultural plants	Lake, 1987
Biota - Plants (mg/kg dry weight)															
Volta, California	--	5.4	--	31	14	--	4.5	--		36	0.43	--	17	Unpolluted site	Ohlendorf *et al.*, 1986
Kesterson NWR, California, emergent plants	--	1.80	<0.2	3.5	4.92	--	<0.8	--	0.01	3.05	52.1	<0.2	13.7	Agricultural returns	Ohlendorf *et al.*, 1986
Kesterson NWR, California, filamentous algae	--	9.6	<0.2-3	3.04	20	--	<2-3	--	0.03	4.0	--	<0.2	31.6	Agricultural returns	Ohlendorf *et al.*, 1986
Inlet Valley, New York, *Carex rostrata*	--	--	--	--	5.3-16	--	--	252-616	--	--	--	--	20-28	Unimpacted marsh	Bernard and Bernard, 1989
D.U.S.T marsh, Fremont, California, *Scirpus* and *Typha*	--	--	--	--	--	--	3-16	100-1,200	--	--	--	--	7-41	Urban runoff	Meiorin, 1989
Mannersdorf, Austria, *Phragmites*	--	--	--	--	10-38	--	1-48	--	--	--	--	--	18-51	Domestic sewage	Haberl and Perfler, 1989
Lead-zinc mine, China, *Typha* and *Phragmites*	--	--	0.3-4.03	--	3-13.9	--	10-444	--	--	--	--	--	30-341	Lead-zinc mine	Lan *et al.*, 1990
U.K. ponds, *Typha*	--	--	4-10	--	17-45	--	20-95	--	--	--	--	--	38-170	Urban runoff and treated effluent	Zhang *et al.*, 1990

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Tundra biome site, 3 species	--	--	--	--	6-21	--	--	152-500	--	--	--	--	41-63	Unpolluted marsh	Nixon and Lee, 1986
Landfill leachate treatment marsh, New York, *Phragmites australis* shoots	--	--	0.09	--	--	65.8	0.21	68.9	--	--	--	--	17.4	Landfill leachate	Surface *et al.*, 1993
Landfill leachate treatment marsh, New York, *Phragmites australis* roots	--	--	0.39	--	--	3,709	8.02	289	--	--	--	--	35.0	Landfill leachate	Surface *et al.*, 1993
Oregon salt marsh, 6 species	--	--	--	--	8-13	--	2.2-97	30-341	--	--	--	--	23-60	Unpolluted marsh	Nixon and Lee, 1986
Okeefenokee Swamp, Georgia, 7 tree species	--	--	--	--	<1	--	<6	196	0.26	--	--	--	98	Unpolluted	Nixon and Lee, 1986
Southeastern U.S. saltmarshes	--	--	--	--	0.1-11	--	0.01-55	6-340	0.01-1.13	--	--	--	0.4-686	70 sites	Nixon and Lee, 1986
Nanakita River *Phragmites*	--	--	0.3	--	8	--	3.2	--	--	2.8	--	--	40	Unpolluted	Suzuki *et al.*, 1989
Northeastern United States saltmarshes	--	--	0.00-0.73	--	1-16	-	0.3-26	11-323	0.01-0.15	--	--	--	5-101	Multiple sites	Nixon and Lee, 1986
Sphagnum bogs (remote), Quebec	--	--	--	--	14	1,731	30.5	--	--	--	--	--	33	Unpolluted	Glooschenko *et al.*, 1986
Sphagnum bogs (near Cumelter), Quebec	--	--	--	--	83	1,295	217	--	--	--	--	--	115	<20 km from smelter	Glooschenko *et al.*, 1986

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Freshwater tidal marsh, Camden, New Jersey	--	--	2.13	--	14.5	--	23.6	--	--	8.3	--	--	124	Summer values, urban runoff	Simpson *et al.*, 1983
Cyperus marshes near Detroit, Michigan	--	--	0.26	--	6	--	7	91	0.034	--	--	--	65	Urban marshes	
Wild rice grains, Manitoba	--	--	<0.01 -6.2	--	1.6-14.4	--	<0.01-6.7	--	--	--	--	--	--	Lakes	Pip, 1993
Duckweed, Hamilton, Ontario	--	--	4.0	38	--	--	200	--	--	--	--	--	158	Municipal wastewater	Murdoch and Capobianco, 1979
Glyceria, Hamilton, Ontario	--	--	<1.0	2.2	--	4.2	--	--	--	--	--	--	16	Municipal wastewater	Murdoch and Capobianco, 1979
Sphagnum bog, northern Finland	--	--	--	6.3	231	5.6	--	--	--	--	--	--	34	Unpolluted	Glooschenko *et al.*, 1986
Biota - Invertebrates (mg/kg dry weight)															
Volta wildlife area, California		1.26	0.189	3.03	20.4	--	0.610	--	0.259	2.12	1.29-2.09	0.152	108	Unpolluted site	Ohlendorf *et al.*, 1986
Kesterson NWR, California		2.46	0.29	1.47	15.6	--	0.207	--	0.063	1.25	22.1 -175	0.093	81.1	Agricultural returns	Ohlendorf *et al.*, 1986
Red River, New Mexico	--	0.9	1.9	4.9	43	1,040	0.5	240	--	7.1	0.9	--	320	Upstream	Lynch *et al.*, 1988
Red River, New Mexico	--	0.5	1.3	2.7	82	1,300	0.9	540	--	13	0.2	--	350	Downstream of mine/mill	Lynch *et al.*, 1988
Constructed marsh, Florida		<1.76	<0.07	--	37.7	--	<3.5	112	0.088	--	--	0.69	99.3	Pulp mill effluent	Knight, 1994 (unpublished data)

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Action Levels: Biota - Fish (mg/kg dry weight)															
Concentration protective of human health	--	4-20	43	215	40-400	--	2-40	4,320	4	--	--	215	8,000		EPA, 1993c
Biota - Fish (mg/kg dry weight)															
National contaminant biomonitoring program	--	0.72	0.16	--	2.84	--	0.76	--	0.48	--	--	--	89.2		Schmitt and Brumbaugh, 1990
Kesterson wildlife area, California, mosquitofish	--	0.664 -1.54	0.041	0.88	6.76-7.14	--	<0.9-1	--	0.03-0.068	1.05	170	0.122	155-167	Agricultural return flows	Ohlendorf *et al.*, 1986
Volta wildlife area, California, mosquitofish	--	0.426	--	0.389	3.58	--	--	--	0.330	1.09	1.29	0.040	126	Unpolluted site	Ohlendorf *et al.*, 1986
Merced wetlands, California, mosquitofish	44	<1.1	<0.027	<0.81	4.9	--	0.22	12	0.32	<2.2	1.0	<0.27	110	Municipal wastewater	Ohlendorf, 1992 (unpublished data)
Constructed wetlands, mosquitofish	--	<10	<0.04	<8	--	--	<2	36	0.08	--	--	0.2	103	Pulp mill effluent	Knight, 1994 (unpublished data)
Constructed wetlands, catfish	57	<8	<0.4	1.4	1.7	95	<4	25	<1.6	<3.2	<16	<0.8	104	Pulp mill effluent	Knight, 1994 (unpublished data)
Biota - Birds															
Kesterson NWR, California[a] (in livers)	--	<0.79	0.362	--	--	--	<3.2	--	1.05	--	28.6-37.2	1.02	105	Agricultural return flows	Ohlendorf *et al.*, 1986

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TABLE 2-16 (CONTINUED)
Action Levels and Occurrence of Selected Metals in Wetland and Related Surface Waters, Plants, and Soils

Description	Metal													Description or Wastewater Source	Reference
	Al	As	Cd	Cr	Cu	Fe	Pb	Mn	Hg	Ni	Se	Ag	Zn		
Volta wildlife area, California[a] (in livers)	--	0.251	0.583	--	--	--	0.255	--	1.04	--	4.14 -6.1	0.201	120	Unpolluted site	Ohlendorf *et al.*, 1986
Kesterson NWR, California[b] (in breast tissue)	--	--	--	--	--	--	--	--	--	--	9.61 -110	--	--	Agricultural return flows	Ohlendorf *et al.*, 1986
Volta wildlife area, California (in breast tissue)	--	--	--	--	--	--	--	--	--	--	2.45-13.2	--	--	Unpolluted site	Ohlendorf *et al.*, 1986

[a]U.S. Food and Drug Administration (FDA) action levels were converted from wet weight by using 0.25 dry/wet ratio.
[b]Converted from wet weight by using 0.25 dry/wet ratio.
$CaCO_3$ = calcium carbonate   DUST = urban stormwater treatment   NOAEL = no observable adverse effect limit
Source: Kadlec and Knight, 1996.

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Metals removal from wetland waters by plant roots has been demonstrated in a number of studies (Wang and Peverly, 1996; Peverly *et al.*, 1995; Shutes *et al.*, 1993; Greipsson and Crowder, 1992; St-Cyr and Crowder, 1990; Schierup and Larsen, 1981). In particular, iron root plaque formation and emergent plant roots are important factors in biogeochemical processes in wetlands because (1) iron, with organic compounds, composes the most important redox buffer system in wetlands, and (2) emergent plant roots contribute to the aeration of sediment, adsorption of heavy metals, oxidation of methane, and the diversity of microorganisms in the rhizosphere (Wang and Peverly, 1996). Their study indicates that iron plaques are not composed entirely of oxidized iron (Fe^{3+}) compounds as commonly believed, but also contain a substantial proportion (33 percent) of compounds with the reduced iron form (Fe^{2+}). The positive effect of plant rhizospheres on microbial populations was also noted in terrestrial environments (Anderson and Walton, 1995).

The effect of increasing acidity in waters of constructed wetlands was not shown to significantly affect mobilization of metals into surface waters (Stark *et al.*, 1995; Albers and Camardese, 1993). Increased metals uptake by aquatic plants and invertebrates was noted in acidified wetlands as compared with nonacidified constructed wetlands (Albers and Camardese, 1993). Carbon or organic matter supplementation appears to only have limited effect on increasing metals retention (Stark *et al.*, 1995; Srinivasan and Kadlec, 1995).

Metal removal efficiencies of treatment wetlands are highly correlated with influent concentrations and mass loading rates (Stark *et al.*, 1995; Kadlec and Knight, 1996). For this reason, it is important to consider reported removal efficiencies only in light of these other two factors. Bishay *et al.* (1995b) observed that heavy metals in oil sands processing wastewaters were generally reduced by treatment wetlands but that the removal efficiency varied greatly depending on the metal and treatment water. Table 2-17 summarizes reported removal rates by natural and constructed wetlands for individual metals.

Effluent Toxicity

Ecological Toxicity

Most compounds, regardless of origin, may be toxic to one or more organisms in receiving waters if concentrations are sufficiently high. Toxicity levels vary widely between differing plant and animal species; however, environmental regulations typically protect the most sensitive life stages. Toxicity tests can be used to demonstrate whether or not test organisms, exposed to the wastewater sample, are subject to adverse effects on survival (acute toxicity) or to growth, behavior, or reproduction (chronic toxicity) (EPA, 1994b).

One way to screen a list of chemicals in a wastewater effluent for their potential to exceed toxicity thresholds is to compare their concentrations with published "ecotox" thresholds. Table 2-18 provides surface water and sediment ecotox thresholds for 67 chemicals that might be found in petroleum industry wastewaters. Table 2-18 also presents published phytotoxic thresholds for many of these same metals.

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TABLE 2-17
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Aluminum								
Freshwater marsh, Barataria Basin, Louisiana	--	--	--	--	--	413	--	Feijtel *et al.*, 1989
Forested swamp receiving urban runoff, Sanford, Florida	176	--	--	21.97	8.11	13.86	63	Harper *et al.*, 1986
AMD wetland, Kentucky (Fabius IMP1)	30	40	-33	1.10	1.82	-0.72	-66	Edwards, 1993 (unpublished data)
AMD wetland, Kentucky (Widows Creek)	300	340	-13	45.26	51.1	-5.84	-13	Edwards, 1993 (unpublished data)
Natural wetland, Tennessee	110	110	0	36.5	36.5	0	0	Edwards, 1993 (unpublished data)
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	0.3	0.1	67	--	--	--	--	Crites *et al.*, 1995.
Cadmium								
Creekbank salt marsh, Louisiana	--	--	--	0.08	0.02	0.06	75	DeLaune *et al.*, 1981
Cypress swamp, Waldo, Florida	--	--	--	--	--	2.61	82	Best, 1987
Salt marsh, Massachusetts	--	--	--	--	--	0.004		Giblin, 1985
Constructed meadow/marsh/pond, Brookhaven, New York	42.94	0.55	99	2.43	0.031	2.40	99	Hendrey *et al.*, 1979

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (μg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Cadmium (continued)								
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	<0.2	<0.2	0	--	--	--	--	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent, Conway, South Carolina	0.2	<0.2	--	--	--	--	--	CH2M HILL, 1991
Forested swamp receiving urban runoff, Sanford, Florida	3.92	--	--	0.33	0.097	0.23	71	Harper *et al.*, 1986
Shallow artificial streams, South Carolina	4.88	4.13	15	37.6	31.8	5.79	15	Giesy *et al.*, 1979
Shallow artificial streams, South Carolina	9.76	9.18	5.9	75.1	70.7	4.43	5.9	Giesy *et al.*, 1979
Bulrushes in gravel	70	17.5	75	12.6	3.2	9.4	75	Sinicrope *et al.*, 1992
SSF wetlands	70	14.7	79	15.6	3.3	12.3	79	
SF cattail	63	0.19	99.7					Noller *et al.*, 1994
SSF construction wetlands for municipal effluent, Santee, California	--	--	99	--	--	--	--	Gersberg *et al.*, 1985
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	0.1	<0.1	--	--	--	--	--	Crites *et al.*, 1995
Chromium								
Salt marsh, Massachusetts	--	--	--	--	--	0.026	--	Giblin, 1985

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Chromium (continued)								
Constructed meadow/marsh/pond, Brookhaven, New York	160	20	88	9.05	1.13	7.92	88	Hendrey *et al.*, 1979
Freshwater marsh receiving urban stormwater, Orlando, Florida	7.5	4.5	40	--	--	--	--	Schiffer, 1989
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	<2	3	--	--	--	--	--	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent Conway, South Carolina	15.0	15.0	0	--	--	--	--	CH2M HILL, 1991
Forested swamp receiving urban runoff, Sanford, Florida	2.78	--	--	0.23	0.063	0.17	72	Harper *et al.*, 1986
Bulrushes in gravel	100	16	84	18.0	2.9	15.1	84	Sinicrope *et al.*, 1992
SSF wetland (Cr[III])	100	32	68	22.3	7.1	15.2	68	
SF wetland (Cr[VI]) (average of 1987, 1989, 1990)	--	--	--	1.83	0.066	1.76	96	Litchfield and Schatz, 1989; Litchfield, 1993
SF wetland (total) (average of 1987, 1989, 1990)	--	--	--	10.63	1.63	9.00	85	Litchfield and Schatz, 1989; Litchfield, 1993
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	3.4	1.5	5.6	--	--	--	--	Crites *et al.*, 1995

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Copper								
Creekbank salt marsh, Louisiana	--	--	--	0.81	0.21	0.60	74	DeLaune *et al.*, 1981
Cypress swamp, Waldo, Florida	--	--	--	--	--	13.14	78	Best, 1987
Salt marsh, Massachusetts	--	--	--	--	--	0.025	--	Giblin, 1985
Freshwater marsh, Barataria Basin, Louisiana	--	--	--	--	--	0.21	--	Feijtel *et al.*, 1989
Constructed meadow/marsh/pond, Brookhaven, New York	1,510	60	96	85.42	3.39	82.03	96	Hendrey *et al.*, 1979
Freshwater marsh receiving urban stormwater, Orlando, Florida	8.0	1.0	88	--	--	--	--	Schiffer, 1989
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	20.4	6.1	70	0.27	0.060	0.21	78	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent, Conway, South Carolina	12.5	7.8	38	--	--	--	--	CH2M HILL, 1991
Forested swamp receiving urban runoff, Sanford, Florida	19.9	--	--	1.38	0.83	0.55	40	Harper *et al.*, 1986
Bulrushes in gravel	60	22.2	63	10.8	4.0	6.8	63	Sinicrope *et al.*, 1992
SSF wetland	1,200	144	88	268	32	236	88	

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Copper (continued)								
Typha SF	1.4	0.9	36					Noller *et al.*, 1994
Typha and *Melaleuca* SF	13	0.5	96					
Carex SF	280 145 160	13 14.5 6					90 73 95	Eger, 1993 (unpublished)
FWS constructed wetlands for 2° municipal effluent, Mountain View Sanitary District	--	--	96	--	--	--	--	EPA, 1993c
SSF constructed wetlands for municipal effluent, Santee, California	--	--	99	--	--	--	--	Gersberg *et al.*, 1985
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	8.1	3.3	59	--	--	--	--	Crites *et al.*, 1995
Pilot-scale wetlands for tertiary treatment of refinery effluents, St. Charles Parish, Louisiana	--	--	67	--	--	--	--	Hawkins *et al.*, 1995
Iron								
Salt marsh, Massachusetts	--	--	--	--	--	11.20	--	Giblin, 1985
Freshwater marsh, Barataria Basin, Louisiana	--	--	--	--	--	161	--	Feijtel *et al.*, 1989
Constructed meadow/marsh/pond, Brookhaven, New York	6,430	2,140	67	363.8	121.1	242.7	67	Hendrey *et al.*, 1979

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Iron (continued)								
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	241.4	765.8	-217	3.18	7.48	-4.29	-135	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent, Conway, South Carolina	298	488	-64	--	--	--	--	CH2M HILL, 1991
Subsurface flow reed wetlands receiving landfill leachate, New York	21,700	--	--	1,225	262	963	79	Surface *et al.*, 1993
Average for 137-AMD constructed wetlands	60,600	15,400	58	--	--	--	--	Wieder, 1989
Average AMD constructed wetlands	--	--	--	--	--	36,500	--	Kleinmann and Hedin, 1989
Forested swamp receiving urban runoff, Sanford, Florida	105	--	--	6.08	11.56	-5.48	-90	Harper *et al.*, 1986
AMD wetland, Kentucky (Fabius IMP1)	44,000	900	98	1,847	36.5	1,810.5	98	Edwards, 1993 (unpublished data)
AMD wetland, Kentucky (Widows Creek)	205,000	6,300	97	30,828	949	29,879	97	Edwards, 1993 (unpublished data)
Natural wetlands, Tennessee	1,290	1,170	9	449	405	44	10	Edwards, 1993 (unpublished data)
Lead								
Creekbank salt marsh, Louisiana	--	--	--	1.08	0.18	0.90	83	DeLaune *et al.*, 1981
Salt marsh, Massachusetts	--	--	--	--	--	0.115	--	Giblin, 1985

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Lead (continued)								
Fresh water marsh, Barataria Basin, Louisiana	--	--	--	--	--	1.1	--	Feijtel *et al.*, 1989
Freshwater marsh receiving urban stormwater, Orlando, Florida	18.0	3.0	83.3	--	--	--	--	Schiffer, 1989
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	1.96	5.5	-181	0.026	0.054	-0.028	-107	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent, Conway, South Carolina	2.8	3.5	-27.3	--	--	--	--	CH2M HILL, 1991
Forested swamp receiving urban runoff, Sanford, Florida	24.7	--	--	1.97	0.89	1.08	54.8	Harper *et al.*, 1986
AMD wetland, Kentucky (Widows Creek)	2.2	1.63	25.9	0.33	0.245	0.085	25.8	Edwards, 1993 (unpublished data)
Bulrushes in gravel	300	42	86	53.9	7.5	46.4	86	Sinicrope *et al.*, 1992
SSF wetland	300	60	80	66.9	13.4	53.5	80	
Typha SF	12	0.2	98					Noller *et al.*, 1994
Typha/Melaleuca SF	9	0.5	94					
Stormwater wetlands (n = 9) median (all SF)							83	Strecker *et al.*, 1992

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (μg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Lead (continued)								
Constructed wetlands to supplement air stripper for petroleum groundwater remediation	65	16	75	--	--	--	--	Rogozinski *et al.*, 1992
FWS constructed wetlands for urban stormwater	--	--	98	--	--	--	--	Lenehan, 1992
FWS constructed wetlands for 2° municipal effluent, Mountain View Sanitary District, California	--	--	20	--	--	--	--	EPA, 1993c
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	1.7	0.4	76	--	--	--	--	Crites *et al.*, 1995
Pilot-scale wetlands for tertiary treatment of refinery effluent, St. Charles Parish, Louisiana	--	--	89	--	--	--	--	Hawkins *et al.*, 1995
Manganese								
Creekbank salt marsh, Louisiana	--	--	--	7.39	3.64	3.75	51	DeLaune *et al.*, 1981
Cypress swamp, Waldo, Florida	--	--	--	--	--	26.3	68	Best, 1987
Salt marsh, Massachusetts	--	--	--	--	--	0.105	--	Giblin, 1985
Freshwater marsh, Barataria Basin, Louisiana	--	--	--	--	--	2.7	--	Feijtel *et al.*, 1989

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Manganese (continued)								
Constructed meadow/marsh/pond, Brookhaven, New York	210	120	43	11.88	6.79	5.09	43	Hendrey *et al.*, 1979
Subsurface flow reed wetlands receiving landfill leachate, New York	5,250	--	--	291	177	114	39	Surface *et al.*, 1993
Forested swamp receiving urban runoff, Sanford, Florida	3.10	--	--	0.26	0.24	0.02	7.7	Harper *et al.*, 1986
AMD wetland, Kentucky (Fabius IMP1)	5,900	1,200	79	244	51.1	193	79	Edwards, 1993 (unpublished data)
AMD wetland, Kentucky (Widows Creek)	7,400	3,900	47	1,113	588	526	47	Edwards, 1993 (unpublished data)
Natural wetland, Tennessee	210	130	40	73	44	29	40	Edwards, 1993 (unpublished data)
Typha SF	600	11	98					Noller *et al.*, 1994
Typha/Melaleuca SF	1,300	330	75					
Mercury								
Salt marsh, Massachusetts	--	--	--	--	--	0.0002	--	Giblin, 1985
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	<0.2	0.21	--	0.0021	0.0020	0.0001	4.8	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent, Conway, South Carolina	<0.2	0.55	--	--	--	--	--	CH2M HILL, 1991

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Mercury (continued)								
Shallow artificial streams, South Carolina	1.2	1.0	18	10.7	8.9	1.8	18	Kania *et al.*, 1976
Shallow artificial streams, South Carolina	5.7	4.7	17	51.0	42.0	8.9	17	Kania *et al.*, 1976
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	0.0179	0.006	66	--	--	--	--	Crites *et al.*, 1995
Nickel								
Constructed meadow/marsh/pond, Brookhaven, New York	35.0	10.27	71	1.98	0.58	1.40	71	Hendrey *et al.*, 1979
Freshwater marsh receiving urban stormwater, Orlando, Florida	4.0	3.0	25	--	--	--	--	Schiffer, 1989
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	17.0	9.12	46	0.224	0.089	0.135	60	CH2M HILL, 1992
Cypress-gum receiving municipal effluent, Conway, South Carolina	18.2	13.2	28	--	--	--	--	CH2M HILL, 1991
Forested swamp receiving urban runoff, Sanford, Florida	2.71	--	--	0.23	0.069	0.16	70	Harper *et al.*, 1986
Bulrush in gravel	300	111	63	53.9	19.9	34.0	63	Sinicrope *et al.*, 1992
SSF wetland	300	153	49	66.9	34.1	32.8	49	

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (μg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Nickel (continued)								
Typha/Melaleuca SSF	52	<5	90					Noller *et al.*, 1994
Carex SF	60	7					88	Eger, 1993 (unpublished data)
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	7.5	3.8	49	--	--	--	--	Crites *et al.*, 1995
Silver								
Carolina Bay receiving municipal effluent, Myrtle Beach, South Carolina	0.36	0.53	-49	0.0047	0.0052	-0.0005	-11	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent, Conway, South Carolina	4.0	1.0	76	--	--	--	--	CH2M HILL, 1991
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	0.7	0.3	57	--	--	--	--	Crites *et al.*, 1995
Zinc								
Creekbank salt marsh, Louisiana	--	--	--	2.33	0.21	2.10	91	DeLaune *et al.*, 1981
Cypress swamp, Waldo, Florida	--	--	--	--	--	26.3	77	Best, 1987
Salt marsh, Massachusetts	--	--	--	--	--	0.055	--	Giblin, 1985
Freshwater marsh, Barataria Basin, Louisiana	--	--	--	--	--	0.47	--	Feijtel *et al.*, 1989

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (μg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Zinc (continued)								
Constructed meadow/marsh/pond, Brookhaven, New York	2,200	230	90	124.5	13.01	111.5	90	Hendrey *et al.*, 1979
Freshwater marsh receiving urban stormwater, Orlando, Florida	75.0	25.0	67	--	--	--	--	Schiffer, 1989
Carolina Bay receiving municipal effluent Myrtle Beach, Florida	20.6	5.6	73	0.272	0.055	0.217	80	CH2M HILL, 1992
Cypress-gum swamp receiving municipal effluent, Conway, South Carolina	20.8	7.0	66	--	--	--	--	CH2M HILL, 1991
Forested swamp receiving urban runoff, Sanford, Florida	3.90	--	--	0.44	0.26	0.18	41	Harper *et al.*, 1986
AMD wetland, Kentucky (Widows Creek)	30	20	33	4.38	2.92	1.46	33	Edwards, 1993 (unpublished data)
Bulrush in gravel	399	63	79	53.9	11.3	42.6	79	Sinicrope *et al.*, 1992
SSF wetland	2,500	725	71	558	162	396	71	
Carex SF	1,590 1,920 800 45	41 44 28 7					96 90 96 33	Eger, 1993 (unpublished data)
FWS constructed wetlands for urban stormwater	--	--	96	--	--	--	--	Lenehan, 1992

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TABLE 2-17 (CONTINUED)
Metal Dynamics in Wetlands

Description	Concentration (µg/L)			Mass Rate (kg/ha/yr)				Reference
	In	Out	Removal (%)	In	Out	Removal	Removal (%)	
Zinc (continued)								
FWS constructed wetlands for 2° municipal effluent, Mountain View Sanitary District, California	125	70	44	--	--	--	--	EPA, 1993c
SSF constructed wetlands for municipal effluent, Santee, California	0.0113	0.00037	97	--	--	--	--	Gersberg *et al.*, 1985
FWS constructed wetlands for 2° municipal effluent, Sacramento Co., California	36.4	10.9	70	--	--	--	--	Crites *et al.*, 1995
Pilot-scale wetlands for tertiary treatment of refinery effluent, St. Charles Parish, Louisiana	--	--	98	--	--	--	--	Hawkins *et al.*, 1995

AMD = acid mine drainage

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TABLE 2-18
Ecotox Thresholds for 67 Chemicals Commonly Found at Superfund Sites (USEPA, 1996)

CAS Registry No.	Chemical	Surface Water (µg/L)			Sediment (mg/kg)			
		Freshwater		Marine	EPA SQC [c]			
		AWQC or FCV[a]	Tier II [b]	AWQC or FCV[a]	Fresh-water	Marine	EPD SQB [d]	ERL[e]
Metals (20)								
22569728	Arsenic III	190		36				8.2 t
17428410	Arsenic V		8.1 •					
7440393	Barium		3.9 •					
7440417	Beryllium		5.1 •					
7440439	Cadmium	1.0 h		9.3				1.2
1308141	Chromium III	180 h						81
18540299	Chromium VI	10		50				
7440484	Cobalt		3.0 •					
7440508	Copper	11 h		2.4				34
7439896	Iron	1000						
7439921	Lead	2.5 h		8.1				47
7439965	Manganese		80 •					
7439976	Mercury, inorganic	1.3		1.1				0.15 t
22967926	Mercury, methyl		0.003 •					
7439987	Molybdenum		240 •					
7440020	Nickel	160 h		8.2				21
7782492	Selenium	5.0		71				
7440622	Vanadium		19 •					
7440666	Zinc	100 h		81				150
57125	Cyanide	5.2		1.0				
Organic Compounds (47)								
83329	Acenaphthene			40 S	0.62	1.1		0.016
71432	Benzene		46 I				0.057	
50328	Benzo(a)pyrene		0.014 •					0.43
92524	Biphenyl		14 #				1.1	
117817	Bis(2-ethylhexyl)phthalate		32 •					
101553	Bromophenyl phenyl ether, 4-		1.5 #				1.3	
85687	Butylbenzyl phthalate		19 #				11	

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TABLE 2-18 (CONTINUED)
Ecotox Thresholds for 67 Chemicals Commonly Found at Superfund Sites

		Surface Water (µg/L)			Sediment (mg/kg)			
		Freshwater		Marine	EPA SQC [c]			
CAS Registry No.	Chemical	AWQC or FCV[a]	Tier II [b]	AWQC or FCV[a]	Fresh-water	Marine	EPD SQB [d]	ERL[e]
108907	Chlorobenzene		130 •				0.82	
50293	DDT		0.013 +					0.0016
333415	Diazinon	0.043 F					0.0019	
132649	Dibenzofuran		20 •				2.0	
95501	Dichlorobenzene, 1,2-		14 #				0.34	
541731	Dichlorobenzene, 1,3-		71 #				1.7	
106467	Dichlorobenzene, 1,4-		15 #				0.35	
75343	Dichloroethane, 1,1-		47 •					
60571	Dieldrin	0.062 S		0.11 S	0.052	0.095		
84662	Diethyl phthalate		220 •				0.63	
84742	Di-n-butyl phthalate		33 •				11	
115297	Endosulfan, mixed isomers		0.051 #				0.0054	
959988	Endosulfan, alpha		0.051 #				0.0029	
33213659	Endosulfan, beta		0.051 #				0.014	
72208	Endrin	0.061 S		0.01 S	0.02	0.0035		
100414	Ethylbenzene		290 •				3.6	
206440	Fluoranthene	8.1 S		11 S	2.9	1.4		0.6
86737	Fluorene		3.9 #				0.54	
76448	Heptachlor		0.0069 +					
67721	Hexachloroethane		12 #				1.0	
58899	Lindane/ hexachlorocyclohexane	0.08					0.037	
121755	Malathion		0.097				0.00067	
72435	Methoxychlor		0.019 #				0.019	
91203	Naphthalene		24 •				0.48	0.16
608935	Pentachlorobenzene		0.47 #				0.69	
87865	Pentachlorophenol	13 pH		7.9				
1000	Polynuclear aromatic hydrocarbons							4.0
11096825	Polychlorinated biphenyls		0.19 •					0.023
85018	Phenanthrene	6.3 S		8.3 S	0.85	1.1		0.24
129000	Pyrene							0.66

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TABLE 2-18 (CONTINUED)
Ecotox Thresholds for 67 Chemicals Commonly Found at Superfund Sites

		Surface Water (µg/L)			Sediment (mg/kg)			
		Freshwater		Marine	EPA SQC [c]			
CAS Registry No.	Chemical	AWQC or FCV[a]	Tier II [b]	AWQC or FCV[a]	Fresh-water	Marine	EPD SQB [d]	ERL[e]
79345	Tetrachloroethane 1,1,2,2-		420 *				0.94	
127184	Tetrachloroethylene		120 *				0.53	
56235	Tetrachloromethane		240 #				1.2	
108883	Toluene		130 *				0.67	
8001352	Toxaphene		0.011	0.21			0.028	
75252	Tribromomethane		320 #				0.65	
120821	Trichlorobenzene 1,2,4-		110 #				9.2	
71556	Trichloroethane 1,1,1-		62 *				0.17	
79016	Trichloroethylene		350 *				1.6	
108383	Xylene, m-		1.8 #				0.025	

[a]EPA chronic ambient water quality criteria (AWQC) or EPA-derived final chronic values (FCVs) (EPA, 1986b, 1986c, 1987). Metals concentrations are for total dissolved chemical.

[b]Values calculated by using Great Lakes Water Quality Initiative Tier II methodology (40 Code of Federal Regulations [CFR] 9, 122, 123, 131, and 132, 1995).

[c]EPA Sediment Quality Criteria (SQC) assumes 1 percent organic carbon (EPA, 1993d). Values are lower limit of 95 percent confidence interval.

[d]Sediment quality benchmarks (SQBs) by equilibrium partitioning assumes 1 percent organic carbon (EPA, 1996).

[e]ERL = Effects Range - Low (Long *et al.*, 1995).

Notes:

h	=	Hardness-dependent ambient water quality criterion (100 mg/L as $CaCO_3$ used).
pH	=	pH-dependent ambient water quality criterion (7.8 pH used).
S	=	Final chronic value calculated using Great Lakes Water Quality Initiative Tier I methodology.
F	=	Final chronic value derived for EPA Sediment Quality Criteria documents (EPA, 1993e).
t	=	Value is for total of all chemical forms.
*	=	Value as calculated in Suter and Mabrey, 1994.
+	=	Value with EPA support documents.
#	=	Value calculated by using methods described in Suter and Mabrey, 1994.

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Toxicity Testing Approaches

Traditional analytical methods to determine the concentrations of chemicals in environmental media (water, soil, or sediments) do not necessarily provide data that can be directly correlated to toxic responses in wetland organisms. Additional chemical analytical techniques such as EqP and AVS approaches can be used to strengthen predictions of media toxicity (MacDonald and Salazar, 1994). Even when contaminated media are well characterized, toxicological response information for particular contaminants and organisms may be lacking. Toxicity tests provide a way to reduce uncertainty of predictions by determining whether the contaminant concentrations in the media are high enough to cause measurable adverse effects in living organisms.

Most toxicity tests are conducted under controlled conditions in the laboratory by using test organisms exposed to media samples collected from the site. Some toxicity tests are conducted *in situ* by exposing test organisms or caged indigenous organisms to soil, sediment, or water on the site. The advantages of toxicity tests are that they can (EPA, 1994b):

- Demonstrate whether contaminants are bioavailable
- Evaluate the aggregate toxic effects of all contaminants in a medium, even those substances whose biological effect may not be well documented
- Characterize the nature of a toxic effect
- Characterize the distribution of toxicity in different media at a site
- Help establish remedial goals and monitoring locations at a site
- Help determine a site's potential to support viable ecological communities after remediation

Toxicity tests use various test organisms under standard methods and conditions to determine acute or chronic toxicity levels in a particular environmental medium. For aquatic environments, standard test practices have been documented for field sampling and toxicity testing for water and sediment (American Society for Testing and Materials [ASTM], 1993).

The choice of test methods and test organisms should be based on the investigator's knowledge of actual site conditions, ecological community structure, and the objectives of the test. The following general guidelines have been suggested for choosing toxicity tests (EPA, 1994b):

- Toxicity tests should only be used when they are capable of detecting or measuring an effect from the contaminants of concern
- Where several contaminants may be in the waste stream, aquatic toxicity testing should include more than one type of organism (i.e., a fish *and* an invertebrate species)
- Test organisms that are sensitive to the site contaminants should be selected
- When testing water, a test organism that can tolerate the water conditions should be used.

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Seven different toxicity tests (SOS-chromotest, bacterial luminescence, algal growth inhibition, seed germination/root elongation, seed germination and emergence, earthworm survival, and nematode survival and maturation) were evaluated for their suitability to assess toxicity of solid and liquid wastes associated with oil sand processing (Gulley *et al.*, 1995). The evaluation indicated the importance of choosing a toxicity test method that is sensitive enough to show treatment effects. *In situ* toxicity tests that use caged individuals of *Ceriodaphnia dubia* and *Chironomus tentans* also have shown potential for evaluating toxicity of wastewater from oil sand processing and toxicity reductions in treatment wetlands (Barjaktarovic *et al.*, 1995).

New toxicity tests using duckweed (*Lemna minor*) may be more sensitive than tests using *Ceriodaphnia dubia* or fathead minnows in assessing the toxicity of industrial effluents (Taraldsen and Norberg-King, 1990). Other organisms have been used or suggested for assessment of hydrocarbon toxicity, including bacteria *(Salmonella typhimurium)* (Marvin *et al.*, 1995) and marine bivalves (*Mytilus* spp.) (Arnold and Biddinger, 1995). *Mytilus* may be a particularly well-suited test organism for assessing oil refinery wastes because it has less developed PAH metabolic capabilities than fish or crustaceans and can accumulate PAHs more readily. In addition, a bioconcentration model and sublethal critical body residue (CBR) data exist that enable prediction of PAH bioconcentration and assessment of risk from tissue PAH concentrations (Arnold and Biddinger, 1995).

Three different test organisms (*Ceriodaphnia dubia*, Pimephales promelas [fathead minnow], and *Selenastrum capricornutum*, [a freshwater alga]) were compared for use in an assessment of urban stormwater runoff toxicity. The comparison indicated that *Ceriodaphnia dubia* was the most sensitive of the three organisms to the contaminants in the stormwater runoff. The sensitivity of *Ceriodaphnia dubia* was attributed to concentrations of the insecticide diazinon in the runoff, which was likely the primary cause of toxicity (Katznelson *et al.*, 1995).

A sediment-dwelling microinvertebrate, *Hyallela azteca*, was used to monitor toxicity of urban stormwater runoff in treatment ponds but did not appear to be a particularly sensitive indicator species. Even though analysis of the macroinvertebrate communities indicated that several ponds were degraded by stormwater runoff, the *Hyallela azteca* toxicity tests did not reveal toxic effects (Karouna-Reiner, 1995). No significant differences in survival and amphipod weight between test and control samples were observed.

Wetland Effects on Effluent Toxicity

Comparison of toxicity reductions in treatment wetlands from different studies is complicated by a wide array of conditions in wastestream contaminants and loading rates, treatment wetlands, and test organisms. In addition, investigators use toxicity tests to answer different questions depending on the objectives of their studies. The methods of sample collection and data summary are often different. Table 2-19 summarizes reported information on toxicity reduction by treatment wetlands and descriptions of selected constructed wetlands follows.

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In studies of a pilot-scale subsurface flow and surface flow treatment wetlands at a U.S. refinery, reductions in chronic toxicity to fathead minnows, *Pimephales promelas*, were found to be positively related to hydraulic retention time (HRT). More than 50 percent of the toxicity was removed using a 12-hour HRT, with increasing but smaller incremental reductions using 24-, 36-, and 48-hour HRTs. Nearly all toxicity to fathead minnows was removed with the 48-hour HRT.

At a non-U.S. oil terminal, toxicity tests on the influent and of the treatment wetlands effluent (at 100 percent concentration) using the Microtox™ (bacteria luminescence) test organism reduced EC_{50}[1] values by 98 percent (Farmer, 1996 [unpublished]).

A full-scale surface flow constructed wetlands at the Chevron refinery in Richmond, California, has used rainbow trout to assess effluent toxicity and has consistently shown no mortality (Duda, 1992).

Seven-day toxicity tests were conducted on laboratory-scale wetlands by using zinc-amended water to simulate wastewater from an oil refinery in St. Charles, Louisiana. The study results indicate that zinc removal (average of 80 percent) from the water resulted in a decrease in toxicity to *Ceriodaphnia dubia* from the influent to the effluent. With an average influent zinc concentration of 1.70 mg/L, the 7-day LC_{50}[2] increased from 155 mg/L to 189 mg/L due to wetland treatment. Toxicity responses were determined to be similar for static-renewal and flow-through laboratory tests. The 7-day static renewal tests indicated that at zinc concentrations of 1.7, 0.85, and 0.43 mg/L, *Ceriodaphnia dubia* survival in wetland influent samples was zero, while survival in the wetland effluent samples was approximately 23 percent, 38 percent, and 88 percent, respectively. At a zinc concentration of 0.22 mg/L, influent and effluent survival rates were approximately 10 percent and 98 percent , respectively. When the zinc concentration was 0.11 mg/L, influent and effluent survival was around 88 percent and 100 percent, respectively (Hawkins *et al.*, 1995).

A pilot-scale wetland has been used to treat wastewater from an oil sand processing facility at Fort MacMurray, in Alberta, Canada. Studies indicate that the treatment wetlands have reduced toxicity to the aquatic invertebrate *Dapnia magna* (Gulley and Nix, 1993; Nix and Gulley, 1995; Bishay *et al.*, 1995b), as well as the luminescent bacteria Microtox™ (Bishay *et al.*, 1995b).

Champion International tested pilot wetlands for effluent polishing at their Cantonment, Florida, bleached kraft paper mill (Knight, 1994, unpublished data). Whole water toxicity was measured with a cladoceran, *Ceriodaphnia dubia,* and fathead minnows by using 7-day chronic tests. No acute toxicity was found; however, chronic toxicity in the wetland influent was significantly reduced in the wetland effluents. Chronic toxicity measured with the cladoceran was reduced between the influent (chronic

[1] EC_{50} The concentration shown to cause a negative effect in 50 percent of the organisms

[2] LC_{50} The concentration shown to cause death in 50 percent of the organisms

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TABLE 2-19
Summary of Toxicity Reduction in Constructed Wetlands

Description	Toxicity Measurement In	Out	Reduction (%)	Reference
EC_{50} (as a percentage of control) to reduce luminescence of the bacteria Microtox™ on wastewaters from an oil terminal	1.8	88	98	Farmer, 1996 (unpublished)
LC_{50} for *Ceriodaphnia dubia* (static-renewal, 7-day tests) on laboratory-scale wetlands for Zn-amended water to simulate wastewater in study of St. Charles, Louisiana, oil refinery **(average 1.70 mg/L zinc)**	0.155 µg/L	0.189 µg/L	22	Hawkins *et al.*, 1995
Percent survival for *Ceriodaphnia dubia* [a]				Hawkins *et al.*, 1995
Control (no zinc)	100	93	-7	
1.70 mg/L zinc	0	23	--	
0.85 mg/L zinc	0	38	--	
0.43 mg/L zinc	0	88	--	
0.22 mg/L zinc	10	98	90	
0.11 mg/L zinc	88	100	12	
Percent survival for *Daphnia magna* on pilot-scale wetlands used to treat wastewaters from oil sands processing facility Alberta, Canada				Bishay *et al.*, 1995b (values estimated from graph)
Ditch (reference water consisting of surface runoff and groundwater seepage)	75	63	16	
Dike (seepage from saturated tailings)	61	80	31	
Pond (tailing ponds top water with highest expected contaminant levels)	0	63	--	
Percent production relative to control of *Daphnia magna* on pilot-scale wetlands used to treat wastewaters from oil sands processing facility Alberta, Canada				Bishay *et al.*, 1995b (values estimated from graph)
Ditch (reference water consisting of surface runoff and groundwater seepage)	113	82	32	
Dike (seepage from saturated tailings)	115	138	20	
Pond (tailing ponds top water with highest expected contaminant levels)	0	123	--	

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TABLE 2-19 (CONTINUED)
Summary of Toxicity Reduction in Constructed Wetlands

Description	Toxicity Measurement In	Toxicity Measurement Out	Reduction (%)	Reference
EC_{50} (as a percentage of control) to reduce luminescence of the bacteria *Microtox*™ on pilot-scale wetlands used to treat wastewaters from oil sands processing facility, Alberta, Canada				Bishay *et al.*, 1995b
Ditch (reference water consisting of surface runoff and groundwater seepage)	>100%	>100%	--	
Dike (seepage from saturated tailings)	63.8%±3.7%	75.1%±17.8	18	
Pond (tailing ponds top water with highest expected contaminant levels)	37.6%±3.8%	84.8%±9.5%	126	
Ceriodaphnia dubia reproduction (number of offspring) tests in water from treatment wetlands receiving municipal wastewater, Collins, Mississippi	0	31.1 29.6 (control)	100	McAllister, 1992
Ceriodaphnia dubia survival (%) tests in water from treatment wetlands receiving municipal wastewater, Collins, Mississippi	0	100 100 (control)	100	McAllister, 1992
Ceriodaphnia dubia time toxicity (LT_{50}) tests from wetlands receiving municipal wastewater, Almeda Co., California. (**toxicity intensity factor** = 168 hours - LT_{50})[b]				
10/27/91 (2 inches rainfall) at 30 hours after storm (before log baffle)	123	113	8	WCC, 1994; 1995
11/18/91 (0.2 inch rainfall) at 30 hours after storm (before log baffle)	63	16	75	
10/30/92 (1.2 inches rainfall) at 30 hours after storm (before log baffle)	120	74	38	
11/1/92 at 80 hours after storm (before log baffle)	81	103	-27	
12/7/92 (0.7 inch rainfall) at 30 hours after storm (before log baffle)	104	32	69	
12/10/92 at 90 hours after storm (before log baffle)	114	110	4	
12/11/92 (0.7 inch rainfall) at 30 hours after storm (before log baffle)	106	52	51	
12/13/92 at 90 hours after storm (before log baffle)	63	70	-11	
4/18/93 (0.5 inch rainfall) at 30 hours after storm (log baffle installed)	151	0	100	
4/20/93 at 80 hours after storm (log baffle installed)	118	8	93	
11/28/93 (0.4 inch rainfall) at 4 hours after storm	133	0	100	

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TABLE 2-19 (CONTINUED)
Summary of Toxicity Reduction in Constructed Wetlands

Description		Toxicity Measurement In	Out	Reduction (%)	Reference
11/29/93	at 20 hours after storm (log baffle installed)	84	0	100	
11/30/93 (0.3 inch rainfall)	at 50 hours after 11/28/93 storm (log baffle installed)	42	0	100	
12/2/93	at 100 hours after 11/28/93 storm (log baffle installed)	63	0	100	
4/9/94 (0.6 inch rainfall)	at 13 hours after storm (log baffle installed)	51	0	100	
4/9/94	at 18 hours after storm (log baffle installed)	37	0	100	
4/10/94	at 40 hours after storm (log baffle installed)	MT	0	100	
4/12/94	at 90 hours after storm (log baffle installed)	0	0	100	

[a]Percent survival of *Ceridaphnia dubia* was estimated from graph.

[b]The toxicity index reported for **In** is the highest value (i.e., most toxic) from all stations sampled at a given time. The **Out** toxicity index is always reported for the last station (No.9) within the wetland.

MT marginally toxic

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values between 12.5 to 65 percent) and the wetland effluent (chronic values from 17.8 to >100 percent). Inflow samples were chronically toxic to fathead minnows in two of three samples, and no toxicity was observed for the minnows in the wetland outflow samples. Reduction of chronic toxicity to cladocerans and minnows was strongly related to hydraulic loading rate to the wetlands.

In Mississippi, toxicity related to two municipal wastewater treatment wetlands was evaluated by using acute and chronic tests with *Ceriodaphnia dubia.* No significant toxicity effects were noted for one of the systems. The other system showed 100 percent mortality (no survival or reproduction) in the wetland influent, but survival and reproduction rates in the effluent were comparable to controls. Fathead minnow acute toxicity tests showed no effects for either system (McAllister, 1992).

In an evaluation of two municipal wastewater treatment wetlands in the arid western United States, no significant toxicity effects were noted for the fathead minnow. One of the systems showed no significant effect on survival of *Ceriodaphnia dubia,* whereas significant reduction in reproduction and nonsignificant reduction in survival occurred in the other system (McAllister, 1993a).

In Florida, two municipal wastewater treatment wetlands were evaluated but no statistically significant toxicity effect was noted at either site for *Ceriodaphnia dubia* acute or chronic tests. One of the Florida treatment wetlands was also tested with fathead minnows, but no acute toxicity effect was noted (McAllister, 1993b).

A brackish marsh treatment system for urban stormwater runoff was monitored by using 7-day *Ceriodaphnia dubia* tests from 1991 through 1994. Reductions in effluent toxicity were observed at various stations throughout the wetland. The study demonstrated that effluent toxicity was effectively controlled by the marsh only after a log-baffle was installed to eliminate short circuiting and promote mixing. With the installation of the log-baffle, most of the stormwater toxicity was entirely reduced within the wetland (WCC, 1994; 1995).

Low levels of various hydrocarbons in wastewaters have not caused stress in cattails (*Typha* spp.) or bulrushes (*Schoenoplectus* spp.) (Nix and Gulley, 1995; Hall, 1996). However, very strong effluents have caused acute toxicity to *Typha* and *Schoenoplectus* and especially to *Phragmites australis* (Altman *et al.*, 1989).

In summary, treatment wetlands have been found to generally reduce acute and chronic toxicity to both cladocerans and some fish species in almost every case studied. The magnitude of toxicity reduction is typically inversely related to the wastewater loading rate and directly related to the effectiveness of mixing (water flow distribution) within the treatment wetland. These general observations suggest that toxicity reductions in treatment wetlands are likely a secondary benefit of the myriad of pollutant removal processes in these complex biological systems.

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Nutrient Removal

Nitrogen

Processes

Nitrogen is a key element in biogeochemical cycles. Nitrogen occurs in a number of different oxidation states in wastewaters and in treatment wetlands, and numerous biological and physio-chemical processes can transform nitrogen among these different forms (Figure 2-16).

The dominant nitrogen forms of importance to wastewater treatment in wetlands include organic nitrogen, ammonia nitrogen, nitrate and nitrite nitrogen, and nitrogen gases (di-nitrogen gas [N_2] and di-nitrogen oxide [N_2O]). A fraction of organic nitrogen is readily mineralized to total ammonia nitrogen in aquatic and wetland environments. Total ammonia nitrogen is distributed as the ionized form (ammonium) and a smaller percentage as un-ionized ammonia, based on water temperature and pH. Un-ionized ammonia is volatile and may be lost directly to the atmosphere. Ammonium nitrogen can be oxidized to nitrite and nitrate nitrogen through an aerobic microbial process called *nitrification*. Free dissolved oxygen and carbonate alkalinity are consumed in this process. Ammonium nitrogen may also be biologically assimilated and reduced back to organic N or may be removed from the dissolved form by adsorption to solid surfaces, including wetland sediments. This adsorbed ammonium is readily released back to the dissolved state under anaerobic conditions.

Nitrite nitrogen is converted to nitrate nitrogen under aerobic conditions. Free dissolved oxygen is utilized in this process. Nitrate nitrogen is readily transformed to di-nitrogen gas in treatment wetlands through a process called denitrification. Denitrification occurs in the absence of free oxygen, primarily in wetland sediments where available organic carbon is high. Organic carbon is consumed in this microbial process, and alkalinity is produced. In turn, atmospheric di-nitrogen gas can be microbially fixed as organic N through the process of nitrogen fixation.

Because of the complex transformations affecting nitrogen forms in wetlands, a sequence of reactions must be considered to adequately describe treatment performance, even on the most elementary level. Figure 2-17 illustrates these major interconversions. Mass balance equations for inter-related reactions relating to plug flow hydraulics in treatment wetlands have been compiled (Kadlec and Knight, 1996).

Performance

Nearly all treatment wetlands studies have reported reductions in total nitrogen and organic nitrogen. Figure 2-18 illustrates the range of possible TN outflow concentrations observed over the range of inlet TN loadings in the NADB and LWDB. Figure 2-19 is a similar plot for total ammonia N in treatment wetlands. Both of these figures show no major difference between the performance of natural and constructed treatment wetlands for nitrogen forms.

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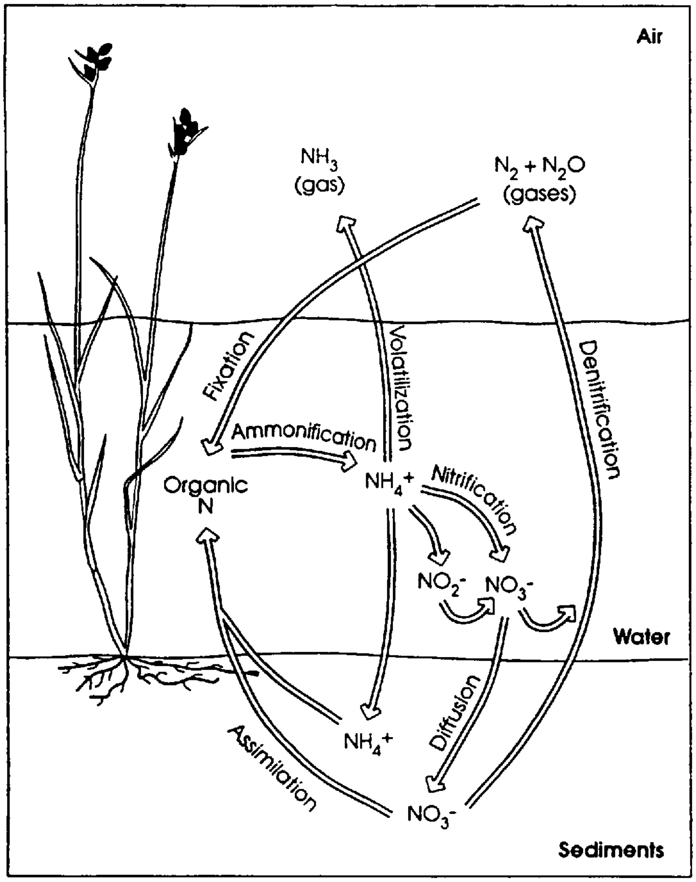

FIGURE 2-16
Nitrogen Transformation Processes in Wetlands
Source: Kadlec and Knight, 1996.

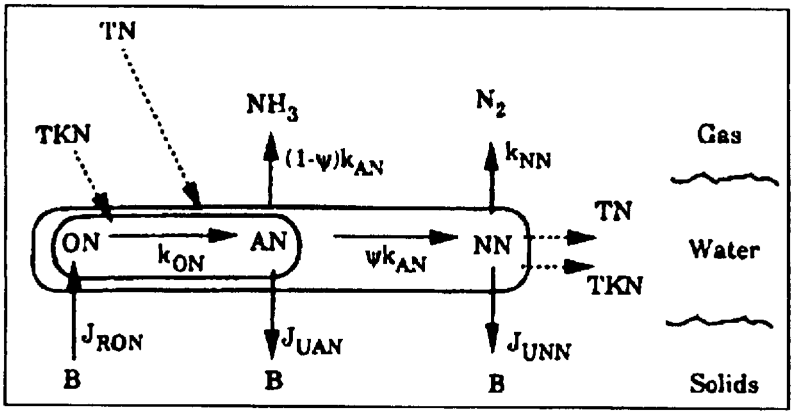

FIGURE 2-17
Simplified Reaction Sequence and Transfer Network for Nitrogen in the Wetland Environment
Organic nitrogen (ON) may be ammonified to ammonium nitrogen (AN). The wetland contributes organic nitrogen from decomposition of biomass (B). Ammonium may be lost by volatilization of ammonia, nitrification, sorption, and plant uptake. Nitrate (NN) is formed by nitrification and lost by denitrification and uptake. Transfers to and from the wetland sediments and biomass are denoted by the fluxes (J). The first-order areal rate constants are denoted by k.
Source: Kadlec and Knight, 1996.

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In a number of cases, outflow concentrations of ammonium or nitrate N have been found to be higher than inflow concentrations. This concentration increase rarely occurs for organic or total N. The conclusion from these observations is that while the sequential nitrogen transformation processes result in an overall one-directional conversion of elevated total and organic nitrogen forms to oxidized or gaseous nitrogen forms in treatment wetlands, these processes can also lead to increasing concentrations of intermediate nitrogen forms as the result of temporal, spatial, or chemical limitations. Figure 2-20 illustrates this series of transformations with transect data from one treatment wetland system.

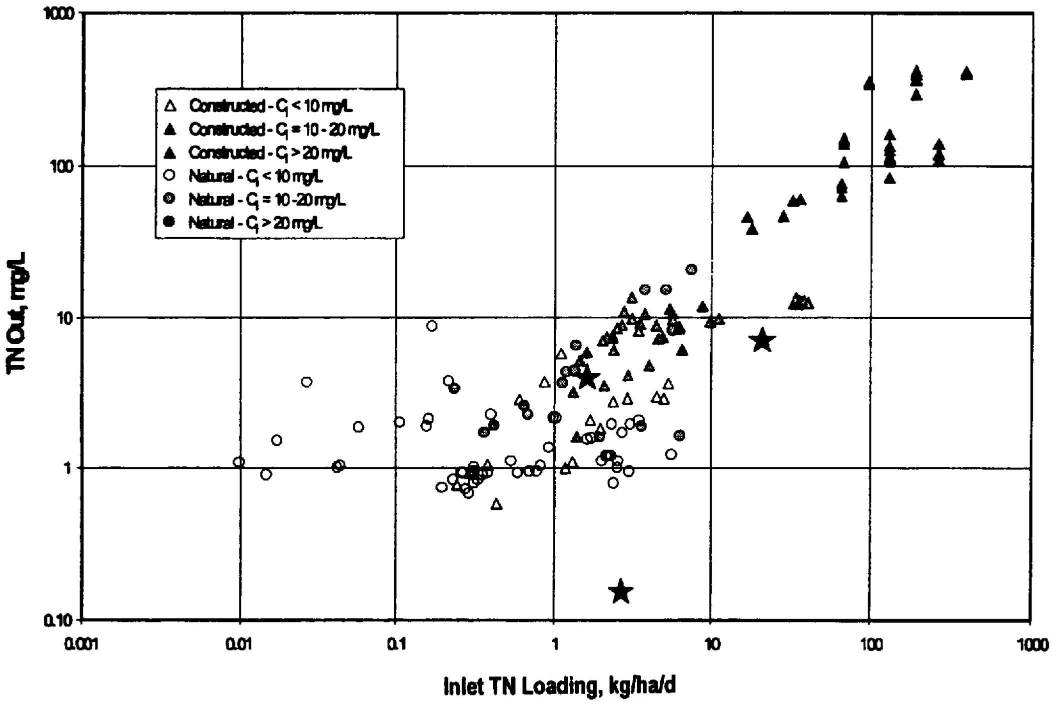

FIGURE 2-18
Annual TN Performance Data (o and –)
Data are for 58 free-water surface treatment wetland systems at 27 sites in the NADB and LWDB. Petroleum industry data are highlighted (†). Data from both natural and constructed wetlands are plotted over the range of recorded inlet concentrations (C_i).

The sequential k-C* model represents this process reasonably well and can be used to compare rate constants among wetland systems (Table 2-20). Table 2-21 presents average global rate constants, background concentrations, and temperature correction values for nitrogen forms (Kadlec and Knight, 1996).

Petroleum industry data for nitrogen forms are summarized in Table 2-22. Because flow data or data for variable operational conditions are limited, they cannot be used to calibrate the k-C* model. Values for the one parameter rate constant k_1 are summarized in Table 2-22. These rate constant values are comparable to or higher than values for other treatment wetlands.

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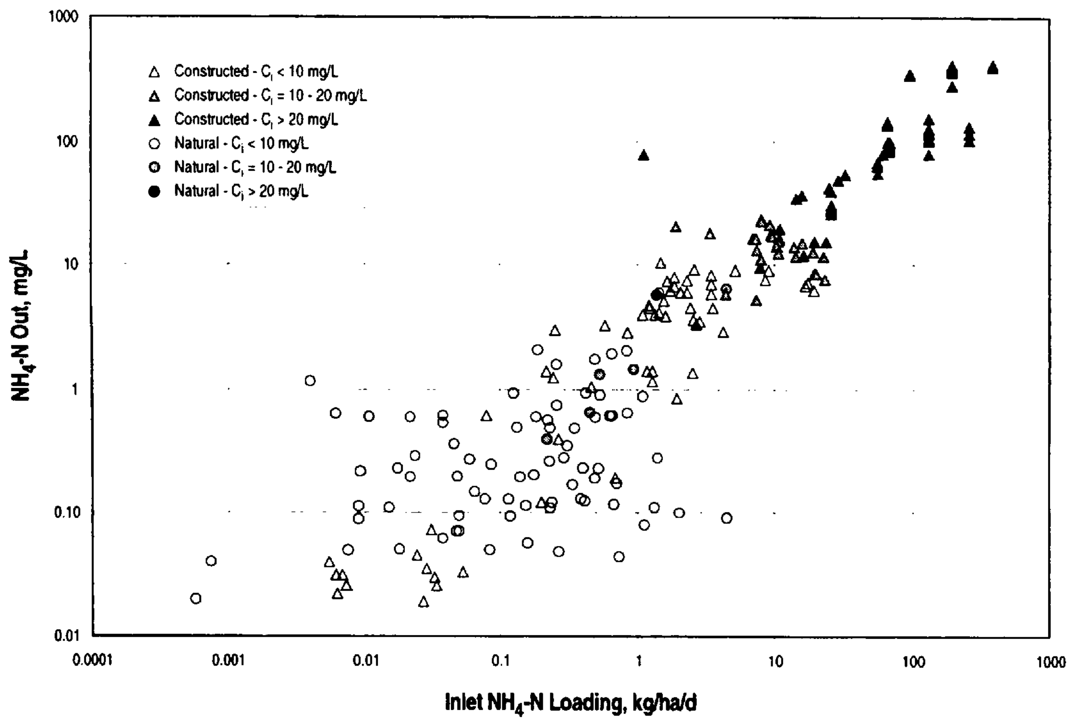

FIGURE 2-19
Annual NH_4-N Performance Data
Data are for 77 free water surface treatment wetland systems at 40 sites in the NADB and LWDB. Data from both natural and constructed wetlands are plotted over the range of recorded inlet concentrations (C_i).

Rate constants for individual treatment wetland systems are variable because of a variety of factors described above that have not yet been well quantified. General observations are that ammonium N removal performance is significantly retarded by low dissolved oxygen conditions in the wetland water column. Likewise, nitrate nitrogen removal performance may be retarded by elevated dissolved oxygen concentrations.

The effect of low available organic carbon on denitrification in lightly loaded surface flow treatment wetlands has not been quantified.

Treatment wetland input/output data can also be summarized by use of a regression model. Comparing linear and log normal regressions of the surface flow nitrogen data in the NADB and incorporating hydraulic loading rate and concentration produces the regression equations in Table 2-23 (Kadlec and Knight, 1996). Low correlation coefficients for these data indicate the importance of other factors not included in these simple regression models.

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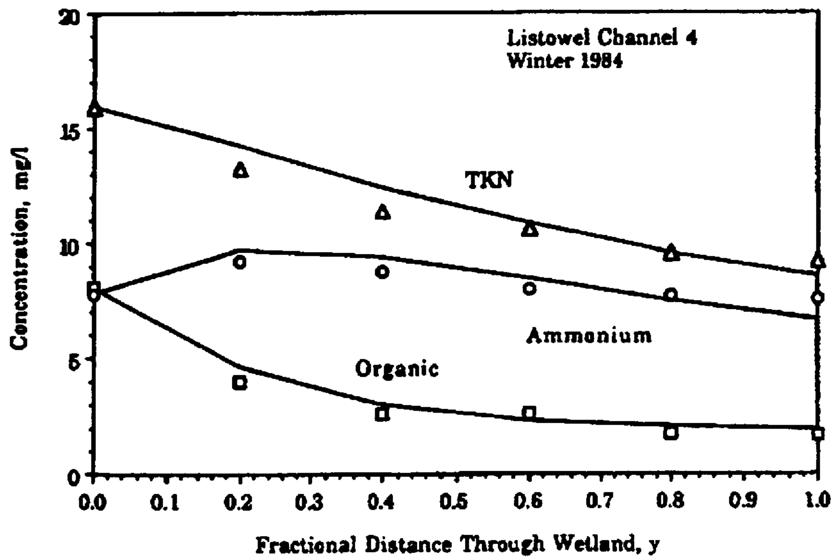

FIGURE 2-20
Profiles of Major Dissolved Nitrogen Species
Lines are for model calibration; symbols denote data points that are averages of biweekly data collected over 3 months.
Source: Kadlec and Knight, 1996.

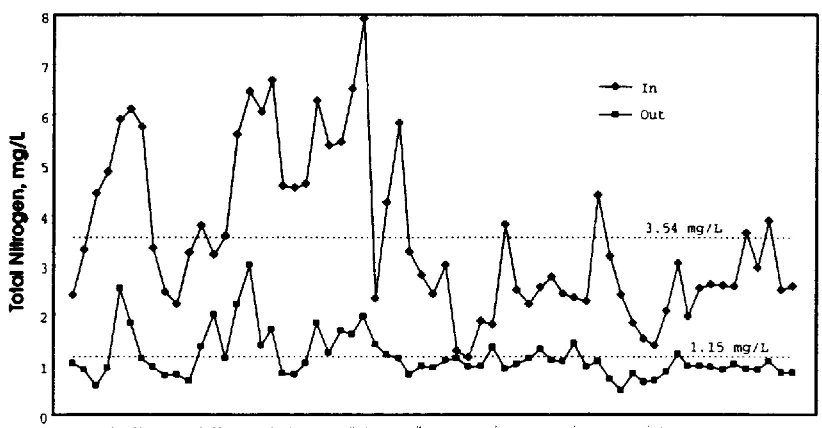

FIGURE 2-21
Range of Inlet and Outlet TN Concentrations for Cells 1 through 12 at the Iron Bridge Surface Flow Treatment Wetland Near Orlando, Florida
Source: PBSJ, 1989-93.

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TABLE 2-20

Nitrogen Rate Constants for Surface Flow Treatment Wetlands

						Total N				Org N				NH_4-N				NO_x-N			
Location	Wetland	Type	Data Qtrs.	Temperature (°C)	HLR (cm/d)	In (mg/L)	Out (mg/L)	k_{TN} (m/yr)	C^*_{TN} (mg/L)	In (mg/L)	Out (mg/L)	k_{OrgN} (m/yr)	C^*_{OrgN} (mg/L)	In (mg/L)	NH_4-N Out (mg/L)	Apparent k_{NH4} (m/yr)	Sequential k_{NH4} (m/yr)	NO_x-N In (mg/L)	NO_x-N Out (mg/L)	Apparent k_{NOx} (m/yr)	Reference
Surface-Flow Marshes																					
Listowel, Ontario	1	CM	16	8.0[a]	2.67	12.77	8.70	4.36	1.5	5.10	2.89	7.3	1.5	7.40	5.30	3.3	14.1				Herskowitz, 1986
	2	CM	16	8.0[a]	2.84	12.77	9.18	3.55	0.4	5.10	3.23	4.3	0.4	7.40	5.66	2.8	6.8				Herskowitz, 1986
	3	CM	16	7.84	1.92	12.77	7.14	5.09	1.5	5.10	2.54	7.9	1.5	7.40	4.37	3.7	7.9				Herskowitz, 1986
	4	CM	16	8.02	1.95	18.92	9.49	5.56	1.5	9.97	2.79	18	2.1	8.58	6.43	2.1	6.0				Herskowitz, 1986
	5	CM	16	8.0[a]	2.6	18.92	12.15	4.63	1.4	9.97	3.49	12.5	1.4	8.58	8.45	0.1	5.0				Herskowitz, 1986
Cobalt, Ontario	1	CM	5	0.4[a]	5.31					3.04	1.15	21.7	0.2								Miller, 1989
Cobalt, Ontario	1	CM	4		7.5	7.33	2.84	40.25	1.5												Miller, 1989
Benton, Kentucky	1	CM	4	16.14	1.71					8.71	2.61	11.7	1.7	5.04	7.89	-2.8	1.7				Choate *et al.*, 1990
	2	CM	4	17.75	1.71					8.71	3.08	8.9	1.5	5.04	6.43	-1.5	2.6				Choate *et al.*, 1990
Benton, Kentucky	1	CM	7		6.23	13.3	9.81	7.97	1.5												Choate *et al.*, 1990
	2	CM	7		6.23	14.05	9.44	10.41	1.5												Choate *et al.*, 1990
Gustine, California	1A	CM	4	17[a]	4.19	31.36	25.28	3.48	1.5	15.50	9.52	7.5	b	17.65	19.97	-1.4	1.9				Walker and Walker, 1990
	1B	CM	4	17[a]	2.09	31.36	26.26	1.43	1.5	16.22	6.08	7.5	b	17.65	19.97	-1.4	1.9				Walker and Walker, 1990
	1C	CM	4	17[a]	1.05	35.61	30.94	0.56	1.5	14.39	8.08	2.2	b	17.65	19.97	-1.4	1.9				Walker and Walker, 1990
	1D	CM	4	17[a]	4.19	40.52	33.77	2.90	1.5	18.05	8.09	12.3	b	17.65	19.97	-1.4	1.9				Walker and Walker, 1990
	2A	CM	4	17[a]	4.46	47.67	34.95	5.25	1.5	26.85	8.89	18.0	b	17.65	19.97	-1.4	1.9				Walker and Walker, 1990
West Jackson Co., Mississippi	1-7	CM	11	18[a]	2.42					7.77	2.22	b	2.6								NADB, 1993
West Jackson Co., Mississippi	1-7	CM	2		2.41	8.26	3.9	9.11	1.5												NADB, 1993
Richmond, New South Wales	1	OW	8	19.70	6.41					8.29	6.90	4.3	0.0	35.20	17.50	15.4	16.9				Bavor *et al.*, 1988
Des Plaines, Illinois	EW3	CM	6	20.2	9.66													1.66	0.75	28.3	Hey *et al.*, 1994
	EW4	CM	6	19.8	1.40													1.65	0.21	10.5	Hey *et al.*, 1994
	EW5	CM	6	21.1	6.02													1.66	0.73	18.1	Hey *et al.*, 1994
Des Plaines, Illinois	EW3	CM	5		8.14	2.72	1.68	21.49	0.7												NADB, 1993
	EW4	CM	5		1.44	2.71	1.21	7.21	0.7												NADB, 1993
	EW5	CM	5		6.32	2.71	1.53	20.40	0.7												NADB, 1993
Lakeland, Florida	1	CM	21	2.6[a]	3.71	11.01	3.72	19.70	1.5									6.62	1.14	23.8	NADB, 1993
	2	CM	16		3.37	3.83	2.54	8.77	1.3												NADB, 1993
	3	CM	15		1.44	2.54	1.6	7.46	1.3												NADB, 1993
Sea Pines, South Carolina	1	NM	15	18.7[a]	2.72													6.92	0.52	25.8	NADB, 1993
Ames, Iowa	40 cells	CM		20[a]	Batch													3 to 20	0.00	63.0	Crumpton *et al.*, 1993
Orange Co., Florida	1	CM	11		1.38	2.3	1.39	4.70	0.8												NADB, 1993
Iron Bridge, Florida	1-12	CM	16		2.68	3.41	1.09	18.15	0.7												NADB, 1993
Fort Deposit, Alabama	1-2	CM	1		0.82	10.88	3.6	4.48	1.5												NADB, 1993
Leaf River, Mississippi	1	CM	2		9.72	11.71	8.3	14.42	1.5												NADB, 1993
	2	CM	2		12.65	14.58	9.26	24.11	1.5												NADB, 1993
	3	CM	1		13.32	14.58	7.34	39.20	1.5												NADB, 1993

TABLE 2-20 (CONTINUED)

Surface Flow Treatment Wetland Nitrogen Rate Constants

Total N	Org N	NH_4-N	NO_x-N

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Location	Wetland	Type	Data Qtrs.	Temperature (°C)	HLR (cm/d)	In (mg/L)	Out (mg/L)	k_{TN} (m/yr)	C^*_{TN} (mg/L)	In (mg/L)	Out (mg/L)	$k_{Org N}$ (m/yr)	$C^*_{Org N}$ (mg/L)	In (mg/L)	NH_4-N Out (mg/L)	Apparent k_{NH4} (m/yr)	Sequential k_{NH4} (m/yr)	NO_x-N In (mg/L)	NO_x-N Out (mg/L)	Apparent k_{NOx} (m/yr)	Reference
Santa Rosa, California	1	CM	1		16.83	16.17	9.57	36.71	1.5												NADB, 1993
	2	CM	1		16.83	9.57	4.24	66.36	1.5												NADB, 1993
	3	CM	1		16.83	4.24	2.59	56.62	1.5												NADB, 1993
	4	CM	1		16.83	2.59	2.51	4.68	1.5												NADB, 1993
Forested Surface Flow																					
Reedy Creek, Florida	WTS1	FOR	37		3.57	7.88	1.88	22.65	0.6												NADB, 1993
Reedy Creek, Florida	OFWTS	FOR	28		5.63	8.24	1.24	50.10	0.6												NADB, 1993
Reedy Creek, Florida	WTS1	FOR	34	22.3[a]	3.57													3.66	0.42	28.2	NADB, 1993
Reedy Creek, Florida	OFWTS	FOR	28	22.3[a]	5.63													3.82	0.25	56.0	NADB, 1993
Reedy Creek, Florida	WTS1	FOR	42	22.30	3.51					1.86	0.80	34.3	0.7								NADB, 1993
Central Slough, South Carolina	1	FOR	17		0.56	16.12	4.16	3.48	1.5												NADB, 1993
Poinciana, Florida	1	FOR	9		0.20	6.24	2.80	0.78	1.0												NADB, 1993
Vereen, South Carolina	1	FOR	12		0.37	16.69	2.81	2.92	1.0												NADB, 1993
Vereen, South Carolina	1	FOR	17	17.40	0.36					2.46	2.24	[b]	2.6								NADB, 1993
Drummond, Wisconsin	1	FOR	6		2.30	9.06	2.13	15.91	0.9												NADB, 1993
Floating/Submergent Aquatics																					
New Zealand	2 Wetland	FAP	7	15	5.52	197.00	102.00	13.41	1.5	16.00	2.70	50.2	1.5	60.00	37.00	9.7	15.3	121.00	64.00	12.8	van Oostrom and Cooper, 1990
New Zealand	Pilot	FAP	8	15	7.34													35.20	24.00	10.3	van Oostrom, 1994
Richmond, NSW	4	SAB	8	17.16	7.34	44.07	26.04	14.76	1.5	8.29	1.59	45.5	0.0	35.20	24.00	10.3	14.7				Bavor *et al.*, 1988
Hyacinth Pilot, California	1	FAP	igh	≈ 25	40.80									27.42	8.25	178.9	37.3				Weber and Tchobanoglous, 1986
Hyacinth Pilot, California	1	FAP	ow C	≈ 25	44.00									6.45	1.65	218.9	≈ 300				Weber and Tchobanoglous, 1986

[a] Estimated as mean annual, mean daily air temperature.

[b] Data range precludes an accurate parameter estimate.

CM constructed marsh
FAP floating aquatic plant
FOR natural forested
NM natural marsh
NO_x nitrate and nitrite nitrogen
OW open water
SAB submerged aquatic bed

Source: Adapted from Kadlec and Knight, 1996.

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TABLE 2-21
Average Rate Constants, Background Concentrations, and Temperature Correction Values for Nitrogen

	Surface Flow			Subsurface Flow		
Parameter	**k (m/yr)**	**C* (mg/L)**	**θ**	**k (m/yr)**	**C* (mg/L)**	**θ**
Org-N	17	1.5	1.05	35	1.5	1.05
NH_4^+-N	18	0.0	1.04	34	0.0	1.04
NO_3-N	35	0.0	1.09	50	0.0	1.09
TN	22	1.5	1.05	27	1.5	1.05

Source: Kadlec and Knight, 1996.

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TABLE 2-22
Petroleum Industry Treatment Wetland Operating Data for Nitrogen Forms

TN	Wetland Size	Wetland Type	Concentration IN (mg/L)	Concentration OUT (mg/L)	Reduction (%)	k_1 (m/yr)	Reference
Amoco, Mandan, North Dakota	16.6 ha	FWS					Litchfield and Schatz, 1989
Texaco A	400 m²	FWS	8.1	0.05	99	93	Hall, 1996
Texaco B	400 m²	FWS	5.3	0.2	96	60	Hall, 1996
Chevron, Richmond, California 1989-91	36 ha	FWS					Duda, 1992
1992-95	36 ha	FWS					Chevron, 1996
Suncor, Fort McMurray, Alberta	500 m²	FWS					Gulley and Nix, 1995
1994	500 m²	FWS	16.2	4.3	74	5	Bishay *et al.*, 1995
Non-USA Oil Terminal	600 m²	SSF	3.2	1.8	44		Farmer, 1996
Yanshan Pilot, P.R. China	1.5 ha	FWS			21		Dong and Lin, 1994
Yanshan Pond/Wetland, P.R. China	25 ha	FWS	9.86	5.76	42	44	Dong and Lin, 1994

Ammonium	Wetland Size	Wetland Type	Concentration IN (mg/L)	Concentration OUT (mg/L)	Reduction (%)	k_1 (m/yr)	Reference
Amoco, Mandan, North Dakota	16.6 ha	FWS	16.9	2.6	85	11	Litchfield and Schatz, 1989
Texaco A	400 m²	FWS	6.3	0.1	98	76	Hall, 1996
Texaco B	400 m²	FWS	0.2	0.1	50	13	Hall, 1996
Chevron, Richmond, California			0.4	0.1	77	14	
1989-91	36 ha	FWS	2.1	0.0	98		Duda, 1992
1992-95	36 ha	FWS					Chevron, 1996
Suncor, Fort McMurray, Alberta	500 m²	FWS	14.7	2.5	83	6	Gulley and Nix, 1995
1994	500 m²	FWS	14.6	3.7	75	5	Bishay *et al.*, 1995
A U.S. Refinery		FWS			9-61		Farmer, 1992
Non-USA Oil Terminal	600 m²	SSF					Farmer, 1996
Yanshan Pilot, P.R. China	1.5 ha	FWS					Dong and Lin, 1994
Yanshan Pond/Wetland, P.R. China	25 ha	FWS	5.8	3.5	40	42	Dong and Lin, 1994

Nitrate	Wetland Size	Wetland Type	Concentration IN (mg/L)	Concentration OUT (mg/L)	Reduction (%)	k_1 (m/yr)	Reference
Amoco, Mandan, North Dakota	16.6 ha	FWS					Litchfield and Schatz, 1989
Texaco A	400 m²	FWS					Hall, 1996
Texaco B	400 m²	FWS	1.1	0.1	91		Hall, 1996
Chevron, Richmond,			5.9	1.9	68		
California 1989-91	36 ha	FWS	3.7	0.1	97		Duda, 1992
1992-95	36 ha	FWS					Chevron, 1996
Suncor, Fort McMurray, Alberta	500 m²	FWS	0.01	0.40	-4,888		Gulley and Nix, 1995
1994	500 m²	FWS					Bishay *et al.*, 1995
U.S. Refinery		FWS			6 - 74		Farmer, 1992

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TABLE 2-23
Regression Equations for Nitrogen Outlet Concentration in Treatment Wetlands

Parameter	Equation	Statistics R^2	n	Standard Error C_2	Hydraulic Loading Rate q (cm/d)	Data Range C_1 (mg/L)	(Median) C_2 (mg/L)
Surface Flow							
Organic N	$C_2 = 1.00\ C_1^{0.476}$	0.52	243	1.8	0.02 - 27.4 (2.9)	0.09 - 19.9 (2.8)	0.16 - 15.5 (1.4)
Ammonium N	$C_2 = 0.336\ C_1^{0.728} q^{0.456}$	0.44	542	4.4	0.1 - 33.3 (2.9)	0.04 - 58.5 (2.2)	0.01 - 58.4 (0.6)
Nitrate N	$C_2 = 0.093\ C_1^{0.474} q^{0.745}$	0.35	553	4.9	0.02 - 27.4 (2.7)	0.01 - 24.5 (1.7)	0.01 - 21.7 (0.2)
TKN	$C_2 = 0.569\ C_1^{0.840} q^{0.282}$	0.74	419	1.9	0.1 - 24.3 (2.9)	0.2 - 97.0 (8.7)	0.15 - 48.0 (3.0)
TN	$C_2 = 0.409\ C_1 + 0.122q$	0.48	408	3.5	0.2 - 28.6 (2.5)	2.0 - 39.9 (9.1)	0.4 - 29.1 (2.2)
Subsurface Flow							
Organic N	$C_2 = 0.1C_1 + 1.0$	0.07	89	1.9	0.7-48.5 (6.2)	0.6-21.8 (6.9)	0.1-11.1 (1.1)
Ammonium N	$C_2 = 0.46C_1 + 3.3$	0.63	92	4.4	0.7-48.5 (5.5)	0.1-43.8 (6.7)	0.1-26.6 (6.1)
Nitrate N	$C_2 = 0.62C_1$	0.8	95	2.4	0.7-48.5 (5.5)	0.01-27.0 (0.3)	0.01=21.0 (0.4)
TKN	$C_2 = 0.752\ C_1^{0.821} q^{0.076}$	0.74	92	1.7	0.7-48.5 (5.5)	0.7-58.2 (15.2)	0.6-36.1 (8.2)
TN	$C_2 = 0.46C_1 + 0.124q + 2.6$	0.45	135	6.1	0.7-48.5 (7.1)	5.1-58.6 (21.0)	2.3-37.5 (13.6)

Source: Kadlec and Knight, 1996.

As summarized above, removal of all major nitrogen forms is sensitive to temperature. Theta value estimates range from about 1.04 for ammonium to 1.09 for nitrate N. Because nitrogen is a major plant growth element, plant uptake is a major component of this element's biogeochemical cycle. The effect of wetland system startup on nitrogen rate constants has not been reported. During a period of rapid biomass increase, ammonium and nitrate removal rate constants may be significantly higher than steady-state values.

Figure 2-21 illustrates the typical range of inlet and outlet TN concentrations for the first 12 cells of the Iron Bridge constructed surface flow wetland at Orlando, Florida. Individual maximum month outlet concentrations are more than twice the long-term average.

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The effects of plant species on nitrogen performance have been reported for a few systems. Bulrush provided slightly better performance than cattail for TN and TP outflow concentrations for one wetland system (Post, Buckley, Schuh, and Jernigan [PBSJ], 1989, 1990, 1991, 1992, and 1993).

Phosphorus

Processes

Constructed and natural wetlands are capable of absorbing new phosphorus (P) loadings and, in appropriate circumstances, can provide a low cost alternative to chemical and biological treatment. Phosphorus interacts strongly with wetland soils and biota, which provide both short-term and sustainable long-term storage of this nutrient.

Soil sorption can provide initial removal, but this partly reversible storage eventually becomes saturated. For some antecedent soil conditions, an initial release of P could occur. A new source of P acts to fertilize the wetland, and some P is used to establish a larger standing crop of vegetation.

The sustainable removal processes involve accretion of new wetland sediments. Uptake by small organisms, including bacteria, algae, and duckweed, forms a rapid-action, partly reversible removal mechanism (Figure 2-22). Cycling through growth, death, and decomposition returns most of the microbiotic uptake via leaching, but an important residual contributes to long-term accretion in newly formed sediments and soils. Macrophytes, such as cattails and bulrushes, follow a similar cycle but on a slower time scale of months or years. The detrital residual from the macrophyte cycle also contributes to the long-term storage in accreted solids. Direct settling and trapping of particulate P may contribute to the accretion process. Biological enhancement of mineralogical processes, such as iron and aluminum uptake and subsequent P binding in detritus and the algae-driven precipitation of P with calcium, can also occur.

Performance

Surface flow wetlands provide sustainable removal of phosphorus, but at relatively slow rates. The internal progression of removal causes concentrations to decrease exponentially to a background value, along the water flow path (Figure 2-23). The first-order areal mass balance model is currently the most supportable level of detail for describing long-term sustainable performance. It typically explains about 80 percent of the variability in transect data and explains internal profiles as well as input/output data for individual wetlands. This model must be applied over more than three to five detention times to avoid transit time effects.

The background concentration C* for total phosphorus is not a well-known quantity, but appears to be in the range of 10 to 50 μg/L based on information from large natural and constructed wetlands. Therefore, it does not exert a strong influence on model predictions until outlet concentrations reach this low range. The first-order rate constants for a number of nonforested wetlands show a central tendency of $k \approx 10$ m/yr

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(Table 2-24). Forested systems have lower rate constants, k ≈ 3 m/yr (Kadlec and Knight, 1996). The first-order model and a set of marsh data are shown in Figure 2-24, which further emphasizes intersystem variability.

Petroleum industry treatment wetland performance data for TP are summarized in Table 2-25. Reductions in TP are significant. Rate constants k_1 are high relative to other treatment wetlands, and performance is generally better than for other treatment wetlands. Loadings are high compared to other treatment wetlands.

The first-order model is a surrogate for a slow biogeochemical cycle, with a turnover time of many months for macrophyte-dominated systems. Consequently, it is not applicable on a short time scale such as daily or weekly. There is typically considerable stochastic scatter in the time sequence of output concentrations (Figure 2-25), which is the result of variability in influent flow rate and concentration, meteorology, and biological processes. There is not yet a calibrated general model available to describe the daily, weekly, and monthly scatter, and consequently it is necessary to be aware of the probability distribution associated with the mean long-term performance. The occasional random spikes and valleys in output are reflected in the tails of these distributions and are not predictable from models. The maximum monthly outlet P concentration is typically 1.8 times higher than the long-term mean (Kadlec and Knight, 1996).

The regression of input/output data provides an alternative description of the general trends in intersystem performance. Within the set of linear and log-linear regressions on average hydraulic loading rate (q avg) and inlet concentration (C_i), the best predictor of marsh outlet TP concentration (C_O) is produced by:

$$C_o = 0.195 q_{avg}^{0.53} C_i^{0.91} \quad (2\text{-}49)$$

$R^2 = 0.77$, N = 373

Standard Error in ln C_O = 1.00

0.02 $< C_i < 20$ mg/L

0.009 $< C_o < 20$ mg/L

0.1 $< q_{avg} < 33$ cm/d

Startup processes differ from the long-term sustainable processes. Sorption and biomass growth enhance early results; leaching of antecedent loads decreases performance. According to the data, 1 to 4 years are required for the startup phenomena transients to disappear (Kadlec and Knight, 1996).

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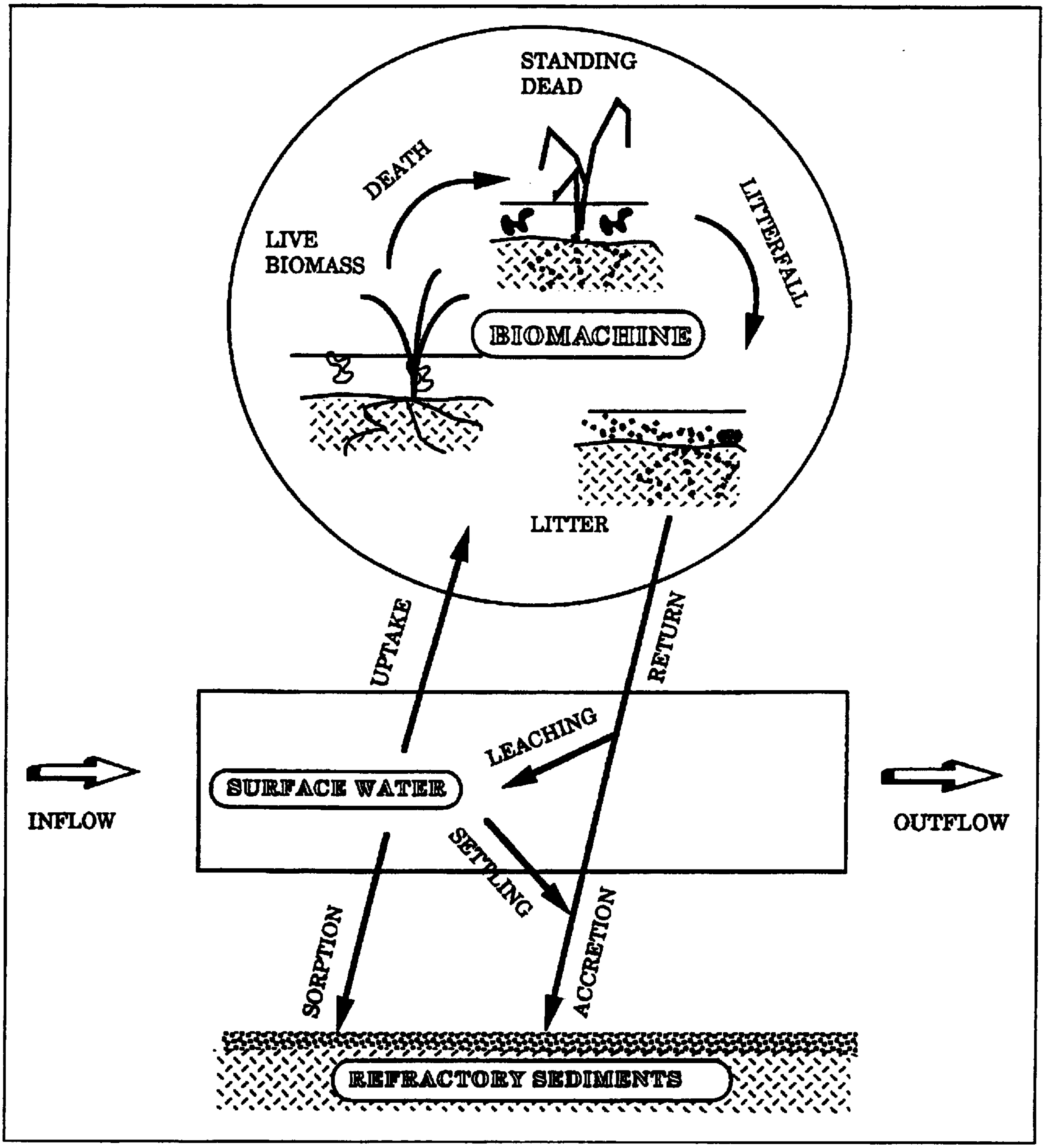

FIGURE 2-22
Wetland Biogeochemical Processing of Phosphorus
The two temporary sinks for P are sorption on antecedent soils and expansion of the biomachine. Macrophytes (plants) and microphytes (algae) can both be important, depending on wetland type. The sustainable removal pathway is accretion of new soils and sediments via the deposition of organic and inorganic forms of P.
Source: Kadlec and Knight, 1996.

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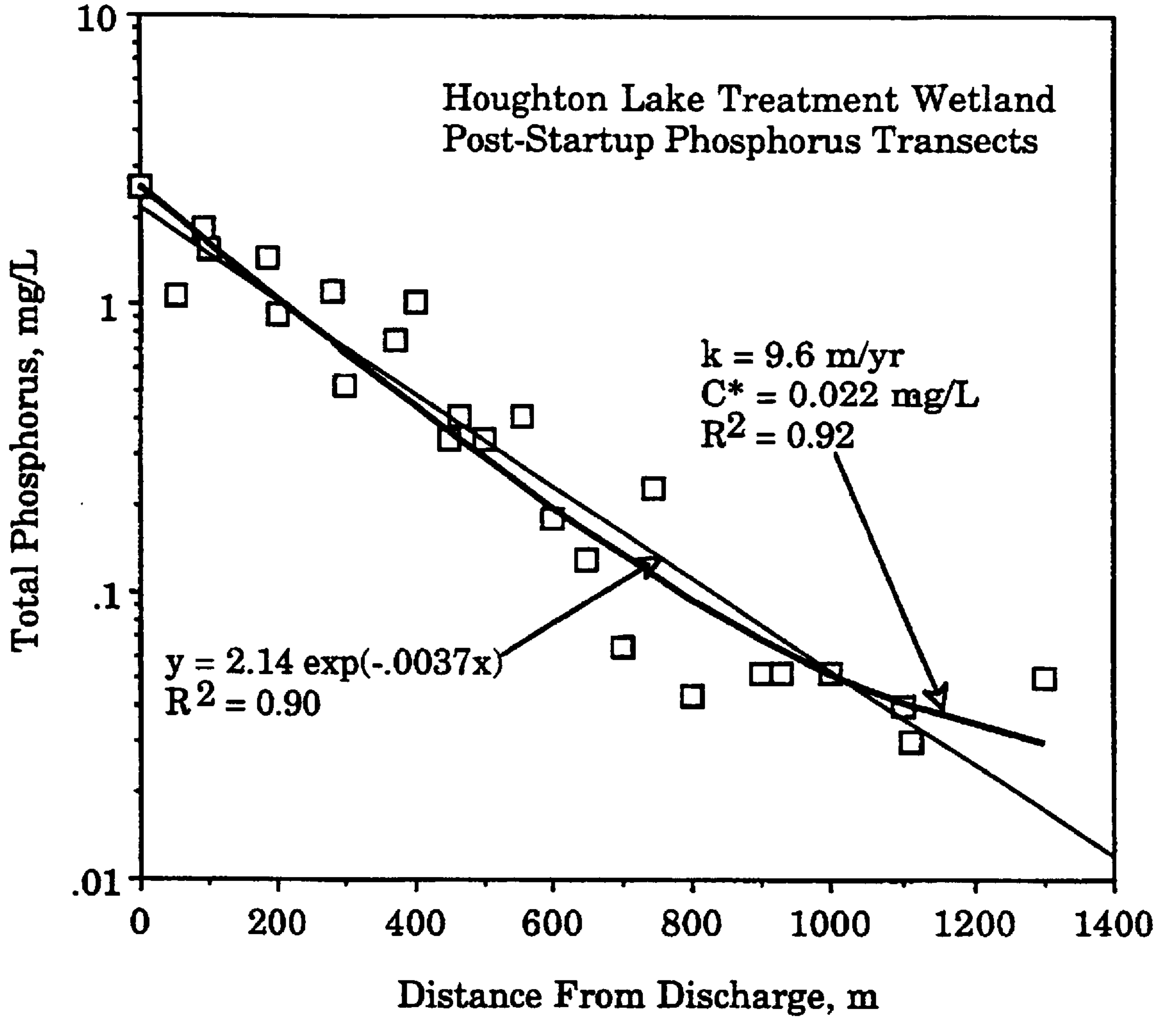

FIGURE 2-23
Transect Data for the Houghton Lake Wetland Treatment System
Each data point is the average of values for the period 1987 to 1995 for each distance. The straight regression line is for C = 0.00 mg/L, and the curve is for C* = 0.022 mg/L. Because of the low value of C*, both produce good fits. These regressions are not corrected for rainfall and evapotranspiration; if corrected, the rate constant is slightly higher. (Note: Data are from Table 2-24.)*

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TABLE 2-24
First-order Phosphorus Rate Constant for Nonforested Treatment Wetlands

Site	No. of Wetlands	Data Years	HLR (cm/day)	TP In (mg/L)	TP Out (mg/L)	k Value (m/yr)
Boney Marsh, Florida	1	11	2.21	0.051	0.019	9.9
Kitchener, Ontario	1	1	2.42	0.078	0.039	6.2
Hidden River, Florida	1	3	0.59	0.100	0.045	1.3
Des Plaines, Illinois	4	7	4.55	0.106	0.022	12.0
WCA2A, Florida	1	17	0.93	0.122	0.019	10.2
Bellevue, Washington	1	2	67.50	0.123	0.101	13.3
ENR, Florida	4	1	2.75	0.125	0.025	16.2
OCESA, Florida	4	6	0.97	0.212	0.042	6.0
Iron Bridge, Florida	5	8	1.21	0.252	0.069	11.7
Franklin Co., Ohio	1	1	10.65	0.460	0.382	6.9
Kis-Balaton, Hungary	1	10	3.30	0.540	0.230	8.6
Tarrant County, Texas	9	2	3.17	0.600	0.173	12.2
Byron Bay, Australia	8	5	6.48	0.739	0.577	7.5
Yasato-machi, Japan	1	4	3.18	0.970	0.240	16.3
Cobalt, Ontario	1	2	7.71	1.678	0.774	20.9
Listowel, Ontario	5	4	2.41	1.909	0.717	8.2
Great Meadows, Massachusetts	1	1	0.95	1.996	0.507	5.7
Houghton Lake, Michigan	1	18	0.44	2.983	0.100	11.2
Pembroke, Kentucky	2	2	0.77	3.015	0.115	9.3
Sea Pines, South Carolina	1	8	20.20	3.940	3.360	11.7
Fontanges, Quebec	1	2	5.60	4.150	2.400	11.2
Benton, Kentucky	2	2	4.72	4.540	4.098	2.4
Leaf River, Mississippi	3	5	11.68	5.167	3.964	11.2
Beaumont, Texas	1	2	3.14	6.080	2.320	11.5
Lakeland, Florida	7	7	7.43	6.540	5.690	3.4
Jackson Bottoms, Oregon	17	2	6.34	7.513	4.138	14.2
Clermont, Florida	1	3	1.37	9.140	0.150	23.4
Humboldt, Saskatchewan	5	3	3.04	10.160	3.240	12.8
Brookhaven, New York	1	3	1.50	11.075	2.325	8.9
Frambork, Poland	1	1	3.85	11.560	11.190	0.9
Netherlands			0.88	14.000	4.200	3.9
				Site Average		10.1±5.3
Soil-Based Wetland, Denmark	65	1 - 5	5.24	9.06	5.83	9.8±5.9

Note: The value of C* is set to zero.
Source: NADB, 1993.

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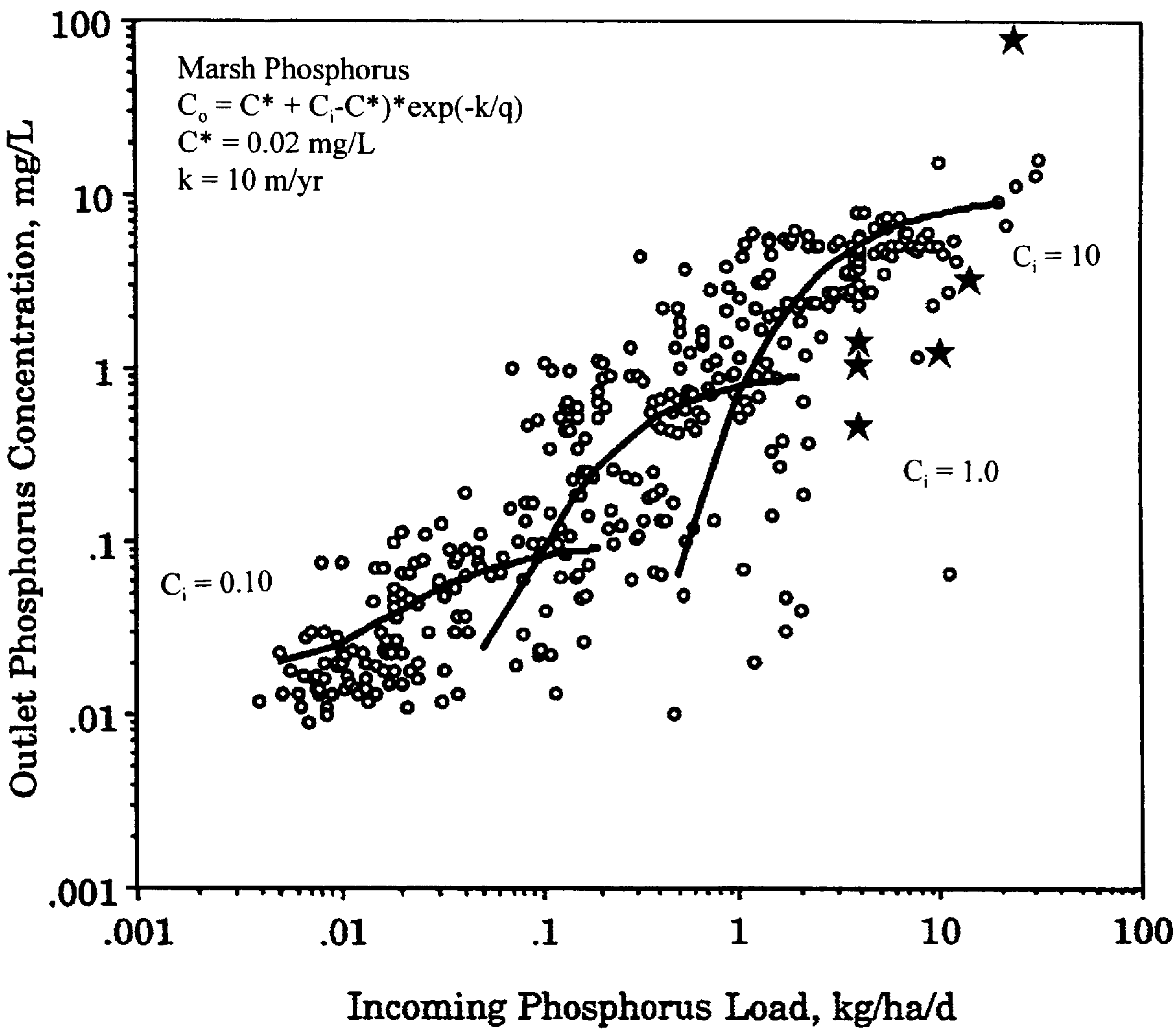

FIGURE 2-24
Intersystem Performance for Phosphorus Removal.
Data are from 58 wetland cells at 19 sites. Petroleum industry data are highlighted (✦). The k-C model is shown for different inlet concentrations; it spans the data set and provides a description of the central tendency of the diverse data sets.*

TABLE 2-25
Petroleum Industry Treatment Wetland Operating Data for TP

Site	Wetland Size	Wetland Type	Inlet TP (mg/L)	Outlet TP (mg/L)	Reduction (%)	k_1 (m/yr)	Reference
Texaco A	400 m²	FWS	5.9	1.1	81	31	Hall, 1996
Texaco B	400 m²	FWS	5.9	1.3	78	28	Hall, 1996
Chevron, Richmond, California							
1989-91	36 ha	FWS	98.7	82.6	16	2	Duda, 1992
1992-95	36 ha	FWS	28.7	18.9	34		Chevron, 1996
Suncor, Fort McMurray, Alberta							
	500 m²	FWS	0.078	0.151	-94	-2	Gulley and Nix, 1995
Yanshan Pond/Wetland, P.R. China	25 ha	FWS	1.51	0.43	72	103	Dong and Lin, 1994
Jinling, Beijing, P.R. China	3,750 m²	FWS	3.5	3.2	9	16	Tang and Lu, 1993
	3,750 m²	FWS	3.3	1.3	61	85	Tang and Lu, 1993

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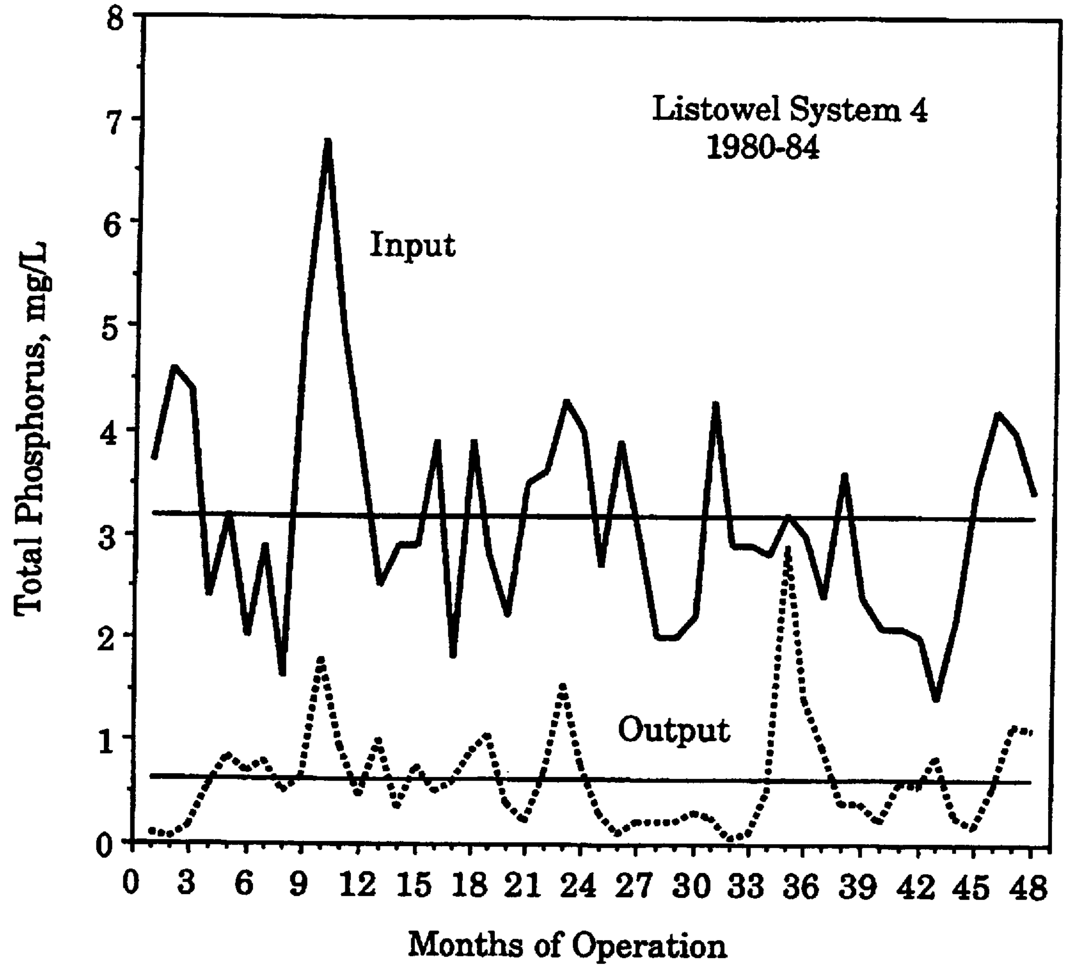

FIGURE 2-25
Input-Output Phosphorus Concentration Data for Listowel System 4 Operations 1980-1984
The mean inlet concentration of 3.17 mg/L was reduced to 0.62 mg/L. The value of k = 12.2 m/yr; C* does not affect the data fit at these high concentrations. The output does not track the input at all times, indicating significant stochastic influences.
Source: Data from Herskowitz, 1986.

Seasonal and temperature effects are of minor importance. The theta factors are close to unity: $\theta = 0.999$, $R^2 = 0.006$; and $\theta = 1.005$, $R^2 = 0.003$ for Listowel Systems 4 and 5, respectively. The low R^2 value indicates that the use of a temperature correction accounts for only 0.3 to 0.6 percent of the variability in rate constants for these systems.

Nutrients, including phosphorus, are often a major determinant of the structure and function of the wetland. Therefore, it is difficult if not impossible to select and maintain some wetland plant species in high nutrient environments. More opportunistic species such as cattails, bulrushes, and reed canary grass (*Phalaris arundinacea*) are likely to dominate high-nutrient environments.

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SECTION 3

Design Principles for Treatment Wetlands

Treatment wetland design involves a number of diverse activities, including waste characterization, pretreatment, identification of water quality goals, site selection, wetland sizing, hydraulic design, civil design, and plant selection. Detailed methods for treatment wetland design are available from a variety of sources including Kadlec and Knight (1996) and Reed *et al.* (1988). This section highlights some of the design considerations that will be important when considering the general feasibility of applying the wetland technology to petroleum industry wastewaters.

Table 3-1 lists design considerations that are important for constructed wetlands. The following subsections describe these specific elements of constructed wetland treatment system design:

- Site selection
- Treatment goals
- Size and depth
- Hydraulics and water control
- Vegetation

Site Selection

A site evaluation is critical before a treatment wetland is designed and constructed. Possible site constraints include land ownership, surrounding land uses, topography, site soils, depth to groundwater, depth to bedrock, existing natural wetlands, presence of protected species, and significant cultural resources. A site-specific study can help to minimize project costs and permitting constraints.

Constructed wetland treatment systems can be built in any geographical area of North America where sufficient land is available. Wetland treatment systems must be relatively level to ensure even flow distribution and minimize earthwork expenses. A site should be selected with minimal natural slopes, groundwater at least 2 to 3 feet below the land surface, minimum bedrock within several meters of the ground surface, and suitable onsite soils for berm construction. Less favorable sites will increase wetland construction costs.

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TABLE 3-1
General Considerations Important in Treatment Wetland Design

	Factor	Related Consideration
1.	**Site Constraints**	
	Climatic Factors	Maximum and minimum monthly temperature Rainfall and evaporation Ice and snow cover
	Topography	Cut and fill requirements Erosion potential on slopes Water courses/drainage - Site drainage - 100-year flood protection
	Geology/Soils	Absence of bedrock near surface Soil permeability Soil erodibility Geotechnical stability Presence/absence of faults
	Aquifers	Water sources susceptible to contamination Salt accumulation Groundwater flows and depths
	Biological	Existing land cover Section 404 wetlands jurisdiction Threatened or endangered species
	Socioeconomic	Potential for nuisance conditions Land ownership/adjacent land uses Cultural resources
2.	**Treatment Goals**	
	Secondary treatment (reduction of COD, BOD_5, TSS, oil and grease)	Minimum of primary pretreatment including screening and oil/water separation
	Advanced treatment (COD, BOD_5, TSS, NH_4-H, TN, TP, organics, metals, and toxicity reduction)	Minimum of secondary pretreatment by biological processes (facultative lagoon, activated sludge, etc.)
3.	**System Sizing**	
	Constructed Wetlands	Use information in Section 2
4.	**Other Design Criteria**	
	Water depth (SF only)	15 to 60 cm with water level control
	Bed depth (SSF only)	Bed depth 30 to 90 cm with water level control
	Substrate	Loamy topsoils in SF systems Coarse sand or gravel in SSF systems
	Basin design	Lined in leaky soils or for secondary treatment Minimum two parallel systems

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TABLE 3-1 (CONTINUED)
General Considerations Important in Treatment Wetland Design

	Factor	Related Consideration
		Slight bed slope for drainage Berm freeboard for storm events and substrate accretion Emergency overflows for berm protection
	Water control	Effective inflow distribution Adjustable outlet weirs
	Post aeration	As necessary to meet effluent limitations
5.	**Regulatory Issues**	NPDES Permit Environmental Assessment/Environmental Impact Statement Section 404 Wetland Permit Local Permits

Climatic factors are not prohibitive but do affect the required wetland treatment system area for some pollutants, as discussed in Section 2. Constructed wetland sites should be selected so they do not present a nuisance to surrounding land uses. Constructed treatment wetlands generally do not have odor or mosquito problems and can be attractive and desirable neighbors. Surface flow constructed wetlands frequently attract waterfowl and other birds. Although this function can often provide an environmental benefit, restrictions may apply to wetlands sited near airports. Subsurface flow design can be used when wildlife attraction is not a desired goal.

Constructed wetlands should not be sited in floodplains or in other seasonally flooded areas (jurisdictional wetlands) unless permit and operational constraints have been addressed. In some cases, a study of the project's net ecological benefits may show that a treatment wetland located in an existing infrequently flooded area may enhance overall environmental and public values.

Treatment Goals and Pretreatment

Constructed surface flow wetlands can provide up to tertiary treatment of a variety of wastewaters. Because of the potential to develop nuisance conditions (odors, mosquitoes, and poor plant growth) under high organic loading rates, constructed surface flow wetlands must be used with caution for poorly pretreated industrial wastewaters. Subsurface flow constructed wetlands can be designed for secondary or for tertiary wastewater treatment. Because the water surface is below ground level in properly designed subsurface flow systems, nuisance conditions caused by excessive anaerobic conditions are less likely to be an issue.

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Tertiary treatment functions typically provided by constructed surface flow wetlands include further reductions in concentrations of COD, BOD_5, organics, metals, TSS, ammonia nitrogen, nitrate+nitrite nitrogen, TN, and TP. As discussed below, HLR and influent quality greatly affect wetland effluent quality. Typical goals for constructed surface flow wetland treatment systems include one or more of the following:

- Further reduction of COD, BOD_5, and TSS concentrations beyond secondary treatment
- Reductions in concentrations of oils and grease, organics, and metals
- Nitrification of ammonia nitrogen to nitrate
- Denitrification of nitrate nitrogen with concurrent reduction of TN concentration
- Reduction of TP concentration
- Reduction of other parameters, including fecal coliforms and whole effluent chronic toxicity

Subsurface flow constructed wetlands are generally designed to provide secondary or tertiary effluent quality. Typical treatment goals that might be part of a subsurface flow constructed wetland treatment system design include the following:

- Secondary treatment of screened and settled primary effluent
- Further reduction of COD, BOD_5, and TSS concentrations beyond secondary treatment
- Reductions in concentrations of oils and grease, organics, and metals
- Denitrification of nitrate nitrogen in a previously nitrified wastewater

Subsurface flow constructed wetlands are not particularly cost-effective for nitrification or for phosphorus removal because they have essentially the same removal rates for ammonia nitrogen and phosphorus as surface flow wetlands and typically cost 5 to 10 times more for a given wetland area. Generally, subsurface flow systems are preferred over surface flow systems for small-scale applications, or when the designer wishes to intentionally discourage the use of the wetlands by wildlife because of the potential for food chain impacts.

Influent quality expected for a constructed wetland can be based on actual measured quality from an existing wastewater source and treatment system or can be estimated from typical published values for similar wastewater sources.

System Sizing

Because wetland design methods are still being developed, a clear consensus on sizing guidelines is not yet available. Some of the published sizing guidelines are inaccurate or not robust enough to work in every case. Some constructed wetland treatment designs have been based on incorrect hydraulic and kinetic models that overestimate treatment performance. Until recently, empirical methods that use operational data provided the best guidance for system sizing. Although rule-of-thumb methods can help develop conservative sizing guidelines, they are not useful for optimizing wetland treatment areas for specific applications.

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General design guidelines for constructed wetland treatment systems from WPCF (1990) are helpful, but the information is not specific enough for cost-effective design. The volumetric-based, first-order wetland design equation (based on hydraulic residence time) used in WPCF (1990) and elsewhere (Reed *et al.*, 1988; EPA, 1988a; EPA, 1993a) does not accurately explain a variety of operational wetland data.

The idea that more time in the wetland improves water quality is intuitively appealing. Early in the history of the technology, successful TSS and BOD_5 reductions were achieved in wetlands that had 7 to 10 days of nominal detention. The urge to replicate this range is therefore strong, but clearly this basis is inadequate for other constituents and may represent over-design for TSS and BOD_5. Wetland detention time must be coupled with a knowledge of the irreducible background concentration of the contaminant, as well as other design factors.

Depth is one primary controlling factor for nominal detention time and wetland area is the other. The relationship between these variables includes the water void fraction and was described previously by Equation 2-2.

Pollutant removal activity in the wetland is associated with the immersed sediments and biota. The reactive surfaces of these features dominate the removal processes for all biologically active substances. As a consequence, removal rate depends highly on vegetation density: an unvegetated soil, shallow pond has the minimum efficiency; a densely vegetated, fully littered wetland of the same depth has a higher efficiency.

If the detention time is increased by deeper submergence of these active components, keeping wetland area constant, only limited further removal activity is observed. In contrast, increasing the area of the wetland while retaining a constant volume increases the total biotic material in contact with the water, and improves overall treatment performance.

Cooper (1990), Brix (1990), and Kadlec and Knight (1996) have developed area-based, first-order wetland design models to predict treatment area requirements. Kinetic constants in these models are based on information from wetland systems in Great Britain, Denmark, and in the NADB. Rate constants presented in this report represent average conditions for various wetland designs. They are not based on data from industrial treatment wetlands. Treatment wetland rate constants do not currently exist for a number of pollutants of specific interest to the petroleum industry. Section 2 summarizes published rate constants.

Area-based, first-order design models allow realistic calculation of the wetland area necessary to reduce an average inflow pollutant concentration, C_1, to an average outflow concentration, C_2, at a given average flow rate, Q. Natural processes result in background concentrations, C^*, for some pollutants. Conservative design must assume that pollutant concentrations will not be consistently lowered below these irreducible, background concentrations. Equation 2-12 can be used with these rate constants and background concentrations to estimate necessary wetland treatment area.

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The models in Table 3-2 predict annual average removal rates; actual outflow concentrations will vary around these averages. Regulatory criteria that are given as maximum month averages can be used by converting monthly limitations to annual averages by using observed ratios from wetland treatment systems. When 12 monthly averages are calculated during a year of operation, one average will be higher than the rest. The ratio between the annual average and the maximum month average can be calculated to account for regulatory limits in the design. For the wetland treatment systems in the NADB, typical ratios between annual average and maximum month average are 0.59 for BOD_5, 0.53 for TSS, 0.4 for NH_4-N, 0.4 for NO_3+NO_2-N, 0.67 for TKN, 0.62 for TN, and 0.56 for TP. Ratios for other pollutants are not yet available. For a maximum month limit, this maximum month value should be multiplied by the above ratios to determine the value of C_2 for use in Equation 2-12.

Table 3-2 gives an example of sizing a constructed surface flow treatment wetland to polish a facultative lagoon effluent before discharge. In this example, wetland area is controlled by the TN discharge limit, and consistent compliance with the desired TSS limit may be unrealistic because the permit limit is so close to a typical wetland background concentration. Approximate sizing for subsurface flow treatment wetlands follows the same method as described for surface flow, except that appropriate rate constants should be used.

Hydraulic Design

Some wetland treatment systems, both surface flow and subsurface flow, have failed because of hydraulic problems. The wetland must be able to convey the design flow without overtopping either the berms or the media.

Research and development related to overland flow in wetlands have a brief history. Mathematical descriptions, which are often adaptations of open channel flow formulae, are discussed in detail in a number of texts (for example, French, 1985). The general approach uses mass, energy, and momentum conservation equations coupled with an equation for frictional resistance. A Manning's coefficient based on vegetated channel flow must be coupled with the free surface water mass balance to compute the head loss through the wetland.

The general approach for subsurface flow constructed wetland design uses Darcy's law of friction combined with the water mass balance. Some designers fail to use the mass balance, and errors result.

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TABLE 3-2
Constructed Wetland Sizing Example

Project Goal: Upgrade an existing facultative lagoon effluent to allow for either surface water or groundwater discharge.

Existing lagoon effluent flow and quality (annual averages):

Flow	-	5,680 m^3/d (1.5 mgd)
BOD_5	-	30 mg/L
TSS	-	60 mg/L
TKN	-	15 mg/L
NO_3-N	-	5 mg/L

Final discharge limits (maximum month average):

BOD_5	-	15 mg/L
TSS	-	15 mg/L
TN	-	10 mg/L

Determine minimum wetland size:

A. Define annual average design goals based on annual average/maximum month ratios:

BOD_5	=	15 x 0.59	=	8.8 mg/L
TSS	=	15 x 0.53	=	7.9 mg/L
TN	=	10 x 0.62	=	6.2 mg/L

B. Calculate areas for each parameter assuming average temperature is 20° C:

$$A = \frac{-Q}{k}\left[\ln\left(\frac{C_2 - C^*}{C_1 - C^*}\right)\right]$$

Q = 2,073,200 m^3/yr (1.5 mgd)

	Concentration (mg/L)				Estimated Area	
Parameter	C1	C2	C*	K_{20} (m/yr)	ha	acres
BOD_5	30	8.8	6	34 (Table 2-2)	13.1	32.3
TSS	60	7.9	14.6	1,266 (Table 2-11)	--	--
TN	20	6.2	1.5	22 (Table 2-21)	12.9	31.9

C. These results indicate that a constructed wetland may not be able to achieve the maximum monthly limit for TSS; however, examination of actual wetland data and estimation of the area necessary to produce an annual average TSS of 15 mg/L (0.77 ha) indicate that a wetland sized for BOD_5 or TN compliance, will produce background concentrations of TSS.

The minimum wetland design area is set by BOD_5 and TN at 13 ha .

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The idea of flowing water through a planted bed of porous media seems simple enough; yet numerous difficulties have arisen in practice. Gravel bed subsurface flow wetlands in the United States frequently flood. The two probable causes are clogging of the media with particulates and improper hydraulic design. The same appears to be true for other countries as well (Brix, 1994), especially in subsurface flow wetlands with a soil medium. The underlying cause of such hydraulic failure is the *ad hoc* procedure of designing to guessed values for hydraulic parameters. If a subsurface flow constructed wetland technology fails hydraulically, the resulting flooded operation simulates a surface flow wetland. Thus, the failure has some redeeming value. However, high construction cost for subsurface flow compared with surface flow wetlands makes proper hydraulic design essential to obtain any advantage from the subsurface flow constructed wetland alternative.

Water and Bed Depth

Water depth in surface flow constructed wetland treatment systems affects the survival and reproduction of plants, the effective hydraulic residence time, and the ability of oxygen to diffuse from the atmosphere to microbial populations. Normal water depths in the emergent marsh portion of wetland treatment systems range from about 15 to 60 cm. When combined with high organic loadings, greater depths provide poor root oxygenation resulting in poor plant growth. Generally, water depth in constructed wetlands should be adjusted to optimize plant growth as long as treatment goals are being accomplished. The constructed wetland outlet structure should allow control of water depths from zero up to the maximum design depth (typically less than 60 cm).

Areas of deeper water are also often included in treatment wetlands. Water depth will generally exceed 1.0 to 1.5 meters to prevent the establishment of rooted emergent vegetation in these areas. These deep zones are often arranged perpendicular to the direction of water flow to assist with flow distribution and to prevent hydraulic short-circuiting. Deep zones offer other benefits, including increased hydraulic and solids retention times and habitat for fish and birds.

Bed depth of subsurface flow constructed wetlands is typically the most important factor in system cost. WPCF (1990) recommends a bed depth of 30 to 90 cm. European designers who have applied this technology to hundreds of systems (Cooper, 1990) recommend a bed depth of about 60 cm.

Wetland Substrate

Surface flow constructed wetlands typically use native soils as a substrate for plant growth. Treatment wetlands can be constructed on almost any soil type and on gravel, but preferred soils are loams and sands because they help plants develop extensive root systems and propagate through rhizome development. Loamy soils are advantageous because of their fertility and texture. Clays may have excellent fertility, but their imperviousness hinders root penetration and diffusion of oxygen and other gases to and from the roots.

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Preferred wetland construction includes from 15 to 30 cm of loamy or sandy topsoil within the wetland to provide a suitable rooting medium for the wetland plants.

Substrate conditions are critical to the design of subsurface flow wetlands. These wetlands have been constructed with substrates ranging from coarse sands (rarely loams) to pea gravels with diameters less than 1 cm to large rocks (up to 10 to 15 cm diameter). Excessive fines associated with wetland substrate can result in hydraulic failure and should be avoided. Media permeability must be determined to correctly design the cross-sectional area to avoid surface flow.

Wetland Liner Requirements

Underlying soil permeability must be considered in the design of a constructed wetland. The most desirable soil permeability is less than 10^{-6} to 10^{-7} meter per second (m/s). Lining is sometimes needed to decrease soil permeability and thus reduce seepage losses through the bottom of the wetland. Lining can consist of installing artificial materials, such as a geomembrane, or placing a layer of less permeable soil (clay) in the bottom of the wetland. Mechanical compaction of existing or imported soils can also be effective in creating a less permeable barrier to seepage.

Generally, liners are required for constructed wetlands receiving primary treated wastewaters, but may not be required for systems receiving secondary or tertiary quality wastewaters, depending on groundwater contamination potential. Systems designed with multiple cells may only require liners in those cells receiving primary effluent. If the effluent discharged from one cell to another is of secondary quality, then a liner may not be required in the downstream cells.

Constructed wetlands may also be lined to prevent excessive loss of wastewater that is intended for some other beneficial use such as landscape irrigation or wildlife habitat. In these cases, lining may be partial to reduce infiltration through particularly permeable site soils and may be accomplished by adding less permeable subsoils or topsoils to portions of the site.

Need for an engineered liner is a determination that is made on an individual project basis. A liner may add significant cost, and, in some instances, may hamper performance of the system. At sites where site characteristics can be demonstrated to perform hydrologically like a liner, no liner may be required.

Water Control

Constructed wetland treatment systems transform and assimilate pollutants on an areal basis. In other words, the populations of plants and associated attached microbes that use pollutants for energy and nutrients depend more on the surface area of the wetland than on the depth of the surface water or subsurface substrate. This dependency results from the distribution of major energy and material inputs to wetlands in proportion to the wetland's surface area (sunlight, wind, and oxygen diffusion) and from the

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areal distribution of substrate surfaces for microbial and plant activity. Thus, treatment performance is tied closely to effective distribution of wastewater to all parts of the wetland area. Influent flow distribution, internal flow control, and diffused outlet design are essential to optimize treatment in constructed wetlands.

Various methods are available to distribute influent wastewater to treatment wetlands (Figure 3-1). Specific techniques include gated distribution header pipes, level-spreader swales or deep zones, multiple inlet ports from a gravity or pressurized pipe, and low-head sprinkler systems. The important element in the design is flexibility to adjust flows between ports or inlet locations so that slight inaccuracies during construction can be corrected after startup.

Flow tends to channelize in shallow constructed wetlands. Because shallow water may be desired to enhance plant cover, the design should provide methods to maintain relatively even flow distribution across the width of the constructed wetland cells. Deep zones perpendicular to the flow path can help maintain good flow distribution along the length of the wetland (Knight and Iverson, 1990). These perpendicular deep zones also enhance treatment by increasing hydraulic residence time and provide habitat for some wildlife.

Outlet structures also can enhance distribution. In surface flow constructed wetlands, multiple outlet weirs or a terminal, transverse, deep channel will recollect distributed flows. In subsurface flow wetlands, a perforated outlet pipe at the bottom of the gravel substrate adjacent to the outlet effectively recollects flows.

Outlet structures must also provide flexibility to regulate water depths within the constructed wetland. For surface flow systems, a moveable weir or removable stoplogs are commonly used to change water levels. In subsurface flow systems, water depth in the bed substrate is frequently controlled by use of a swivel elbow on the outflow drain pipe located within an excavated basin adjacent to the wetland outlet.

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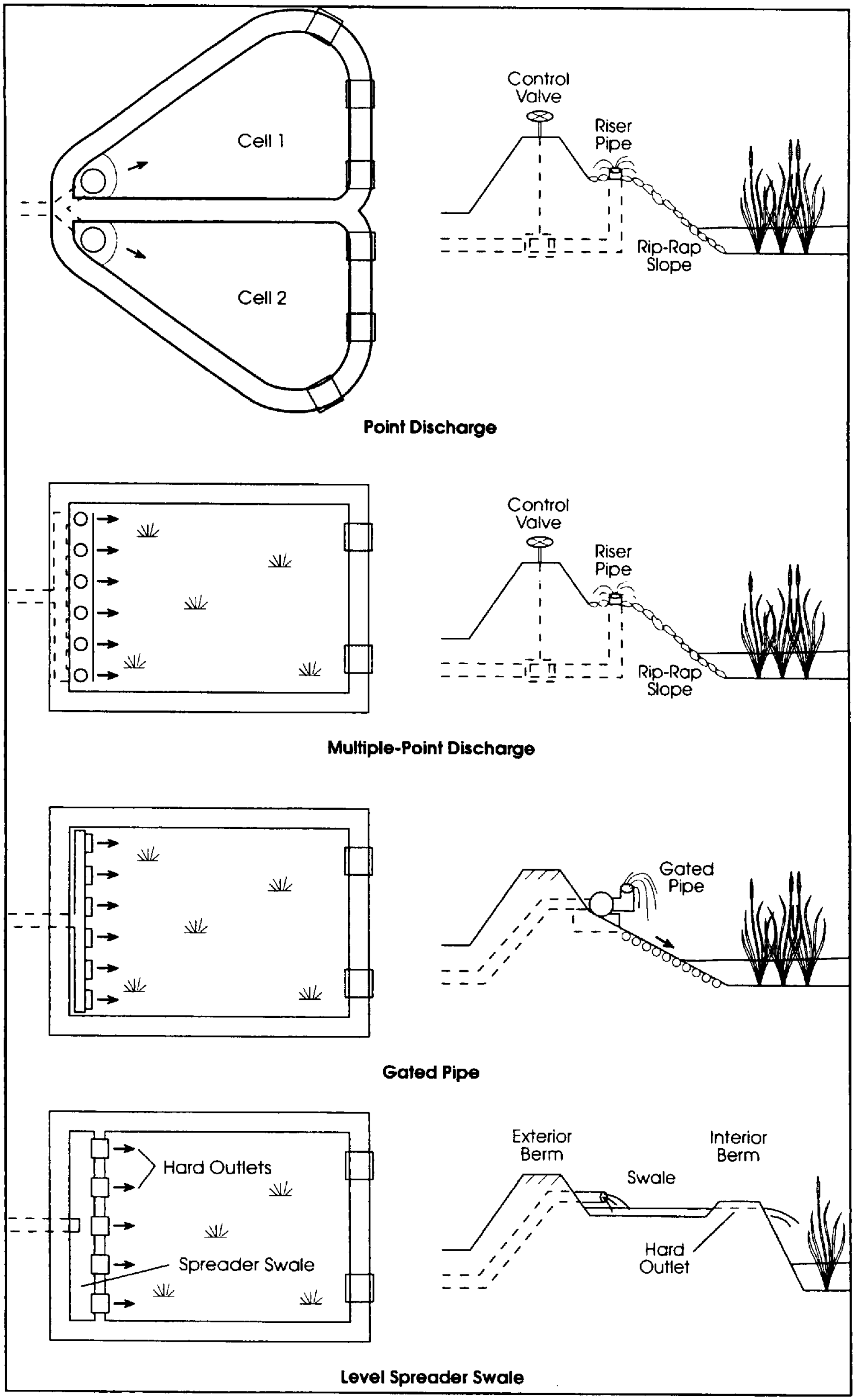

FIGURE 3-1
Influent Flow Distribution Structures for Constructed Wetlands.
Evenly distributed flow is essential to optimize treatment performance.

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Basin Configuration

All constructed wetland treatment systems should have a minimum of two parallel treatment cells or trains of cells in series (Figure 3-2). This redundancy ensures continued operation during maintenance. For larger systems, additional parallel flow systems are preferable to minimize the loading placed on operational cells when one portion of the system is temporarily removed from service.

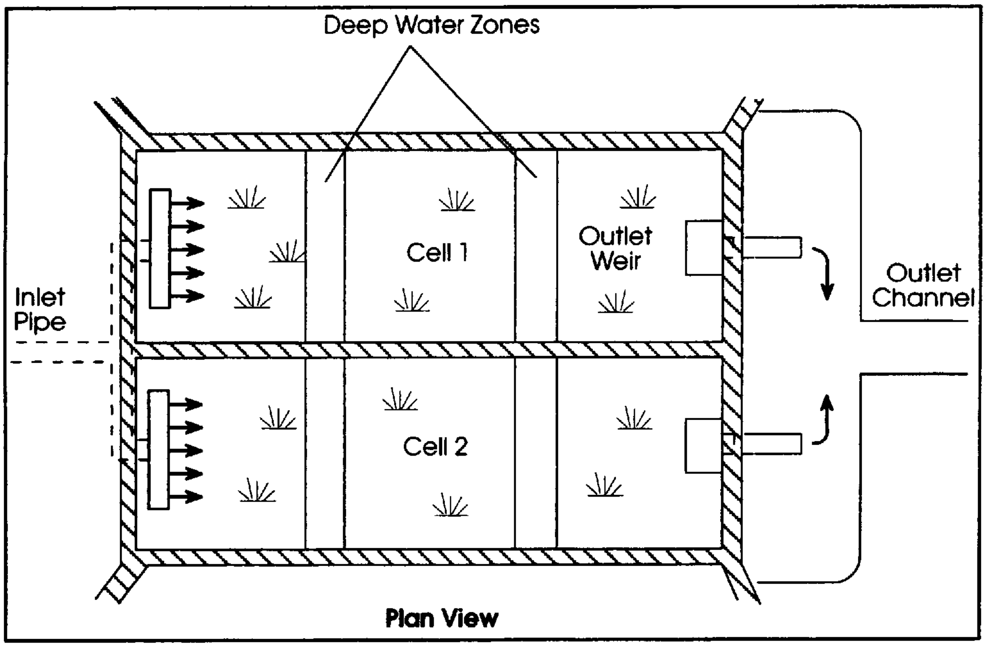

FIGURE 3-2
Typical Configuration of a Constructed Surface Flow Wetland Treatment System
Parallel basins provide the ability to shut off a portion of the system for maintenance.

The size of wetland cells has no apparent upper limit. Individual cells larger than 300 ha are in use at some constructed wetlands in the United States. Site topography may limit cell size because of excessive earthwork necessary to create large wetland cells. Terraced cells may be the best approach to construct wetlands on sites with excessive natural slopes.

Limited treatment wetland data do not support the hypothesis that high length-to-width ratios in wetland cells are useful in terms of minimizing short circuiting. High length-to-width ratios also have the disadvantage of increasing wetland cost by increasing the ratio of berm volume to wetland treatment area (Knight, 1987) and of increasing headloss due to higher flow velocities (Kadlec and Knight, 1996). Length-to-width ratios of 1:1 to 2:1 are acceptable in surface flow constructed treatment wetlands as long as internal flow distribution structures such as perpendicular deep zones or low parallel berms parallel to the flow direction are included. Length-to-width ratios in subsurface flow wetlands are based on required inlet width and system area, and are often less than 1:1.

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Berm heights above the maximum design water level must be sufficient to store direct and indirect rainfall and to allow for gradual filling of the constructed wetlands with solids. Solids accumulation rates in wetlands depend on the amount of inorganic solids entering the wetland and on internal productivity of the wetland plants. Typical solid accumulation rates are less than 0.5 cm/yr, with rates up to 1 cm/yr possible in inlet areas. Internal deep zones within the wetland can provide a sump for solids so that solids accumulation will not factor into determining berm freeboard.

For wastewaters with high concentrations of mineral or stabilized organic solids, pretreatment wetland cells or ponds should be used. These pretreatment cells can be designed to be emptied of solids on a periodic basis if necessary to protect the overall system from excessive sedimentation. Based on maximum solids accumulation rates, a 30 cm freeboard height would provide from 30 to 60 years of solids storage in a constructed wetland. The need for solids removal is unlikely in most constructed wetlands. However, if residual solids are expected to accumulate in a constructed wetlands, the designer should plan for testing, removal, and environmentally sound disposal during design. It is currently assumed that any solids that might accumulate in a wetland could be treated in the same manner as other wastewater residuals (i.e., biosolids from activated sludge units).

Berm freeboard in constructed surface flow and subsurface flow wetlands should generally equal or exceed about 30 cm to accommodate rainfall and filling. A wave action analysis should be used to determine berm height in larger wetland impoundments with open water areas. In addition, emergency overflow points will allow safe passage of flood flows caused by excessive rainfall or blocked outlets without loss of berm integrity. Overflow points should route excess water to the area of least potential impact.

Side slopes are based on geotechnical constraints related to soil compaction and erosion potential. Side slopes in the range of 2:1 (horizontal:vertical) to 3:1 are generally satisfactory for constructed wetland berms.

Post Aeration

Constructed treatment wetlands typically have wetland outflow dissolved oxygen concentrations below saturation. Post aeration may be necessary to meet standards for discharge to classified surface waters. Post aeration can be provided by a passive, cascade system of adequate height and width, or by mechanical aeration. Post aeration requirements to meet specific numerical limits can be calculated by using standard wastewater design texts such as Tchobanoglous and Burton (1991).

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Vegetation

The most commonly used plant species in constructed wetlands designed for water quality improvement are cattails (*Typha* spp.), bulrush (*Scirpus* spp.), and common reed (*Phragmites australis*). All three of these species have very high colonization and growth rates, establish extensive surface area that continues through the winter dormant season, have high pollutant treatment potential, and are very robust in continuously flooded environments. Of these three plant groups, bulrush provides the greatest overall wildlife benefit, but cattails also provide habitat for nesting and roosting birds. Common reed has little habitat value but is an extremely robust wetland plant in North America. Other plant species that can be used in constructed wetlands to enhance ecosystem diversity and to create greater wildlife value are listed in Table 3-3.

All three of the major plant groups can be propagated from field-harvested or nursery-grown plant stock (rhizomes or seedlings). Wetland plant communities can also be established from seed or from natural colonization and regrowth. Because plant propagation is frequently the least successful aspect of project implementation, owners should use experienced subcontractors. Maintaining wet soils without excessive flooding is critical to success during initial plant propagation.

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TABLE 3-3

Aquatic and Wetland Plants for Use in Constructed Wetlands

Plant Species	Common Name	Growth Form	Persistence	Growth/Spread Rate	Vegetative Growth Method	Spacing	Propagules	Habitat	Shade Tolerance	Wildlife Benefits	Water Regime	Salinity Tolerance
Acer negundo	Box elder	Tree	Perennial; deciduous	Fast; 4.5 to 6 m / 5 yrs			Container	Forested wetlands	Full sun	Songbirds; waterbirds; small mammals	Irregular to regular inundation or saturation	Fresh water; resistant to salt water
Acer rubrum	Red maple	Tree	Perennial; deciduous	Medium to fast; 5 to 7 m/ 10 yrs			Seed; whip; bare root	Fresh marsh; swamp; alluvial woods	Partial shade	Gamebirds; songbirds; browsers	Irregular to seasonally inundated or saturated	Fresh water; < 0.5 ppt
Acorus calamus	Sweet flag	Emergent; herbaceous	Perennial; nonpersistent	Moderate; 15 cm/yr	Rhizome	0.3 to 0.9 m O.C.	Rhizome; bare root plant	Fresh to brackish marshes	Partial shade	Waterfowl; muskrat	Regular to permanent inundation; < 15 cm	Fresh to brackish; < 10 ppt
Alnus serrulata	Smooth alder	Shrub	Perennial; deciduous	Rapid; 60 cm/yr			Container	Fresh marshes and swamps	Full sun	Songbirds; gamebirds; ducks; woodcock; blackbirds; beaver	Seasonal to regular inundation; up to 7 cm	Fresh water; < 0.5 ppt
Carex spp.	Sedges	Emergent; herbaceous	Perennial; nonpersistent	Slow to rapid	Rhizome	0.15 to 1.8 m O.C.	Seed; bare root plant	Fresh marshes; swamps; lake edges	Full shade to full sun	Rails; sparrows; snipe; songbirds; ducks; moose	Irregularly to permanently inundated; <015 cm	Fresh water; <0.5 ppt
Cepahlanthus occidentalis	Buttonbush	Shrub	Perennial; deciduous	Medium; 30 to 60 cm/yr			Seedling; bare rootplant	Fresh marshes; swamps; edge of ponds	Full shade to full sun	Ducks; deer; rails; blackbirds; muskrats; beaver	Irregular to permanent inundation; up to 90 cm	Fresh water; tolerates infrequent salt water
Ceratophyllum demersum	Coontail	Submerged aquatic	Perennial	Rapid	Fragmentation		Whole Plant	Lakes; slow streams		Ducks; coots; geese; grebes; swans; marshbirds; muskrats	Regular to permanent inundation; 0.3 to 1.5 m	Fresh water; <0.05 ppt

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TABLE 3-3 (CONTINUED)

Aquatic and Wetland Plants for Use in Constructed Wetlands

Plant Species	Common Name	Growth Form	Persistence	Growth/Spread Rate	Vegetative Growth Method	Spacing	Propagules	Habitat	Shade Tolerance	Wildlife Benefits	Water Regime	Salinity Tolerance
Cyperus esculentus	Chufa	Emergent herbaceous	Perrenial; nonpersistent	Rapid	Rhizome		Seed; tuber	Fresh marshes; wet meadows	Full sun	Waterfowl; songbirds; small mammals	Irregular to regular inundation; <0.3 m	Fresh water; <0.5 ppt
Eichhornia crassipes	Water hyacinth	Nonrooted floating aquatic	Perennial; nonpersistent	Rapid	Stolons		Whole plants	Fresh water ponds and sluggish streams	Full sun	Coots; cover for invertebrates and fish	Permanent inundation	Fresh water; < 0.5 ppt
Hydrocotyle umbellata	Water-pennywort	Emergent to floating; herbaceous	Perennial; nonpersistent	Rapid	Stolons or rhizomes		Bare root plant; whole plant	Shorelines; shallow marshes	Partial shade	Wildfowl; waterfowl	Regular to permanent inundation; <30 cm	Fresh water; <0.5 ppt
Iris versicolor	Blue flag	Emergent; herbaceous	Perennial; nonpersistent	Slow; <60 cm/yr	Bulb	0.15 to 0.45 m O.C.	Seed; bulb; bare root plant	Marshes; wet meadows; swamps	Partial shade	Muskrat; wildfowl; marsh birds	Regular to permanent inundation; <15 cm	Fresh to moderately brackish
Juncus effusus	Soft rush	Emergent; herbaceous	Perennial; persistent	Slow; <6 cm/yr	Rhizome	0.15 to 0.45 m O.C.	Seed; rhizome; bare root plant	Marshes; shrub swamps; wet meadows	Full sun	Wildfowl; marshbirds; songbirds; waterfowl	Regular to permanent inundation; <30 cm	Fresh water; <0.5 ppt
Nuphar luteum	Spatterdock	Rooted floating to emergent; herbaceous	Perennial; nonpersistent	Slow; <6 cm/yr	Rhizome	0.15 to 0.45 m O.C.	Bare root plant	Marshes; swamps; ponds	Partial shade	Ducks; muskrat; fish	Regular to permanent inundation; up to 1.8 m	Fresh water to infrequent brackish
Nymphea odorata	Fragent water lily	Rooted floating aquatic	Perennial; nonpersistent		Rhizome		Bare root seedling	Ponds and lakes	Partial shade	Cranes; ducks; beaver; muskrat; moose	Permanent inundation; 0.3 to 0.9 m	Fresh water; <0.05 ppt

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TABLE 3-3 (CONTINUED)

Aquatic and Wetland Plants for Use in Constructed Wetlands

Plant Species	Common Name	Growth Form	Persistence	Growth/Spread Rate	Vegetative Growth Method	Spacing	Propagules	Habitat	Shade Tolerance	Wildlife Benefits	Water Regime	Salinity Tolerance
Nyssa sylvatica	Black gum	Tree	Perennial; deciduous	Slow	Suckers		Seed; bare root plant	Forested wetlands; swamps	Partial shade	Ducks; woodpeckers; songbirds; aquatic furbearers	Irregular to permanent inundation	Fresh water to infrequent brackish
Phragmites australis	Common reed	Emergent; herbaceous	Perennial; persistent	Rapid; > 30 cm/yr	Rhizome	0.6 to 1.8 m O.C.	Bare root plant	Fresh to brackish marshes; swamps	Full sun	songbirds; marshbirds; shorebirds; aquatic furbearers	Seasonal to permanent inundation; up to 60 cm	Fresh to brackish; up to 20 ppt
Pontederia cordata	Pickerelweed	Emergent herbaceous	Perennial; nonpersistent	Moderate; 15 cm/yr	Rhizome	0.3 to 0.9 m O.C.	Rhizome; bare root plant	Fresh to brackish marshes; edges of ponds	Partial shade	Ducks; muskrat; fish	Regular to permanent; up to 30 cm	Fresh to moderately brackish; up to 3 ppt
Populus deltoides	Eastern cottonwood	Tree	Perennial; deciduous	Fast; 1.2 to 1.5 m/yr			Bare root plant; container	Forested wetlands	Full sun	Gamebirds; songbirds; waterfowl; aquatic furbearers; browsers	Seasonal inundation or saturation	Fresh water to infrequent brackish
Potamogeton nodosus	Long-leaved pond weed	Rooted submerged aquatic	Perrenial; nonpersistent	Rapid	Rhizome	0.6 to 1.8 m O.C.	Seed; bare root plant	Streams; lakes; ponds		Waterfowl; marshbirds; shorebirds; aquatic furbearers; moose; fish	Regular to permanent inundation; 0.3 to 1.8 m	Fresh water; <0.05 ppt
Quercus bicolor	Swamp white oak	Tree	Perennial; deciduous	Fast; 0.4 to 0.6 m/yr			Bare root plant; container	Forested wetlands	Partial shade	Waterfowl; marshbirds; shorebirds; gamebirds; songbirds; mammals	Irregular to seasonal inundation or saturation	Fresh water to infrequent brackish
Rosa palustris	Swamp rose	Shrub	Perennial; deciduous				Container	Fresh marshes; shrub swamps	Full sun	Songbirds; gamebirds	Irregular to regular soil saturation	Fresh water; < 0.5 ppt

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TABLE 3-3 (CONTINUED)

Aquatic and Wetland Plants for Use in Constructed Wetlands

Plant Species	Common Name	Growth Form	Persistence	Growth/Spread Rate	Vegetative Growth Method	Spacing	Propagules	Habitat	Shade Tolerance	Wildlife Benefits	Water Regime	Salinity Tolerance
Sagittaria latifolia	Duck potato	Emergent; herbaceous	Perennial; nonpersistent	Rapid; > 30 cm/yr	Runners; tubers	0.6 to 1.8 m O.C.	Tuber; bare root plant	Fresh marshes; swamps; edge of ponds	Partial shade	Ducks; swans; rails; muskrats; beaver	Regular to permanent inundation; up to 60 cm	Fresh water; <0.5 ppt
Salix nigra	Black willow	Tree	Perennial; deciduous	Fast; 0.9 to 1.8 m/yr	Suckers		Bare root; container	Fresh marshes; swamps	Full sun	Gamebirds; ducks; songbirds; woodpeckers; aquatic mammals	Irregular to permanent inundation	Fresh water; < 0.5 ppt
Scirpus acutus	Hardstem bulrush	Emergent; herbaceous	Perennial; persistent	Rapid	Rhizome	0.9 to 1.8 m O.C.	Seed; rhizome	Fresh to brackish marshes	Full sun	Ducks; geese; swans; cranes; shorebirds; rails; snipe; muskrats; fish	Regular to permanent; up to 90 cm	Fresh to brackish
Scirpus americanus	Olney's bulrush	Emergent; herbaceous	Perennial; semi-persistent	Rapid; > 30 cm/yr	Rhizome	0.6 to 1.8 m O.C.	Rhizome; bare root plant	Brackish and alkali marshes	Full sun	Ducks; geese; swans; cranes; shorebirds; rails; snipe; muskrats; fish	Regular to permanent inundation; up to 30 cm	Fresh to brackish water; up to 15 ppt
Scirpus cyperinus	Wool grass	Emergent; herbaceous	Perennial; persistent	Moderate; 15 cm/yr	Rhizome	0.3 to 0.9 m O.C.	Rhizome; bare root plant	Fresh marshes; wet meadows; sloughs; swamps	Full sun	Ducks; geese; swans; cranes; shorebirds; rails; snipe; muskrats; fish	Irregular to seasonal inundation	Fresh water; < 0.5 ppt
Scirpus validus	Soft stem bulrush	Emergent; herbaceous	Perennial; persistent	Rapid; > 30 cm/yr	Rhizome	0.6 to 1.8 m O.C.	Rhizome; bare root plant	Fresh and brackish marshes	Full sun	Ducks; geese; swans; cranes; shorebirds; rails; snipe; muskrats; fish	Regular to permanent inundation; up to 30 cm	Fresh to brackish water; up to 5 ppt
Sparganium eurycarpum	Giant bur-reed	Emergent; herbaceous	Perennial; nonpersistent	Rapid; > 30 cm/yr	Rhizome	0.6 to 1.8 m O.C.	Seed; rhizome; bare root plant	Marshes; swamps; pond shorelines	Partial shade	Ducks; swans; geese; beaver; muskrats	Regular to permanent inundation; up to 30 cm	Fresh water; < 0.5 ppt

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TABLE 3-3 (CONTINUED)

Aquatic and Wetland Plants for Use in Constructed Wetlands

Plant Species	Common Name	Growth Form	Persistence	Growth/Spread Rate	Vegetative Growth Method	Spacing	Propagules	Habitat	Shade Tolerance	Wildlife Benefits	Water Regime	Salinity Tolerance
Taxodium distichum	Bald cypress	Tree	Perennial; deciduous	Medium; 0.3 to 0.6 m/yr			Seed; bare root plant; container	Fresh water swamps; pond and lake margins	Partial shade	Perching and nesting site for birds	Irregular to permanent inundation	Fresh water; < 0.5 ppt
Typha angustifolia	Narrow-leaved cattail	Emergent; herbaceous	Perennial; persistent	Rapid; > 30 cm/yr	Rhizome	0.6 to 1.8 m O.C.	Rhizome; bare root plant	Fresh and brackish marshes; pond edges	Full sun	Geese; ducks; muskrats; beaver; blackbirds; fish	Irregular to permanent inundation; up to 30 cm	Fresh to brackish; up to 15 ppt
Typha latifolia	Broad-leaved cattail	Emergent; herbaceous	Perennial; persistent	Rapid; > 30 cm/yr	Rhizome	0.6 to 1.8 m O.C.	Rhizome; bare root plant	Fresh marshes; pond margins	Full sun	Geese; ducks; muskrats; beaver; blackbirds; fish	Irregular to permanent inundation; up to 30 cm	Fresh water; < 0.5 ppt

cm/yr centimeters per year
O.C. on center
ppt parts per thousand
Source: Adapted from Thunhorst (1993).

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SECTION 4

Operation and Monitoring of Treatment Wetlands

Constructed treatment wetlands can often be designed to require minimal operations control and maintenance. Ease of operation and low operation and maintenance costs are important benefits of this technology. Proper design and wetland sizing based on accurate information concerning pollutant and hydraulic loads are essential for project success because of the relatively limited range of corrective options available through wetland operation.

This section describes the need for wetland system monitoring to provide feedback to operations. A number of problems that have occurred in existing treatment wetlands are described, and appropriate responses are presented for consideration. This is still a relatively young wastewater management technology, and knowledge about the most effective methods to manage treatment wetlands to achieve water quality and habitat goals is still developing.

Operations and Maintenance

Preparation of an operation and maintenance (O&M) manual to direct treatment wetland management is recommended. The following are example O&M manual components:

- Facility description
- Operator and manager responsibilities
- Permit limits/treatment goals
- Process description
- Operator controls/maintenance
- Monitoring methods/schedule/quality assurance/records
- Operator safety and emergency response plan

The O&M manual should specify what parameters are measured and how often. Table 4-1 outlines a minimum monitoring program for proper control of a treatment wetland.

Quality assurance/quality control (QA/QC) procedures should be included in the O&M manual. These are the procedures an operator will follow when a monitoring parameter is being used to indicate possible problems. The next subsection offers additional guidance on monitoring and operation of treatment wetlands.

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TABLE 4-1
Monitoring Suggestions (Minimum Effort) for Operation of Treatment Wetlands

Parameters	Sampling Locations	Minimum Sampling Frequency
Inflow and Outflow Water Quality		
COD, BOD_5, TSS, pH, DO, conductivity, temperature, TDS, oils and grease, NO_2+NO_3-N, NH_4-N, TKN, TP, Cl-, $SO_4^{=}$	Inflow and outflow	Monthly to weekly
Selected metals, organics, acute and chronic toxicity	Inflow and outflow	Semiannually
Flow	Inflow and outflow	Daily
Rainfall	Adjacent to wetland	Daily
Water Stage	Within wetland	Daily
Biological Plant Cover, Macroinvertebrates, and Fish	Inflow, center, outflow	Quarterly to annually

Monitoring Recommendations

Monitoring a constructed wetland includes both general observations and detailed sampling of parameters. The actual monitoring program at a given site must be integrated with the design of the wetland, treatment goals, habitat goals, permit requirements, and regulatory standards.

Rationale

Treatment wetlands are complex ecosystems that develop site-specific characteristics. Frequent monitoring and evaluation will reveal trends and aberrations that guide operation. A history of monitoring will help to refine system management.

Constructed wetlands are managed by controlling water quantity, quality, depth, and flow rates. With flexible water control, the operator can manage the wetland with minimal effort and, most importantly, react to changing conditions or developing problems. These developing problems are detected by regular monitoring. For effective management, a greater effort is generally devoted to monitoring and less effort to operation.

In addition, EPA and the states require regular monitoring of certain parameters to safeguard the environment and to give early warning of potential problems. Routine testing also ensures that state and federal legal requirements are met.

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Flows and Water Levels

Data should be gathered on a daily, weekly, and monthly basis for water flows into a constructed wetland treatment system and for static water level within the ponded system (Table 4-1). This information documents the system's performance and safeguards it from overfilling, spills, and damage to dikes or islands. For example, the seasonal variability of flow rates needs to be correlated with evapotranspiration so wetland basins will have excess storage capacity to avoid overflows. Outflow rate should be monitored on a daily basis or continuously in treatment systems that discharge offsite. When combined with measurements of water quality described below, inflow and outflow rate measurements allow estimation of mass removals in treatment wetlands.

Water Quality

At a minimum, water quality parameters should be monitored in accordance with permit requirements. Additional sampling will help refine the management of a constructed wetland treatment system. For instance, internal sampling can reflect changes in water quality as it progresses through a wetland, and monthly samples reflect seasonal influences.

Table 4-1 lists the recommended minimum sampling necessary to monitor a constructed treatment wetland. The following parameters can be sampled at least monthly at major inflows and outflows: COD, BOD_5, TSS, pH, DO, water temperature, conductivity, TDS, oil and grease, NO_2+NO_3-N, ammonia nitrogen, TKN, TP, chloride, and sulfate. Acute and chronic toxicity, organics, and metals can be sampled less frequently, unless high or problem levels are anticipated.

Field parameters for pH, DO, temperature, and conductivity can be monitored by the system operator, while other parameters will typically need to be analyzed by a certified laboratory.

These water quality data should be organized in a computer database that can be updated easily to view trends. Frequent review of data trends can allow operational changes to be made before permit violations occur. This database will become more valuable with the addition of each year's data.

Precipitation should be monitored at or near the constructed wetland treatment system. These data will be needed to prepare an overall water budget. Monitoring of evapotranspiration may be important in drier climates, but data from regional monitoring sites are generally adequate.

Mass Loading and Removals

The quality of water supplied to a treatment wetland depends on pretreatment capacity. Although inflow water quality and quantity are consistent under normal conditions, major storms can overload pretreatment systems with limited storage, resulting in poorly treated effluent going into a wetland. For that reason, extra storage capability before or within the wetland treatment system is a good safeguard for adequate

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treatment. Wetlands that are sized larger for additional wildlife habitat have flexibility to handle unusual climatic events.

Overfilling a wetland basin can harm vegetation if emergent plants are overtopped. When this happens, water levels should be drawn down within 2 weeks to avoid serious injury to perennial plants. This situation is more critical during warm or hot weather.

Vegetation

A constructed wetland can have a diversity of plant species or it can depend on just a few. Some diversity of plants is desirable to avoid catastrophic loss of cover from disease or pest infestation. The operator should understand the biological requirements of the plants and manage water levels to provide for their needs. Optimum conditions are not always required, as wetland plants may endure harsh conditions such as periodic drying and fire. The plants' environment is most critical during seed germination and establishment.

Sometimes operators make the mistake of drowning wetland plants. Usually, initial growth is best with transplanted plants in wet but well-aerated soil. Leaving the majority of the growing plants exposed with occasional inundation will allow the plants to obtain oxygen and grow fastest.

Plant cover needs to be periodically assessed and documented. Dramatic shifts can occur as plant succession proceeds. The plant community reflects management and can indicate improvement or problems. For example, submergent plants require light penetration into the water column. The disappearance of these plants indicates problems with water clarity.

Animals

The animals in a constructed wetland are necessary links in an aquatic food chain. They include microscopic plankton that feed on plants grown in the wetland or supplied by the water inputs. Aquatic insects feed on the plankton, fish and amphibians feed on the insects, and birds and mammals feed on the fish. The extent of monitoring depends on the nature of the wastewater and on resources. If bioaccumulation in the food chain is a concern because of influent quality, then early sampling can give a warning that pretreatment may need to be increased. Macroinvertebrate sampling within the wetland can provide a record of food abundance and diversity for fish and birds and can be used as an indicator of stress from excessively low dissolved oxygen concentrations. To document ancillary benefits and to garner public interest, data on higher life forms such as bird use are helpful. Routine bird counts can be conducted along specific survey routes around or through the wetlands on a biweekly or monthly basis. All birds seen within or using the wetland within a standard count time should be identified and tallied.

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Microbes

Microbes are typically the most important biological components for assimilating pollutants in a wetland treatment system. Because microbial populations vary too much for direct monitoring to be easily interpreted, their ecological functioning can best be assessed in most cases by measuring water quality changes through the system. Attention to operational controls discussed earlier such as dense vegetation stands for microbial colonization and avoidance of highly anaerobic conditions in the water column will generally ensure viable microbial populations. Microbial species naturally colonize new treatment wetlands and their inoculation is generally not required.

Sediments

Sediments under a wetland should be sampled before construction to determine baseline levels for any metals or other priority pollutants of concern in the wastewater. After a wetland is established, sediment sampling can be periodically repeated (annually) to see if undesirable materials are accumulating above biologically safe threshold levels. Sediment sampling is generally limited to the rooting depth of wetland vegetation (less than 30 cm or 1 foot for most marsh species).

Groundwater

Before a wetland treatment system is constructed, the anticipated seepage rate and potential for affecting a groundwater aquifer should be investigated. Data previously collected on the soil profile, soil texture, and seepage testing should be made available to the operator. If losses to groundwater are expected, the operator should be familiar with a description of the hydrogeologic conditions underlying the site, the monitoring requirements of the permit, construction of monitoring wells, ambient groundwater quality, and quality of wastewater applied at the site.

A detailed water budget involving inflow and outflow measurements and evapotranspiration estimates is used to estimate seepage rates to the groundwater. A typical groundwater monitoring system includes wells located upgradient and downgradient from the wetland facilities. Water quality in upgradient wells is indicative of ambient groundwater conditions, whereas downgradient wells are indicative of any changes to water quality caused by seepage from the wetland. Water quality testing data often show substantial variability among samples for some constituents, particularly nutrients and metals. Therefore, trends and variability from multiple samples need to be examined to interpret the implications of the water quality monitoring data relative to permit compliance. In some instances, additional monitoring frequency for certain constituents may be needed to increase the reliability of the data interpretations.

In most instances, unlined constructed wetlands that discharge to groundwater should be monitored by testing the aquifer with monitoring wells. Exceptions might be made where adequate monitoring can be conducted at inlet locations or within the wetland water body to demonstrate compliance with groundwater

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standards. The typical groundwater monitoring scheme would include monitoring for pollutants at a well or wells placed at the downgradient edge of the pollutant management boundary. The number of wells and frequency of monitoring will depend on the size and character of the discharge.

Sample Point Access

Monitoring requires frequent access to sampling points. If access is difficult, sampling may not be done as often as needed. Driving across vegetated dikes or wading through muck can also damage the site. Appropriate vehicle access, trails, marked sampling sites, catwalks, and boardwalks should be considered to facilitate monitoring.

Operational Control

Constructed wetland treatment systems are operated by controlling water application rates and quality. Water depths are regulated by in-pond structures such as stand pipes, flash boards, stoplogs, or weir gates (Figure 4-1). If the treatment system has been designed for flexible operation, it will provide various routes for water flow and include stored water that can be released on demand.

Hydraulic Loading

Hydraulic loading multiplied by pollutant concentration is equivalent to mass loading. Mass removal in treatment wetlands is highly correlated to mass loading. An operator can regulate final effluent quality by changing hydraulic loading into the wetland. If data trends indicate that effluent concentrations are approaching permit limits, hydraulic loading must be decreased unless additional pretreatment is possible. Hydraulic loading may be decreased in conservatively designed treatment wetlands by discharging to other portions of the system with excess capacity or by storing influent wastewater.

The water delivery system of a constructed wetland should allow water to be put directly into as many cells as possible and to let water flow through cells in parallel or in series from cell to cell. Intercell structures with flash boards hold water levels at a set height, and excess water flows over the boards into the next cell. The operator then changes boards to regulate water levels in each of a series of cells. Wetland cells should be able to be isolated for management such as vegetation manipulation or seepage monitoring. Similar adjustments can be made with a weir gate.

A water delivery system's design can facilitate treatment. For example, open vegetated channels (grassed swales) treat water as it passes through them. Water flowing through a corridor can provide water for trees and create a riparian habitat for wildlife and people. Vegetated channels treat water through the same mechanisms as constructed wetlands. Storing effluent in a basin so it can be diverted into a wetland is also a form of water treatment. In other words, the more water runs through and is detained in storage basins, open vegetated channels, and riparian corridors, the more treatment occurs.

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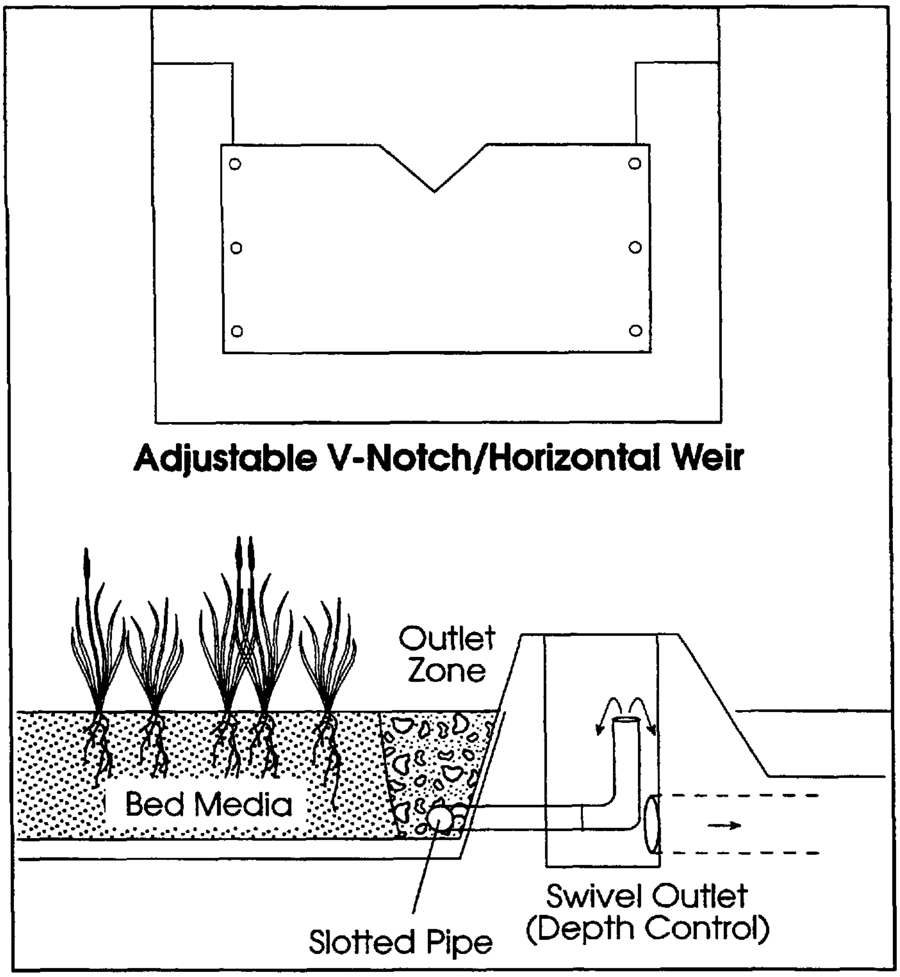

FIGURE 4-1
Water Level Control
Water level in constructed wetlands can be controlled by a weir or swivel riser pipe. Depth of water is critical to plant growth and hydraulic residence time.

If a wetland system is designed for discharge, a linear basin could allow different points of discharge. Depending on its quality, water could flow different distances in the basins before final release.

Discharge Site Rotation

The route water takes through a wetland system is a prime consideration for management. As water progresses, nutrient levels decline. Initial cells receive the most nitrogen and phosphorus. By varying the point of discharge into individual cells, nutrient loads can enhance vegetation.

The ability to dry a wetland cell while the remainder of the wetland continues to function helps in vegetation management, facility maintenance, and wildlife management. Natural wetlands regularly go through drying cycles, and constructed wetlands also benefit from drying. Once established for a year or

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more, perennial plants such as bulrush and cattail can survive up to a year of drying and even burning if removing old vegetation is desired. When water is returned to a dry cell, the depths should be shallow at first to avoid overtopping new sprouts.

Water Level Control

Water levels are key to vegetation establishment and management. Water depths also influence the degree of oxygen availability in the water column. Dissolved oxygen influences microbial action and the system's ability to treat water. Generally, water depths should be lowest during the hotter months when oxygen depletion is most critical. Water levels can be raised in the winter months with few deleterious effects. In areas prone to prolonged freezing conditions, water levels should be raised prior to freeze-over, and then lowered to allow winter operation under the ice.

Vegetation Management

When a wetland is constructed, vegetation should be established as quickly as possible. Planting of marsh species is best accomplished during the local plant growing season. Trees and shrubs generally transplant best when they are dormant. Plants can be established by seeding, planting rootlets or bulbs, or taking soil with seeds or other propagates from an existing wetland and spreading it in the new one. If left unseeded, wind-blown seeds and seeds brought in by animals will enter the wetland. Vegetation establishes faster when wetland plants are transplanted from a nearby existing wetland. Permits may be required for harvesting plants from natural wetlands. Plants such as bulrush can be dug and transplanted, using partial tubers buried in wet soil. Commercial sources for a wide variety of wetland plants are also available but additional time may be necessary for plant propagation.

When seeding, optimum conditions should be provided. Seeds are usually broadcast on wet soil or shallow water areas around pond edges. Seeds need oxygen to germinate but enough water to keep from drying out. Lowering the water level of a pond will provide a wet perimeter, which is a good place to sow seed. After germination, as shoots get taller, water can be raised slowly as the plants grow. Care should be taken to not overtop the new shoots for optimum growth.

Trees and shrubs can also add to the vegetative diversity of a constructed wetland. Willows (*Salix* spp.) prefer to grow along pond banks and on islands. Cottonwood trees (*Populus* spp.) add nesting and roost sites for wildlife in and around the wetlands. These plants are usually propagated by cuttings pushed into wet soil. The presence of trees will add a more diverse set of bird species in a created wetland.

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SECTION 5

Design for Ancillary Benefits

Treatment wetlands can be designed to provide significant benefits for wildlife support, biodiversity, and human use. Table 5-1 summarizes some design considerations for habitat and public use of treatment wetlands.

Fish and Wildlife Enhancement

Wildlife habitat management is one of the primary operational and management issues associated with constructed wetlands. When properly designed, constructed treatment wetlands can provide habitat suitable for wildlife use as an ancillary benefit. Constructed wetlands that have been designed for wastewater improvement have also been promoted for their wildlife habitat functions. Water level manipulation in wetlands is a commonly practiced wildlife management technique (Mitsch and Gosselink, 1993; Weller, 1978) and can result in benefits to plants and wildlife.

Wetland design for the benefit of wildlife incorporates a variety of vegetation types and cover classes. Areas with moderate to dense vegetation can provide adequate nesting sites and nest-building material for waterfowl. Open water also provides resting and foraging habitat. Shorebirds are attracted to shallow water and mudflats, which provide nesting and foraging habitat for these species. In addition to birds; amphibians, reptiles, and mammals also are important biological components in a wetland system. Amphibians and reptiles are dependent upon wetlands for breeding and foraging; the wetland system is critical to survival of amphibian tadpole stages. Mammals such as the muskrat (*Ondatra zibethica*), beaver (*Castor candensis*), and nutria (*Myocastor coypu*) are water-dependent and use the wetland for cover, reproduction, and foraging.

City of Arcata, California

In 1985, two treatment marshes were built adjacent to an existing treatment plant, with a third treatment marsh added in 1989. These effluent disposal wetlands comprise three 10-acre marshes located 0.25 mile west across Jolly Giant Slough in Arcata, California. The effluent from these marshes is returned to the treatment facility where it is chlorinated and dechlorinated before discharge to Humboldt Bay. The restoration of a 10-acre log pond on the site has created another freshwater swamp habitat. This swamp is watered with groundwater available on the site. The Arcata Marsh and Wildlife Sanctuary [AMWS] is now about 150 acres, consisting of the three effluent receiving marshes, one estuarine fishing lake, a freshwater swamp, a closed-out landfill, a restored estuary, and the open land areas in between. Some 174 species of birds were observed at the AMWS during a study conducted from 1984 to 1986 (Gearheart and Higley, 1993). Of these, 98 species were observed on the water areas. Waterbird use-days from 1984 to 1986 were

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TABLE 5-1
Summary of Design Considerations for Treatment Wetland Habitat and Public Use

Water Quality Considerations	
Pretreat toxic metals and organics.	It is important to protect those wildlife species that range outside the boundaries of the treatment wetland.
Pretreat excessive loads of mineral and organic sediments.	Mineral and organic sediments can suffocate plant roots.
Pretreat excessive organic and ammonia N concentrations.	High loadings of oxygen-demanding substances will cause nuisance conditions in wetlands, including poor plant growth.
Limit total organic loadings.	High loadings of oxygen-demanding substances will cause nuisance conditions in wetlands, including poor plant growth.
Maintain nonzero dissolved oxygen.	Anaerobic conditions in the water column will result in negative soil redox potentials and release of hydrogen sulfide and methane.
Wildlife Habitat Considerations	
Design flexibility to control water levels.	Water level control is the principal tool available to regulate plant growth and water quality in treatment wetlands.
Incorporate transverse deep-water zones.	Deep water zones serve multiple purposes, including improved hydraulic mixing, increased hydraulic residence time, a sump for solids storage, and perennial habitat for fish and ducks.
Use a diversity of plant species.	Polyculture will provide greater resilience to pests and operational upsets.
Use plant species with known benefits to wildlife species.	Each plant species benefits different wildlife species/groups.
Incorporate vertical structure by planting herbaceous, shrub, and tree strata.	Structural diversity equates to habitat variety for feeding, roosting, and nesting wildlife.
Incorporate horizontal structure by using littoral shelves and benches, as well as deep zones.	Plant diversity is promoted by varying water regimes that correspond to specific plant preferences.
Increase structural density by using irregular shorelines.	Irregular shorelines and "fingers" provide visual cover and greater ecotone (edge) length.
Include islands in open water areas.	Islands provide a refuge for birds and reptiles in wetlands where predation is a potential problem.
Install dead snags and nesting platforms.	Nesting habitat is frequently limited in newly constructed wetlands.
Public Use Considerations	
Provide parking and safe access to wetlands.	Humans will be attracted to treatment wetlands if they have access and feel safe.
Provide boardwalks and observation points.	Boardwalks offer the unusual opportunity for nonbiologists to get a "feel" for being in a wetland environment.
Incorporate interpretive displays.	The public is eager to learn more about the natural structure and function of wetlands.
Collect public comments for incorporation in design/operation modifications.	The public will provide useful suggestions for wetland improvement.
Publicize wetlands.	The public can be an ally during permitting and funding for treatment wetlands.
Enlist volunteer participation.	Providing the public with a sense of ownership will help to enlist support.
Establish accessible monitoring points.	Treatment wetlands provide excellent classrooms for environmental study.
Provide blinds for wildlife study.	Observing wildlife without disturbing it will optimize both habitat and public uses.
Maintain adequate monitoring records.	The public has a right to know about any hazards or benefits being created by a treatment wetland.

Source: Knight, 1997.

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estimated at 1.4 million. Shorebirds represented 88 percent of all bird use-days, and waterfowl (waterbirds typically eaten by humans), coots, and rails accounted for 88 percent. Peak waterbird use occurred during winter and through spring in both years, with 63 and 61 percent of the annual total bird use-days occurring during those seasons, respectively. Evidence of nesting species during this study was limited to mallards, cinnamon teal (*Anas cyanoptera*), northern shoveler (*Anas clypeata*), pied-billed grebe (*Podylimbus podiceps*), killdeer (*Charadrius vociferus*), and black-necked stilt (*Himantopus mexicanus*).

Herons and egrets used the marshes in a consistent pattern, with peaks occurring in early and mid-fall and lowest numbers in late spring. Herons nested in the surrounding areas; therefore, they did not leave during the summer. Puddle duck peak use occurred in winter both years. The low use of one of the treatment marshes from 1985 to 1986 coincided with the extended drainage of this marsh from early fall to the beginning of late fall 1985. The high numbers recorded from 1985 to 1986 coincided with the draining of this marsh for 2 days in mid-fall and then reflooding it slowly and maintaining the water level at a shallow depth, allowing the birds access to the pond bottom.

Diving ducks are seasonal visitors to the AMWS, arriving during late fall, peaking in winter and early spring and leaving by summer. When only waterfowl use of the respective areas is considered (Table 5-2), the Arcata Marsh Project had about 38 percent higher rates of use on an area basis than corresponding water bodies (Lake Earl, South Humboldt Bay).

TABLE 5-2
Comparison of Bird Use-Days at AMWS to Other Northcoast California Nonwastewater Wetlands

	Average annual			Average annual/12.4 acres	
Study Areas	Waterbird use days	Waterfowl use days	Hectares	Waterbird use days	Waterfowl use days
Lake Earl	3,091,305	1,467,843	923.0	17,117	8,128
South Humboldt Bay	2,968,218	1,420,119	1634.0	12,142	4,345
Arcata Oxidation Pond	884,000	137,745	22.3	50,301	30,883
Arcata Marsh Proper	1,432,253	98,689	37.8	189,451	13,054

Source: Gearheart and Higley, 1993.

Chevron Richmond Refinery Wetland, California

The Chevron Richmond Refinery Wetland (RRW) originated in 1988 as a pilot study marsh in the Number Two oxidation pond at Chevron's Richmond Refinery in Point Richmond, California. The pond was historically used as a polishing pond for refinery effluent between 1963 and 1985. However, water flow to this pond was reduced, and by 1985, the pond no longer provided any positive benefit (Chevron, 1996). Management of the pond was modified, and by 1989, vegetation was planted in the pond and the RRW became fully operational.

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A complete census of the species utilizing the wetland was taken and logged during 1990 and 1991 by Chevron wetland staff and members of the National Audubon Society. The estimated total number of birds using the wetland during 1991 was over 2 million individuals, based on a daily average of about 5,600 individuals. The heaviest usage was during the spring and fall migrations when huge numbers, sometimes as high as 25,000 per day, of transient shorebirds were on the wetland. Up to 85 different species of birds were sighted. These birds included those that have special-status afforded them by either state or federal agencies, such as the California clapper rail (*Rallus longirostris*), common yellowthroat (*Geothlypis trichas*), and osprey (*Pandion haliaetus*). Among the 85 species, ground nesting resident birds include mallard (*Anas platyrhynchos*), gadwall (*Anas strepera*), northern pintail (*Anas acuta*), Canada goose (*Branta canadensis*), black-necked stilt, American avocet (*Recurvirostra americana*), and killdeer. These birds have been recorded as having successfully raised broods in successive years and, for the most part, can be seen year-round (Chevron, 1996).

Public Use and Access

The decision to encourage public use should be made early in the planning process. Basic design can be altered to accommodate public use and still maintain public safety and habitat values. Examples include screening to avoid disturbing wildlife or a boardwalk to allow access into the wetland. Making plans to accommodate public use early in a project's development can garner additional public support for the created wetland.

Nature Study

The use of wetlands for observing wildlife and studying wetland ecosystems is a growing public activity. With a variety of different life forms, wetlands are some of the most vibrant natural areas that people can experience. This type of nonconsumptive use provides recreational opportunities without removing anything from the system.

Created wetlands can become outdoor classrooms for local schools. The very youngest students can enjoy the sights and sounds of a wetland, while the most advanced college classes can include studies on both wildlife use and water treatment aspects. Trails, viewing platforms, displays, and viewing blinds facilitate educational use. An interpretative plan developed early in the planning process would be a great help in coordinating nature study.

Figure 5-1 shows the wildlife viewing blind at the Show Low constructed wetlands in northern Arizona. This wetland is an example of a facility that improves access for nature study at a constructed wetland. The blind is designed to accommodate a class of up to 40 children. The viewing wall is a half circle with viewing ports at varying heights. A paved trail provides access for handicapped individuals who rely on wheelchairs.

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FIGURE 5-1
Viewing Blind at Pintail Lake, Show Low, Arizona
The blind permits visitors to view the wetland without disturbing wildlife.

Viewing blinds should be sited to provide optimum viewing and photographic opportunities. If several types of wetland habitat can be seen from the blind, more species of wildlife will be seen. Viewing lanes of open water should be provided so visitors can see shy species at a distance without disturbing them. Perching trees at the proper distance can afford views of rare species such as bald eagles. Downed trees and rocks can be placed at proper distances from the blind to provide loafing sites for animals.

The aesthetics of a constructed wetland should not be underrated. The variety of textures, color, and form make them very scenic areas. The raw soils left after construction are soon covered by a dense green plant cover. Inclusion of scenic values in design can result in a beautiful wetland.

Fishing, Hunting and Aquaculture

Although fishing can be accommodated, it can have drawbacks. Fisherman may disrupt ground nesting birds and displace normal feeding patterns. Sometimes, the public is reluctant to consume fish from effluent-dominated waters.

If fishing is desired, then deep water areas must be provided. Oxygen levels can be depleted by decomposing vegetation, especially during winter months. If game fish are to be part of the wetland fauna, a fisheries biologist needs to be part of the design team.

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Hunting currently occurs in several of the constructed wetlands throughout North America and primarily focuses on waterfowl. The waterfowl hunting season occurs in the fall after the breeding season ends and when birdwatching activity usually diminishes. Hunters and birdwatchers are somewhat incompatible, and priorities for both groups should be considered during project planning. In addition to waterfowl, deer, turkey, and other game animals are attracted to wetlands for water and forage. Decisions about hunting are best made locally with game and fish department involvement.

Aquaculture is possible in a limited number of constructed wetland. Fish and shellfish are raised in some areas for profit. Water temperatures in constructed wetlands typically favor warm-water fisheries. Bait fish can be raised for market if their habitat requirements are factored in the wetland design. However, submergent vegetation normally associated with wetlands can interfere with normal procedures such as seining to manage populations. Populations of fur-bearing mammals such as muskrats or nutria may be high in some treatment wetlands. Potential for bioaccumulation of metals or organics is a concern for rearing food organisms. Intense aquaculture using animal feeds may result in unacceptably high concentrations of organic matter, solids, and nutrients in the wetland effluent and is not recommended.

Control of Nuisance Conditions

Treatment wetlands are typically enriched, seminatural wetland ecosystems. By nature, they have the potential to create conditions that may be a nuisance to human neighbors or to the wildlife species they harbor. Conceivable nuisances include mosquito breeding habitat, creation of odors, attraction of dangerous reptiles (snakes and alligators), potential for accidental drowning, and attraction of nuisance wildlife. Few quantitative treatment wetland data exist on any of these potential nuisances, and data to help assess their possible effect on implementation of this technology are insufficient.

Wetlands and other stagnant water bodies can provide breeding habitat for mosquitoes. Some of these mosquito species can transmit diseases to humans or to livestock. Also, mosquitoes may be a nuisance as a result of large numbers and painful bites. Few quantitative data have been published on mosquito population densities in treatment wetlands, although a large number of treatment wetland systems are periodically monitored for mosquito larvae and pupae populations. General conclusions are that the numbers of breeding mosquitoes in treatment wetlands are similar to those in adjacent natural wetlands (Crites *et al.*, 1995). When mosquito populations are present, their numbers appear to be directly related to organic loadings (Martin and Eldridge, 1989; Stowell *et al.*, 1985; Wieder *et al.*, 1989; Wile *et al.*, 1985; Wilson *et al.*, 1987).

Mosquito populations appear to be effectively controlled in treatment wetlands by small fish such as the mosquitofish (*Gambusia affinis*) (Dill, 1989; Steiner and Freeman, 1989; Hammer, 1997). However, fish may not be able to control mosquito populations in portions of treatment wetlands that are colonized by dense populations of floating vegetation mats (Walton *et al.*, 1990). Under these circumstances, control by

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use of insecticides such as Abate or bacterial agents such as *Bacillus thuringiensis israelensis* H-14 (Bti) or *B. sphaericus* (Bs) may be required (Tennessen, 1993).

No published qualitative information on odors associated with treatment wetlands was found during preparation of this assessment. Most treatment wetlands have odors similar to the normal range observed in natural wetlands (Kadlec and Knight, 1996).

Dangerous reptiles, including poisonous snakes and alligators, are attracted to treatment wetlands in some regions of the United States. These same species are generally a normal component of natural wetlands in those same areas, and most citizens are aware of the need to avoid these animals when they are encountered.

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Not for Resale

SECTION 6

References

40 CFR 9, 122, 123, 131, and 132. Tuesday, March 23, 1995. *Final Water Quality Guidance for the Great Lakes System*; Final Rule.

Adams, C.E., D.L. Ford, and W.W. Eckenfelder, Jr. 1981. *Development of Design And Operational Criteria For Wastewater Treatment.* Enviro Press, Nashville, TN.

Addleton, A., A. Brown, M.M. Baghat, R.F. Loveridge, J.I. Mitchell, E. May, M.G. Ford, and J.E. Butler. 1996. Potential of Gravel Bed Hydroponics for the Treatment of Industrial Wastewater. In R. Haberl and J. Laber, (Eds.), *Proceedings of the 5th International Conference on Wetland Systems for Pollution Control*, Vienna, pp. X/3-1-8.

ADEQ (Arizona Department of Environmental Quality). 1995. *Arizona Guidance Manual for Constructed Wetlands for Water Quality Improvement.* Prepared for ADEQ by R.L. Knight, R. Randall, M. Girts, J.A. Tress, M. Wilhelm, and R.H. Kadlec.

Albers, P.M., and M.B. Camardese. 1993. Effect of Acidification on Metal Accumulation by Aquatic Plant and Invertebrates, 1. Constructed Wetlands. *Environ. Toxicol. Chem.* 12:959-967.

Altman, B., K.M. Lilie, K. Nowak and V. Schulz-Berendt. 1989. *Pflanzenbiologische Reinigung von Abwässern aus einem Mineralöltanklager* (Macrophyte Purification of Wastewater from a Petroleum Tank Farm). Report on DBMK Project 388, ARGE DGMK/Mobil Oil AG, Hamburg, Germany.

Alvord, H.H. and R.H. Kadlec. 1995a. Fate and Transport of Atrazine in the Des Plaines Wetlands. *Ecol. Modeling*. 90:97-107.

Alvord, H.H., and R.H. Kadlec. 1995b. The Interaction of Atrazine with Wetland Sorbents. *Ecolog. Engin.* 5(4): 469-479.

Anderson, P.A. 1996. Advanced Treatment of Sugar Beet Process Water Using Constructed Wetlands. In R. Haberl and J. Laber, (Eds.), *Proceedings of the 5th International Conference on Wetland Systems for Pollution Control*, Vienna, Session 10. pp. 2-1 to 2-8.

Anderson, T.A., and B.T. Walton. 1995. Comparative Fate of [^{14}C] Trichloroethylene in the Root Zone of Plants from a Former Solvent Disposal Site. *Environ. Toxicol. Chem.* 14(12):2041-2047.

ANL. 1990. *Environmental Consequences of, and Control Processes for, Energy Technologies.* Argonne National Laboratory. Noyes Data Corporation, Park Ridge, NJ. pp. 453.

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Not for Resale

Arnold, W.R. and G.R. Biddinger. 1995. *Probabilistic Ecological Risk Assessment of Selected PAH's in Sediments Near a Petroleum Refinery*. Poster Paper, SETAC World Congress, Vancouver, B.C., Canada, November 5-9.

ASTM. 1993. *ASTM Standards on Aquatic Toxicology and Hazard Evaluation*. ASTM Publication 03-547093-16, Philadelphia, PA.

ATSDR. 1991. *Toxicological Profile for Pyridine*. U.S. Department of Health and Human Services, Public Health Service, ATSDR, Atlanta, Georgia.

ATSDR. 1992. *Toxicological Profile for Benzo(g,h,i) perylene; Benzo(k)fluoranthene; Phenanthrene, Aluminum)*. U.S. Department of Health and Human Services, Public Health Service, ATSDR, Atlanta, Georgia.

ATSDR. 1993. *Toxicological Profile for Chromium, trivalent and Mercury*. U.S. Department of Health and Human Services, Public Health Service, ATSDR, Atlanta, Georgia.

Bahlo, K.E. and F.G. Wach. 1990. Purification of Domestic Sewage With and Without Feces by Vertical Intermittent Filtration in Reed and Rush Beds. In P. F. Cooper and B. C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control*. Pergamon Press, Oxford, UK, pp. 215-221.

Barjaktarovic, L., F.S. Bishay, and P.G. Nix. 1995. *Ceriodaphnia dubia and Chironomus tentans in situ: Toxicity Tests to Assess Oil Sands Wastewater Treatment in Constructed Wetlands*. Poster presentation at SETAC World Congress, Vancouver, B.C., Canada, November 5-9.

Bavor, H.J., D.J. Roser, S.A. McKersie, and P. Breen. 1988. *Treatment of Secondary Effluent*. Report to Sydney Water Board, Sydney, NSW, Australia.

Bernard, J.M. and F.A. Bernard. 1989. Seasonal Changes in Copper, Zinc, Manganese, and Iron Levels in *Carex rostrata* (Stokes). In R.R. Sharitz and J.W. Gibbons (Eds.), *Freshwater Wetlands and Wildlife*. U.S. Dept. of Energy, CONF - 8603101, Oak Ridge, TN. pp. 343-350.

Best, E.P.H. 1996. Personal communication. U.S. EPA Environmental Research Laboratory. Athens, GA.

Best, G.R. 1987. Natural Wetlands - Southern Environment: Wastewater to Wetlands, Where Do We Go from Here? In K.R. Reddy and W.H. Smith (Eds.), *Aquatic Plants for Water Treatment and Resource Recovery*. Magnolia Publishing, Orlando. pp. 99-120

Bishay, F.S., S.E. Bayley, and P.G. Nix. 1995a. *Ammonia Removal in Constructed Wetlands Receiving Oil Sands Wastewater, Fort McMurray, AB*. Paper presented at SETAC World Congress, Vancouver, B.C., Canada, November 5-9.

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No reproduction or networking permitted without license from IHS

Not for Resale

Bishay, F.S., J.R. Gulley, S.H. Hamilton, and P.G. Nix. 1995b. *Constructed Wetlands as a Treatment System for Wastewater from an Oil Sands Mining and Extraction Operation.* Poster presentation at SETAC World Congress, Vancouver, B.C., Canada, November 5-9.

Bolt, G.H., M.F. De Boodt, M.H.B. Hayes, and M.B. McBride (Eds.). 1991. *Interactions at the Soil Colloid-Soil Solution Interface*. Kluwer Academic Publishers, Netherlands.

Brix, H. 1990. Gas Exchange Through the Soil-Atmosphere Interphase and Through Dead Culms of *Phragmites australis* in a Constructed Reed Bed Receiving Domestic Sewage. *Water Research.* 24(2):259-266.

Brix, H. 1994. Constructed Wetlands for Municipal Wastewater Treatment in Europe. In W.J. Mitsch, (Ed.), *Global Wetlands: Old World and New.* Elsevier, Amsterdam.

Brownlow, A.H. 1979. *Geochemistry.* Prentice-Hall, Englewood Cliffs, NJ.

Bulc, T, D. Vrhovsek, and V. Kukanja. 1996. The Use of Constructed Wetland for Landfill Leachate Treatment. In R. Haberl and J. Laber, (Eds.), *Proceedings of the 5th International Conference on Wetland Systems for Pollution Control.* Vienna. pp. X/4-1-8.

Burgoon, P.S. 1993. *Oxidation of Carbon and Nitrogen in the Root Zone of Emergent Macrophytes Grown in Wetland Microcosms.* Ph.D. Dissertation, University of Florida, Gainesville, FL.

Burka, U. and P.C. Lawrence. 1990. A New Community Approach to Wastewater Treatment with Higher Plants. In P. F. Cooper and B. C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control.* Pergamon Press, Oxford, UK. pp. 359-371.

Caswell, P.C., J.C. Emerick, and D. Gelb. 1992. *Engineered Wetlands-Based Biological Treatment Systems for Produced Water.* Research project sponsored by Wyoming DEQ and Marathon Oil Co. and conducted by the Dept. of Environmental Science and Engineering, Colorado School of Mines, Golden, CO.

CEHT (Center for Environmental and Human Toxicology). 1995. *Calculated Values for Soil Cleanup Goals for Use in FDEP.* July.

CH2M HILL. 1988. *Carolina Bay Effluent Discharge Pilot Program. Bear Bay Baseline and Operational Monitoring Report.* Final Project Report, July 1985 - January 1988. 201 Facilities Plan Amendment. Prepared for Grand Strand Water & Sewer Authority.

CH2M HILL. 1991. *Grand Strand Water and Sewer Authority Central Wastewater Treatment Plant Wetlands Discharge.* Central Slough Pilot Study Fifth Annual Report, July 1990-June 1991. Prepared for Grand Strand Water & Sewer Authority.

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Not for Resale

CH2M HILL. 1992. *Carolina Bay Natural Land Treatment Program.* Prepared for the Grand Strand Water & Sewer Authority.

CH2M HILL. 1994a. *Experience with the Use of Constructed Wetland Effluent Treatment Systems in the Pulp and Paper Industry.* Draft Report for the National Council of the Paper Industry for Air and System Improvement, Inc. Gainesville, Florida.

CH2M HILL. 1994b. *Boot Wetland Treatment System Operational Monitoring Report 3 Year Summary* (October 1990 - March 1994). Prepared for Poinciana Utilities. CH2M HILL, Gainesville, Florida.

CH2M HILL. 1995. *Great Swamp Effluent Management System Baseline Monitoring Report.* Summary Report December 1993 - November 1994. Prepared for Beaufort-Jasper Waste and Sewer Authority.

CH2M HILL. 1996. *Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment.* Draft Report Prepared for U.S. Environmental Protection Agency, Bureau of Reclamation, and City of Phoenix Environmental Technology Initiative Project. August, 1996. CH2M HILL, Gainesville, Florida.

CH2M HILL and Payne Engineering. 1997. *Constructed Wetlands for Livestock Wastewater Management. Literature Review, Database and Research Synthesis.* Gulf of Mexico Program, Stennis Space Center, Mississippi.

Chaney, R. (no date). *Proposed No Observable Adverse Effect Limit* (NOAEL). U.S. Department of Agriculture.

Cheadle, S.A., L. Wolfe and S. McCutcheon. 1996. *Phytoremediation of TNT.* Poster paper presented at Proceedings of Symposium on Constructed Wetlands in Cold Climates, Niagara-on-the-Lake, Ontario.

Chen, J., F. Wei, C. Zheng, Y. Wu, and D.C. Adriano. 1991. Background Concentrations of Elements in Soils of China. *Water, Air, and Soil Pollution.* 57-58:699-712.

Chevron Richmond Refinery. 1996. Unpublished data.

Choate, K.D., G.R. Steiner, and J.T. Watson. 1990. *Second Monitoring Report: Demonstration of Constructed Wetlands for Treatment of Municipal Wastewaters, March 1988 to October 1989.* TVA/WR/WQ-90/11. TVA Water Quality Department, Chattanooga, TN.

Conn, W.M. and A.C. Langworthy. 1984. Practical Operation of a Small Scale Aquaculture. Proceedings from *Water Reuse III*, Volume 2. American Water Works Association.

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Not for Resale

Cooper, P.F. 1990. *European Design and Operations Guidelines for Reed Bed Treatment Systems.* Prepared by the EC/EWPCA Emergent Hydrophyte Treatment Systems Expert Contact Group. Water Research Centre, Swindon, UK.

Cooper, P.F. and B.C. Findlater, (Eds.) 1990. Constructed Wetlands in Water Pollution Control. Proceedings of the *International Conference on the Use of Constructed Wetlands in Water Pollution Control.* Cambridge, U.K. September 24-28, 1990. Pergamon Press, Oxford, UK.

Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. *Classification of Wetlands and Deepwater Habitats of the United States.* U.S. Fish and Wildlife Service, Office of Biological Services. FWS/OBS -79/31.

Craft, C.B. and C.J. Richardson. 1993. Peat Accretion and Phosphorus Accumulation Along a Eutrophication Gradient in the Northern Everglades. *Biogeochem.* 22:133-156.

Crites, R.W., R.C. Watson, and C.R. Williams. 1995. *Removal of Metals in Constructed Wetlands.* Paper presented at Water Environment Federation 68th Annual Conference and Exposition, Miami, FL, 21-15 October. Water Environment Federation, Alexandria, Virginia.

Crumpton, W.G., T.M. Isenhart and S.W. Fisher. 1993. The Fate of Non-Point Source Nitrate Loads in Freshwater Wetlands: Results from Experimental Wetland Mesocosms. In G.A. Moshiri, (Ed.), *Constructed Wetlands for Water Quality Improvement.* Lewis Publishers , Boca Raton, FL. pp. 283-291.

Davis, L. 1995. *A Handbook of Constructed Wetlands. A Guide to Creating Wetlands for: Agricultural Wastewater, Domestic Wastewater, Coal Mine Drainage, and Stormwater in the Mid-Atlantic Region.* Volumes 1-5. USDA-NRCS, U.S. EPA Region III, and PA DER.

de Zeeuw, W., Heijnen, G. and J. de Vries. 1990. Reed Bed Treatment as a Wastewater: (Post) Treatment Alternative in the Potato Starch Industry. In P.F. Cooper and B.C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control.* Pergamon, Oxford, UK. pp. 551-554.

DeLaune, R.D., C.M. Reddy, and W.H. Patrick, Jr. 1981. Accumulation of Plant Nutrients and Heavy Metals Through Sedimentation Processes and Accretion in a Louisiana Salt Marsh. *Estuaries.* 4:328-334.

Delfino, J.J., T.L. Crisman, and J. F. Gottgens. 1993. *Spatial and Temporal Distribution of Mercury in Everglades and Okefenokee Wetland Sediments.* Final Project Report. Department of Environmental Engineering Sciences. Volume 1.

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No reproduction or networking permitted without license from IHS

Not for Resale

Dill, C.H. 1989. Wastewater Wetlands: User Friendly Mosquito Habitats. In D.A. Hammer, (Ed.), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural.* Lewis Publishers, Chelsea, MI. pp. 664-668

Dong, K. and C. Lin. 1994. Treatment of Petrochemical Wastewater by the System of Wetlands and Oxidation Ponds and Engineering Design of the System. *Proceedings of the Fourth International Association on Water Quality Conference on Wetland Systems for Water Pollution Control.* Guangzhou, China. November 6-10, 1994. Center for International Development and Research, South China Institute for Environmental Sciences, China. pp. 628-633.

Dragun, J. 1988. The Fate of Hazardous Materials in Soil (What Every Geologist and Hydrologist Should Know), Part 2 *HMC*, May/June.

Duda P.J. 1992. *Chevron's Richmond Refinery Water Enhancement Wetland.* Report to the Regional Water Quality Control Board, Oakland, CA.

Dunn, A.W., J.H. Rodgers, Jr., W.B. Hawkins, P.B. Dorn, D.E. Rowland, T.E. Vipond, and L.W. Ross. 1995. Design and Construction of a Wetland for the Removal of Metals and Toxicity from Refinery Effluent. Manuscript submitted to *Ecological Engineering*.

Edwards, M.E. 1993. Unpublished data from Tennessee Valley Authority.

Eger, P. 1993. Unpublished data from the Minnesota Department of Natural Resources.

EPA (U.S. Environmental Protection Agency). 1985. *Freshwater Wetlands for Wastewater Management Handbook.* EPA Report 904/9-85-135. EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1986a. *Superfund Public Health Evaluation Manual.* EPA Report 540 1-86 060. EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1986b. *Quality Criteria for Water.* EPA Report 440/5-86-001.

EPA (U.S. Environmental Protection Agency). 1986c. *Update #1 to Quality Criteria For Water.* EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1987. *Update #2 to Quality Criteria For Water.* EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1988a. *Design Manual. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment.* EPA Report 625/1-88/022. Office of Research and Development. Center for Environmental Research Information. Cincinnati, OH.

Copyright American Petroleum Institute
Provided by IHS under license with API
No reproduction or networking permitted without license from IHS

Not for Resale

EPA (U.S. Environmental Protection Agency). 1988b. *Superfund Public Health Evaluation Manual.* EPA Report PB89-135859. EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1988c. *Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal.* EPA Report 430/09-88-005. EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1989a. *Risk Assessment Guidance for Superfund: Human Health Evaluation Manual Part A. Exhibit 6-4: Important Physical/Chemical and Environmental Fate Parameters*. EPA Report 9285.701A. Office of Emergency and Remedial Response, EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1989b. Proposed Rule: Standards for Disposal of Sewage Sludge. Part 503 Regulations. *Federal Register.* Vol. 54. p. 5746.

EPA (U.S. Environmental Protection Agency). 1992. *Developing a Work Scope for Ecological Assessments.* ECO Update. EPA Report 9345.0-05I, 1:4.

EPA (U.S. Environmental Protection Agency). 1993a. *Subsurface Flow Constructed Wetlands for Wastewater Treatment: A Technology Assessment*. EPA Report 832-R-93-001. Office of Water, EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1993b. Toxic Substances Spreadsheet. Updated by Region IV Water Quality Standards Section. Section 304(a) of the Clean Water Act. EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1993c. *Constructed Wetlands for Wastewater Treatment and Wildlife Habitat. 17 Case Studies.* EPA Report 832-R-93-005.

EPA (U.S. Environmental Protection Agency). 1993d. *Technical Basis for Deriving Sediment Quality Criteria for Nonionic Organic Contaminants for Protection of Benthic Organisms by Using Equilibrium Partitioning*. EPA Report 822-R-93-011. EPA, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1993e. *Sediment Quality Criteria for the Protection of Benthic Organisms*. September.

EPA (U.S. Environmental Protection Agency). 1994a. *Technical Background Document for Soil Screening Guidance, Review Draft.* July 1994. Office of Solid Waste and Emergency Response, EPA, Washington, DC.

EPA (U.S. Environmental Protection Agency). 1994b. *Using Toxicity Tests in Ecological Risk Assessment.* ECO Update. EPA Report 540-F-94-012, Vol. 2, No. 2, September 1994.

Copyright American Petroleum Institute
Provided by IHS under license with API
No reproduction or networking permitted without license from IHS
Not for Resale

EPA (U.S. Environmental Protection Agency). 1996. *Ecotox Threshholds.* ECO Update. EPA Report 540/F-95/038. Intermittent Bull. Vol. 3, No. 2, January 1996.

EVS Consultants. 1993. *Constructed Wetlands for the Treatment of Oil Sands Wastewater. Technical Report #2.* EVS Consultants, North Vancouver, B.C., Canada.

EVS Consultants. 1994. *Constructed Wetlands for Treatment of Oil Sands Wastewater. Technical Report #3.* Prepared for SUNCOR, Inc. EVS Consultants, North Vancouver, B.C., Canada.

Ewel, K.C. and H.T. Odum, 1984. *Cypress Swamps.* University of Florida Press, Gainesville, FL.

FAC (Florida Administrative Code). 1989. Florida Department of Environmental Protection, Tallahassee, FL.

Farmer, J.M. 1992. Unpublished. *U.S. Oil Refining.* Internal Report on Constructed Wetlands.

Farmer, J.M., 1996. Personal Communication.

Feijtel, T.C. and R.D. DeLaune, and W.H. Patrick, Jr. 1989. Carbon, Nitrogen, and Micronutrient Dynamics in Gulf Coast Marshes. In R.R. Sharitz and J.W. Gibbons (Eds.), *Freshwater Wetlands and Wildlife.* Proceedings of a Symposium held in Charleston, South Carolina, March 24-27, 1986. U.S. Department of Energy. CONF-8603101. pp. 47-60

Fennesey, M.S., C. Brueske, and W.J. Mitsch. 1992. Sediment Deposition Patterns in Restored Freshwater Wetlands Using Sediment Traps. *The Des Plaines River Wetlands Demonstration Project.* Volume 4. Wetlands Research, Inc., Chicago, IL.

Finlayson, C.M., Von Oertzen, I., and A.J. Chick. 1990. Treating Poultry Abattoir and Piggery Effluents in Gravel Trenches. In P.F. Cooper and B.C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control.* Pergamon, Oxford, UK. pp. 559-562.

Fortescue, J.A.C. 1980. *Environmental Geochemistry. A Holistic Approach.* Springer-Verlag, New York, NY.

Fowler, B.A. (Ed.). 1983. *Biological and Environmental Effects of Arsenic. Topics in Environmental Health.* Volume 6. Elsevier, New York, NY.

French, R.H. 1985. *Open-Channel Hydraulics.* McGraw-Hill, New York.

Gale, P.M., I. Dévai, K.R. Reddy and D.A. Graetz. 1993. Denitrification Potential of Soils from Constructed and Natural Wetlands. *Ecolog. Engin.* 2(2):119-130.

Gambrell, R.P., R.A. Khalid, and W.H. Patrick, Jr. 1987. Capacity of a Swamp Forest to Assimilate the TOC Loading from a Sugar Refinery Wastewater Stream. *Journal WPCF.* 39(10):897-904.

Copyright American Petroleum Institute
Provided by IHS under license with API
No reproduction or networking permitted without license from IHS

Not for Resale

Gambrell, R.P. 1994. Trace and Toxic Metals in Wetlands—A Review. *J.Environ. Tech.* 23:883-891.

Gearheart, R.A. 1992. Use of Constructed Wetlands to Treat Domestic Wastewater, City of Arcata, California. *Water, Science, and Technology.* 26:1625-1637.

Gearheart, R.A. and M. Higley. 1993. Constructed Open Surface Wetlands: The Water Quality Benefits and Wildlife Benefits - City of Arcata, California. In G.A. Moshiri (Ed.), *Constructed Wetlands for Water Quality Improvement.* CRC Press, Inc.

Gersberg, R.M., S.R. Lyon, B.V. Elkins, and C.R. Goldman. 1985. The Removal of Heavy Metals by Artificial Wetlands. *Proceedings, Water Reuse Symposium III, Future of Water Reuse.* AWWA Research Foundation.

Giblin, A.E. 1985. Comparisons of the Processing of Elements by Ecosystems, II: Metals. In P.J. Godfrey et al. (Eds.), *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters.* Van Nostrand Reinhold Company, New York, NY. pp. 158-179.

Giesy, J.P., Jr., H.J. Kania, J.W. Bowling, R.L. Knight, S. Mashburn, and S. Clarkin. 1979. Fate and Biological Effects of Cadmium Introduced into Channel Microcosms. EPA-600/3-79-039. 156 pp.

Glooschenko, W.A., L. Holloway, and N. Arafat. 1986. The Use of Mires in Monitoring the Atmospheric Deposition of Heavy Metals. *Aquatic Botany.* 25:179-190.

Greipsson, S., and A.A. Crowder. 1992. Amelioration of Copper and Nickel Toxicity by Ion Plaque on Roots of Rice *Oryza-sativa. Can. J. Bot.* 70:824-830.

Gulley, J.R. and D.J. Klym. 1992. Wetland Treatment of Oil Sands Operation Waste Waters. In R.K. Singhai, A.K. Mehrotra, K. Fytas, and J.L. Collins (Eds.), *Environmental Issues and Waste Management in Energy and Minerals Production.* Balkema, Rotterdam. pp. 1431-1438.

Gulley, J.R., H.R. Hamilton, and B. Taylor. 1995. *Oil Sands Tailings Leachability and Toxicity Evaluation.* Poster presentation at SETAC World Congress, Vancouver, B.C., Canada, November 5-9.

Gulley, J.R. and P.G. Nix. 1993. *Wetland Treatment of Oil Sands Operation Waste Waters.* Preprint of paper presented at Conference of Biogeochemical Cycling in Wetlands, Baton Rouge, LA, February 1993.

Haberl, R. and R. Perfler. 1989. Root-zone System: Mannersdorf - New Results. In D.A. Hammer (Ed.), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural.* Lewis Publishers, Chelsea, MI. pp. 606-621.

Copyright American Petroleum Institute
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Not for Resale

Hall, J.F. 1996. *Summary Report on Free Water Surface Wetlands for Tertiary Treatment of Refinery Effluent*. (Unpublished). Texaco E&P Technology Department, Bellaire, TX.

Hammer, D.A. 1997. *Creating Freshwater Wetlands*. 2nd Edition. CRC Press, Boca Raton, Florida.

Harper. H.H. and Livingston. 1985. Unpublished Data from Hidden Lake, Orlando, Florida.

Harper, H.H., M.P. Wanielista, B.M. Fries, and D.M. Baker. 1986. *Stormwater Treatment by Natural Systems*. Florida Department of Environmental Regulation Report 84-026.

Hawkins, W.B., A. Dunn, and J.H. Rodgers, Jr. 1995. *Evaluation of Pilot-Scale Constructed Wetlands for Tertiary Treatment of Refinery Effluent*. Presented at Second SETAC World Congress, Vancouver, B.C., Canada, November 5-9.

Hawkins, W.B., J.H. Rodgers, Jr., W.B. Gillespie, Jr., A.W. Dunn, P.B. Dorn, and M.L. Cano. 1997. Design and Construction of Wetlands for Aqueous Transfers and Transformations of Selected Metals. *Ecotoxicol. Environ. Safety*. 36(3):238.

Hazen, R.E. and T.J. Kneip. 1980. Biogeochemical Cycling of Cadmium in a Marsh Ecosystem. In J.O. Nriagu (Ed.), *Cadmium in the Environment. Part I: Ecological Cycling*. Wiley-Interscience. New York, NY. pp. 399-424.

Hendrey, G.R., J. Clinton, K. Blumer, and K. Lewin. 1979. *Lowland Recharge Project Operations, Physical, Chemical, and Biological Changes 1975-1978*. Final Report to the Town of Brookhaven. Brookhaven National Laboratory.

Herskowitz, J. 1986. *Listowel Artificial Marsh Project Report*. Ontario Ministry of the Environment, Water Resources Branch, Toronto.

Hey D.L., A.L. Kenimer, and K.R. Barrett. 1994. Water Quality Improvement by Four Experimental Wetlands. *Ecological Engineering*. 3(4):381-398.

Hinchman, R.R., R.G. McNally, and M.C. Negri. 1993. *Biotreatment of Produced Waters*. Research Project sponsored by The Gas Research Institute, Chicago, IL, conducted at Argonne National Laboratory, Argonne, IL.

Hokosawa, Y. and T. Horie. 1992. Flow and Particulate Nutrient Removal by Wetlands with Emergent Macrophytes. *Sci. Total Environ* (Supplement). pp. 1271-1282.

Honig, R. 1988. *Tenneco's Use of a Rock-Reed Filter at a Natural Gas Pipeline Compressor Station*. Poster paper at International Conference on Constructed Wetlands for Wastewater Treatment, Chattanooga, TN.

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No reproduction or networking permitted without license from IHS
Not for Resale

Howard, R.H., R.S. Boethling, W.F. Jarvis, W.M. Meylan and E.M. Michalenko. 1991. *Handbook of Environmental Degradation Rates*. Lewis Publishers, Chelsea, MI.

HSDB. 1994. *Hazardous Substance Data Bank.* Online search for specified chemicals.

Jackson, A.W., J.H. Pardue and R. Araujo. 1997. Monitoring Crude Oil Mineralization in Salt Marshes: Use of Stable Carbon Isotope Ratios. *Environ. Sci. Technol.* 30(4):1139.

Jackson, W.A. and J.H. Pardue. 1996. *Monitoring Crude Oil Mineralization in Salt Marshes: Use of Stable Carbon Isotope Ratios*. Paper presented at 4th Symposium on Biogeochemistry of Wetlands, New Orleans, LA.

Kaczynski, V.W. 1985. Considerations for Wetland Treatment of Spent Geothermal Fluids. In P.J. Godfrey et al. (Eds.), *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters*. Van Nostrand Reinhold Company, New York, NY. pp. 48-65.

Kadlec, R.H. 1996. Unpublished data.

Kadlec, R.H. 1994. Unpublished data from wetlands near Holly, MI.

Kadlec, R.H. and R.L. Knight. 1996. *Treatment Wetlands*. Lewis Publishers, CRC Press, Inc., Boca Raton, FL.

Kadlec, R.H. and K. Srinivasan. 1994. *Wetlands for Treatment of Oil and Gas Well Wastewaters*. Report to U.S. Department of Energy, Contract No. DE-AC22-92MT92010.

Kadlec, R.H. and D.L. Tilton. 1979. The Use of Freshwater Wetlands as a Tertiary Wastewater Treatment Alternative. *CRC Critical Reviews in Environmental Control*. 9(2):185-212.

Kania, H.J., R.L. Knight, and R.J. Beyers. 1976. *Fate and Biological Effects of Mercury Introduced into Artificial Streams.* EPA Report 600/3-76-060. EPA, Washington, D.C.

Karouna-Reiner, N.K. 1995. *An Assessment of Contaminant Toxicity to Aquatic Macroinvertebrates in Urban Stormwater Treatment Ponds*. Masters Thesis, University of Maryland.

Katznelson, R., W.T. Jewell, and S.L. Anderson. 1995. Spatial and Temporal Variations in Toxicity in an Urban-Runoff Treatment Marsh. *Environ. Toxicol. Chem.* 14(3):371-482.

Kirk, P.W. 1987. Pollution Control Legislation. In J.N. Lester (Ed.), *Heavy Metals in Wastewater and Sludge Treatment Processes*. Volume I. Sources, Analysis, and Legislation. CRC Press, Boca Raton, FL. pp. 65-103.

Copyright American Petroleum Institute
Provided by IHS under license with API
No reproduction or networking permitted without license from IHS

Not for Resale

Kiss, M.K., and G. and Lakatos. 1996. Operation of Constructed Wetland System for Post-Purification of Oily Sewage Water. In R. Haberl and J. Laber, (Eds.), *Proceedings of the 5th International Conference on Wetland Systems for Pollution Control*. Vienna, Austria. pp. P18-1-4.

Kleinmann, R.L.P. and R. Hedin. 1989. Biological Treatment of Mine Water: An Update. In M.E. Chalkley, B.R. Conrad, V.I. Lakshmanan, and K.G. Wheeland (Eds.), *Proceedings of the International Symposium on Tailings and Effluent Management*. Halifax, August 20-24, 1989. Pergamon Press, New York, NY. pp. 173-179.

Knight, R.L. 1987. Effluent Distribution and Basin Design for Enhanced Pollutant Assimilation By Freshwater Wetlands. In K.R. Reddy and W.H. Smith (Eds.), *Aquatic Plants for Water Treatment and Resource Recovery*. Magnolia Publishing Company, Orlando, Florida. pp. 913-921.

Knight, R.L. 1994. Unpublished data from a constructed marsh receiving pulp and paper mill effluent.

Knight, R.L. 1997. Wildlife Habitat and Public Use Benefits of Treatment Wetlands. *Water Sci. Tech.* 35(5):35-43.

Knight, R.L. and M.E. Iverson. 1990. Design of the Fort Deposit, Alabama Constructed Wetland Treatment System. D.F. Cooper and B.C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control*. Pergamon Press, Oxford, UK.

Knight, R.L., R.W. Ruble, R.H. Kadlec, and S.C. Reed. 1993a. *Database: North American Wetlands for Water Quality Treatment. Phase II Report.* Prepared for U.S. EPA, September. Washington, D.C.

Knight, R.L., R.W. Ruble, R.H. Kadlec, and S.C. Reed. 1993b. Wetlands for Wastewater Treatment: Performance Database. In G.A. Moshiri, (Ed.), *Constructed Wetlands for Water Quality Improvement.* Lewis Publishers, Boca Raton, FL. pp. 35-58.

Lake, D.L. 1987. Sludge Disposal to Land. In J.N. Lester (Ed.), *Heavy Metals in Wastewater and Sludge Treatment Processes*. Volume II. Treatment and Disposal. CRC Press, Boca Raton, FL. pp. 91-130.

Lan, C., G. Chen, L. Li, and M.H. Wong. 1990. Purification of Wastewater from a Pb/Zn Mine Using Hydrophytes. In P.F. Cooper and B.C. Findlater (Eds.), *Proceedings of the International Conference on the Use of Constructed Wetlands in Water Pollution Control*. Cambridge, U.K. September 24-28, 1990. Pergamon Press, Oxford, U.K. pp. 419-427.

Lenehan, S.M. 1992. Wetland Systems in Stormwater Pollution Control. *Proceedings, AC Wetlands System Conference*. Sydney, Australia.

Lindsay, W.L. 1979. *Chemical Equilibria in Soils*. John Wiley & Sons, New York, NY.

Copyright American Petroleum Institute
Provided by IHS under license with API
No reproduction or networking permitted without license from IHS
Not for Resale

Litchfield, D. K. and D. D. Schatz. 1989. Constructed Wetlands for Wastewater Treatment at Amoco Oil Company's Mandan, North Dakota, Refinery. In D.A. Hammer (Ed.), *Constructed Wetlands for Wastewater Treatment. Municipal, Industrial, and Agricultural.* Lewis, Chelsea, MI. pp. 233-238.

Litchfield, D.K. and D.D. Schatz. 1990. Constructed Wetlands for Wastewater Treatment at Amoco Oil Company's Mandan, North Dakota Refinery. In D.A. Hammer (Ed.), *Constructed Wetlands for Wastewater Treatment - Municipal, Industrial, and Agricultural.* Lewis Publishers, Inc., Chelsea, MI, (second printing).

Litchfield, D.K. 1993. Constructed wetlands for wastewater treatment at Amoco Oil Company's Mandan, North Dakota, Refinery. In G.A. Moshiri (Ed.), *Constructed Wetlands for Water Quality Improvement.* Lewis Publishers, Chelsea, MI. pp. 485-488.

Long, E.R., D.D. MacDonald, S.L. Smith, and F.D. Calder. 1995. Incidence of Adverse Biological Effects Within Ranges of Chemical Concentrations in Marine and Estuarine Sediments. *Environmental Management* 19(1):81-97.

Lynch, T.R., C.J. Popp, and G.Z. Jacobi. 1988. Aquatic Insects as Environmental Monitors of Trace Metal Contamination: Red River, New Mexico. *Water, Air, and Soil Pollution.* 42:19-31.

MacDonald, D.A., and S.M. Salazar (Eds.). 1994. *The Utility of AVS/EqP in Hazardous Waste Site Evaluations.* NOAA Technical Memorandum NOS ORCA 87, AVS Proceedings at Woods Hole, Massachusetts, September 13-15.

MacKay, D. and P. J. Leinonen. 1975. Rate of Evaporation of Low-Solubility Contaminants from Water Bodies to Atmosphere. *Environ. Sci. Technol.* 9: 1178-1180.

MacKay, D., W. Shiu, and C. Kuo. 1992. *Illustrated Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals. Volume II: Polynuclear Aromatic Hydrocarbons, Polychlorinated Dioxins, and Dibenzofurans.* Lewis Publishers, Boca Raton, Florida.

MacKay, D., W. Shiu, and C. Kuo. 1995. *Illustrated Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals. Volume IV; Oxygen, Nitrogen, and Sulfur-Containing Compounds.* Lewis Publishers, Boca Raton, Florida.

Magmedov, V.G. 1996. Combined Systems of Constructed Wetlands in CIS: The First Ten Years Experience. In R. Haberl and J. Laber, (Eds.), *Proceedings of the 5th International Conference on Wetland Systems for Pollution Control.* Vienna. pp. X/10-1-8.

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No reproduction or networking permitted without license from IHS

Not for Resale

Martin, C.V. and B.F. Eldridge. 1989. California's Experience with Mosquitoes in Aquatic Wastewater Treatment Systems. In D.A. Hammer, (Ed.), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural.* Lewis Publishers, Chelsea, MI. pp. 393-398.

Marvin, C.H., J.A. Lundgren, B.E. McCarry, and D.W. Bryant. 1995. Determination and Genotoxity of High Molecular Mass Polycyclic Aromatic Hydrocarbons Isolated from Coal-Tar-Contaminated Sediment. *Environ. Toxicol. Chem.* 14(12):2059-2066.

McAllister, L.S. 1992. *Habitat Quality Assessment of Two Wetland Treatment Systems in Mississippi - A Pilot Study.* EPA Report 600/R-93/229, Environmental Research Laboratory, U.S. EPA, Corvallis, OR.

McAllister, L.S. 1993a. *Habitat Quality Assessment of Two Wetland Treatment Systems in the Arid West—A Pilot Study.* EPA Report 600/R-93/117, Environmental Research Laboratory, U.S. EPA, Corvallis, OR.

McAllister, L.S. 1993b. *Habitat Quality Assessment of Two Wetland Treatment Systems in Florida - A Pilot Study.* EPA Report 600/R-93/222, Environmental Research Laboratory, U.S. EPA, Corvallis, OR.

Meiorin, E.C. 1989. Urban Runoff Treatment in a Fresh/Brackish Water Marsh in Fremont, California. In D.A. Hammer (Ed.), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural.* Lewis Publishers, Chelsea, MI. pp. 677-685.

Melcer, H., W.J. Parker and B.E. Rittman. 1995. Modeling of Volatile Organic Contaminants in Trickling Filter Systems. *Wat. Sci. Tech.* 31(1): 94-104.

Metcalf and Eddy, Inc. 1991. *Wastewater Engineering, 3rd Edition.* McGraw-Hill, New York.

Miller, G. 1989. Use of Artificial Cattail Marshes To Treat Sewage in Northern Ontario, Canada. In D.A. Hammer, (Ed.), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural.* Lewis Publishers, Chelsea, MI. pp. 636-642.

Mitsch, W.J. and J.G. Gosselink. 1993. *Wetlands.* Second Edition. Van Nostrand Reinhold Company, New York.

Murdroch, A. and J.A. Capobianco. 1979. Effects of Treated Effluent on a Natural Marsh. *Journal WPCF.* 51:2243-2256.

NADB (North American Treatment Wetland Database). 1993. Electronic database created by R. Knight, R. Ruble, R. Kadlec, and S. Reed for the U.S. Environmental Protection Agency. Copies available from Don Brown, EPA, (513) 569-7630.

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No reproduction or networking permitted without license from IHS

Not for Resale

Nix, P. 1993. *Constructed Wetlands as a Treatment System for Stormwater Contaminated by Diesel Fuel Hydrocarbons*. Executive Summary Prepared by EVS Consultants, North Vancouver, B.C., Canada.

Nix, P.G. and J.R. Gulley. 1995. *Kinetic and Empirical Design Criteria for Constructed Wetlands*. Poster presentation at SETAC World Congress, Vancouver, B.C., Canada, November 5-9.

Nixon, S.W. and V. Lee. 1986. *Wetlands and Water Quality. A Regional Review of Recent Research in the United States on the Role of Freshwater and Saltwater Wetlands as Sources, Sinks, and Transformers of Nitrogen, Phosphorus, and Various Heavy Metals.* Technical Report Y-86-2. Final Report Prepared for the Department of the Army, U.S. Army Corps of Engineers. Waterways Experiment Station.

Noller, B.N., P.H. Woods and B.J. Ross. 1994. Case Studies of Wetland Filtration of Mine Waste Water in Constructed and Naturally Occurring Systems in Northern Australia. *Water Sci. Technol.* 29(4): 257-265.

Ohlendorf, H.M., D.J. Hoffman, M.K. Saiki, and T.W. Aldrich. 1986. Embryonic Mortality and Abnormalities of Aquatic Birds: Apparent Impacts of Selenium From Irrigation Drainwater. *The Science of the Total Environment.* 52:49-63.

Ohlendorf, H.M. 1992. *Wetlands Expansion Technical Memorandum No. 8*. Prepared for the City of Merced, Wastewater Treatment Master Plan.

Pardue, J.H. 1996. *Fate of Toxic Organic Compounds in Wetlands.* Paper presented at 4th Symposium on Biogeochemistry of Wetlands, New Orleans, LA.

Pardue, J.H., P.H. Masscheleyn, R.D. DeLaune and W.H. Patrick, Jr. 1993. Assimilation of Hydrophobic Chlorinated Organics in Freshwater Wetlands: Sorption and Sediment-Water Exchange. *Environ. Sci. Technol.* 27(5):875-882.

PBSJ (Post, Buckley, Schuh and Jernigan). 1989-93. *Orlando Easterly Wetlands: Monitoring Reports for 1988-92*. Reports to City of Orlando, FL.

Peat Testing Manual. 1979. *Technical Memorandum No. 125*. National Research Council of Canada, Ottawa, Ontario.

Peng, J., J.K. Bewtra and N. Biswas. 1995. Effect of Turbulence on Volatilization of Selected Organic Compounds from Water. *Wat. Environ. Res.* 67(1):101-107.

Peverly, J.H., J.M. Surface, and T. Wang. 1995. Growth and Trace Metal Absorption by Common Reed (*Phragmites australis*) (CAV Tirn.). In Proceedings, *Wetlands Constructed for Landfill Leachate Treatment. IV Int. Wetland Conference*. Columbus, OH. September 13-18, 1992.

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Not for Resale

Pier, P.A, E. Bailey, C.L. McDonald and W.D. Phillips. 1996. *Screening of Wetland Emergent Species for Remediation of Explosives-Contaminated Groundwater*. Paper presented at 4th Symposium on Biogeochemistry of Wetlands, New Orleans, LA.

Pip, E. 1993. Cadmium, Copper, and Lead in Wild Rice from Central Canada. *Arch. Environ. Contam. Toxicol.* 24:179-181.

Polprasert, C. and N.P. Dan. 1994. Phenol Removal in Model Constructed Wetlands Located in the Tropics. *Proceedings of the 67th Annual Conference of the Water Environment Federation.* Volume VIII, Water Environment Federation, Alexandria, VA. pp. 45-55.

Radoux, M. and D. Kemp. 1990. The Impact of Aging on the Purification Efficiency of a Plantation of *Typha latifolia* L. In P. F. Cooper and B. C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control.* Pergamon Press, Oxford, UK, pp. 149-160.

Rainwater, T.R., V.A. Leopold, M.J. Hooper, and R.J. Kendall. 1995. Avian Exposure to Organophosphorus and Carbamate Pesticides of a Coastal South Carolina Golf Course. *Environ. Toxicol. Chem.* 14(12):2155-2161.

Reddy, K.R. and D.A. Graetz. 1988. Carbon and Nitrogen Dynamics in Wetland Soils. In D.D. Hook *et al.*, (Eds.), *The Ecology and Management of Wetlands*. Croom Helm, London. pp. 307-318.

Reddy, K.R. and E.M. D'Angelo. 1994. Soil Processes Regulating Water Quality in Wetlands. In W. Mitsch, (Ed.), *Global Wetlands: Old World and New*, Elsevier, Amsterdam. pp. 309-324.

Reed, S.C., E.J. Middlebrooks, and R.W. Crites. 1988. *Natural Systems for Waste Management and Treatment*. McGraw-Hill, New York, NY.

Reed, S.C., R.W. Crites, and E.J. Middlebrooks. 1995. *Natural Systems for Waste Management and Treatment.* 2nd ed. McGraw-Hill, New York, NY.

Rogozinski, L.R., R.C. Laubaucher, and J.M. Farmer. 1992. *Groundwater Treatment Via Constructed Wetlands*. Presented at the Petroleum Hydrocarbons Conference, Houston, TX, November 4-6, 1992.

Ross, H.B. 1987. Trace Metals in Precipitation in Sweden. *Water, Air, and Soil Pollution*. 36:349-363.

Rudd, T. 1987. Scope of the Problem. In J.N. Lester (Ed.), *Heavy Metals in Wastewater and Sludge Treatment Processes. Volume I. Sources, Analysis, and Legislation*. CRC Press, Boca Raton, FL. pp. 1-29.

Saurer, B. (Ed). 1994. *Pflanzenkläranlagen: Abwasserreinigung mit Bepflantzen Bodenkörpern.* Wasserwirtschaft Land Steiermark, Graz. Austria.

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Not for Resale

Schierup, H., and V.J. Larsen. 1981. Macrophyte Cycling of Zinc, Copper, Lead and Cadmium in the Littoral Zone of a Polluted and Non-Polluted Lake. I. Availability, Uptake and Transportation of Heavy Metals in *Phragmites australis* (CAV) Trin. *Aquat. Bot.* 11:197-210.

Schiffer, D.M. 1989. Water-Quality Variability in a Central Florida Wetland Receiving Highway Runoff. In F.E. Davis (Ed.), *Water: Laws and Management*. AWRA, Bethesda, MD.

Schmitt, C.J. and W.G. Brumbaugh. 1990. National Contaminant Biomonitoring Program: Concentrations of Arsenic, Cadmium, Copper, Lead, Mercury, Selenium, And Zinc In Freshwater Fish. 1976-1984. *Arch. Environ. Contam. Toxicol.* 19:731-747.

Schuler, C.A., R.G. Anthony, and H.M. Ohlendorf. 1990. Selenium in Wetlands and Waterfowl Foods at Kesterson Reservoir, California, 1984. *Arch. Environ. Contam. Toxicol.* 19:845-853.

Shacklette, H.T. and J.G. Boerngen. 1984. *Element Concentrations in Soils and Other Surficial Materials of the Coterminous United States*. United States Geological Survey, Prof. Paper 1270, U.S. Government Printing Office.

Shugui, D., R. Xin, W. Juxian, L. Qingyu, Z. Ruizhi, and S. Rengao. 1994. Removal of Priority Organic Pollutants in Stabilization Ponds. *Wat. Res.* 28(3):681-685.

Shutes, R.B., J.B. Ellis, D.M. Revitt, and T.T. Zhang. 1993. The Use of *Typha latifolia* for Heavy Metal Pollution Control in Urban Wetlands. In G.A. Moshiri (Ed.), *Constructed Wetlands for Water Quality Improvement*. Lewis Publishers, Boca Raton, Florida. pp. 407-414.

Simpson, R.L., R.E. Good, R. Walker, and B.R. Frasco. 1983. The Role of Delaware River Freshwater Tidal Wetlands in the Retention of Nutrients and Heavy Metals. *J. Environ. Quality*. 12:41-48.

Sinicrope, T.L., R. Langis, R.M. Gersberg, M.J. Busanardo and J.B. Zedler. 1992. Metal Removal by Wetland Mesocosms Subjected to Different Hydroperiods. *Ecolog. Engin.* 1(4):309-322.

Sobelewski, A., and M. MacKinnon. 1995. *Interactions Between Nitrifying Bacteria and Hydrocarbon-degrading Bacteria during Detoxification of Oil Sands Process Affected Water*. Poster presentation at SETAC World Congress, Oil Sands Session, Vancouver, B.C., Canada, November 5-9.

SRI (Scientific Resources, Inc.) 1990. *Monitoring Data on the Jackson Bottoms Experimental Wetlands, 1989*. Report prepared for Unified Sewage Authority, Hillsboro, OR.

SRI (Scientific Resources, Inc.) 1991. *Operating Data from Jackson Bottoms Experimental Wetland, 1990*. Report prepared for Unified Sewage Authority, Hillsboro, OR.

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Not for Resale

Srinivasan, K.R., and R.H. Kadlec. 1995. *Wetland Treatment of Oil and Gas Well Wastewaters.* Project Final Report, U.S. Department of Energy, Contract No. DE-AC22-92MT92010, University of Michigan, Department of Chemical Engineering, Ann Arbor, MI.

St-Cyr, L., and A.A. Crowder. 1990. Manganese and Copper in Root Plaque of *Phragmites australis* (CAV) Trin Ex Steudel. *Soil Sci.*, 149:191-198.

Stark, L.R., W.R. Wenerick, F.M. Williams, and P.J. Wuest. 1995. The Effects of pH, Flow Rate, and Carbon Supplementation on Manganese Retention in Mesocosm Wetlands. *J. Environ. Qual.* 24:816-826.

Steiner, G.R. and R.J. Freeman, Jr. 1989. Configuration and Substrate Design Considerations for Constructed Wetlands Wastewater Treatment. In D.A. Hammer, (Ed.), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural.* Chelsea, MI: Lewis Publishers. pp. 363-378.

Stephenson, T. 1987. Water Treatment and Reuse. In J.N. Lester (Ed.), *Heavy Metals in Wastewater and Sludge Treatment Processes*. Volume II. Treatment and Disposal. CRC Press, Boca Raton, FL. pp. 69-90.

Stowell, S. Weber, G. Tchobanoglous, B.A. Wilson, and K.R. Townzen. 1985. Mosquito Considerations in the Design of Wetland Systems for the Treatment of Wastewater. In P.J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, (Eds.), *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters*. Van Nostrand Reinhold Company, New York. pp. 38-47.

Strecker, E.W., J. M. Kersnar, E. D. Driscoll, and R. R. Horner. 1992. *The Use of Wetlands for Controlling Stormwater Pollution.* EPA/600, Terrene Institute, Wash. D.C.

Suntio, L.R., W.Y. Shiu, D. Mackay, J.N. Seiber and D. Glotfelty. 1988. Critical Review of Henry's Law Constants for Pesticides. *Rev. Environ. Contam. Toxicol.* 103:1-59.

Surface, J.M., J.H. Peverly, T.S. Steenhuis, and W.E. Sanford. 1993. Effect of Season, Substrate Composition, and Plant Growth on Landfill-Leachate Treatment in a Constructed Wetland. In G.A. Moshiri (Ed.), *Constructed Wetlands for Water Quality Improvement*. Lewis Publishers, Boca Raton, FL. pp. 461-472.

Suter, G.W. and J.B. Mabrey. 1994. *Toxicological Benchmarks for Screening Potential Contaminants of Concern for Effects on Aquatic Biota: 1994 Revision*. Report No. ES/ER/TM-96/RI. Oak Ridge National Lab, Oak Ridge, Tennessee.

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Not for Resale

Suzuki, T., K. Moriyama, and Y. Kurihara. 1989. Distribution of Heavy Metals in a Reed Marsh on a Riverbank in Japan. *Aquatic Botany*. 35:121-127.

Tang, S-y, and X-w Lu. 1993. The Use of *Eichhornia crassipes* to Cleanse Oil-Refinery Wastewater in China. *Ecolog. Engin.* 2:243-251.

Taraldsen, J.E. and T.J. Norberg-King. 1990. New Method for Determining Effluent Toxicity Using Duckweed (*Lemna minor*). *Env. Toxicol. Chem.* 9:761-767.

Tchobanoglous, G. and F.L. Burton. 1991. *Wastewater Engineering Treatment, Disposal, and Reuse*. 3rd Edition. McGraw-Hill, Inc., New York, NY.

Tennessen, K.J. 1993. Production and Suppression of Mosquitoes in Constructed Wetlands. In G.A. Moshiri (Ed.), *Constructed Wetlands for Water Quality Improvement*. Lewis Publishers, Boca Raton, Florida. pp. 591-601.

TETC (The Earth Technology Corporation). 1991. Evaluation of Background Metals Concentrations in Arizona Soils. Prepared for Arizona Department of Environmental Quality, Groundwater Hydrology Section., Phoenix, AZ.

Thunhorst, G.A. 1993. *Wetland Planting Guide for the Northeastern United States*. Plants For Wetland Creation, Restoration, and Enhancement. Environmental Concern, St. Michaels, MD.

Trapp S. and M. Matthies. 1995. Generic One-Compartment Model for Uptake of Organic Chemicals by Foliar Vegetation. *Enviro. Sci. Technol.* 29(9):2333-2338.

USDA (U.S. Department of Agriculture). Natural Resources Conservation Service (NRCS). 1991. *Constructed Wetlands for Agricultural Waste Treatment, Technical Requirements*. NRCS, Washington, D.C.

van Oostrom, A.J. and R.N. Cooper. 1990. Meat Processing Effluent Treatment in Surface-Flow and Gravel-Bed Constructed Wastewater Wetlands. In P. F. Cooper and B. C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control.* Pergamon Press, Oxford, UK. pp. 321-332.

van Oostrom, A.J. 1994. Nitrogen Removal in Constructed Wetlands Treating Nitrified Meat Processing Wastewater. *Proceedings of the Fourth International Conference on Wetland Systems for Water Pollution Control.* Guangzhou, China. November 6-10, 1984. Center for International Development and Research, South China Institute for Environmental Sciences, China. pp. 569-579.

von Felde, K., and S. Kunst. 1996. N- and COD Removal in Vertical Flow Systems In R. Haberl and J. Laber, (Eds.), *Proceedings of the 5th International Conference on Wetland Systems for Pollution Control.* Vienna. pp. I8-1-8.

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Not for Resale

Vymazal, J., 1990. Use of Reed Bed Systems for Treatment of Concentrated Wastes from Agriculture. In P.F. Cooper and B.C. Findlater, (Eds.), *Constructed Wetlands in Water Pollution Control*, Pergamon Press, Oxford, UK. pp. 347-358.

Walker, L.P. and M.R. Walker. 1990. *City of Gustine Marsh Evaluation Study.* Report to the City of Gustine. Larry Walker Associates, Inc., Davis, California.

Walton, W.E., E.T. Schreiber, and M.S. Mulla. 1990. Distribution of *Culex tarsalis* Larvae in a Freshwater Marsh in Orange County, California. *Journal of the American Mosquito Control Association.* 6:539-543.

Wang, T., and J.H. Peverly. 1996. Oxidation States and Fractionation of Plaque Iron on Roots of Common Reeds. *Soil Sci. Soc. Am.* J. 60:323-329.

Wass, R.D. and P. Fox. 1993. Constructed Wetlands for Nonpoint Source Control of Wastewater from a Vehicle Maintenance Yard. *Proceedings of the Environmental Federation, 66th Annual Conference*, Volume 9. Anaheim, California, October 3-7, 1993. pp. 9-20.

WCC (Woodward-Clyde Consultants). 1994. *Demonstration Urban Stormwater Treatment (DUST) Marsh Special Study RY 92-93.* Alameda County Urban Runoff Clean Water Program. April 4.

WCC (Woodward-Clyde Consultants). 1995. *Demonstration Urban Stormwater Treatment (DUST) Marsh Special Study RY 93-94.* Alameda County Urban Runoff Clean Water Program. January 27.

Weber, A.S. and G. Tchobanoglons. 1986. Prediction of Nitrification in Water Hyacinth Treatment Systems. *Journal WPCF.* 58(5):376-380.

Weller, M.W. 1978. Management of Freshwater Marshes for Wildlife. In R.E. Good, D.F. Whigham, and R.L. Simpson, (Eds.), *Freshwater Wetlands: Ecological Processes and Management Potential.* Academic Press, Inc., New York, NY. pp. 267-284.

Welty, J.R., C.E. Wicks, and R.E. Wilson. 1984. *Fundamentals of Momentum, Heat, and Mass Transfer.* Wiley, New York, NY.

Wieder, R.K. 1989. A Survey of Constructed Wetlands for Acid Coal Mine Drainage Treatment in the Eastern United States. *Wetlands.* 9: 299-315.

Wieder, R.K., G. Tchobanoglous, and R.W. Tuttle. 1989. Preliminary Considerations Regarding Constructed Wetlands for Wastewater Treatment. In D.A. Hammer, (Ed.), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural.* Lewis Publishers, Chelsea, MI. pp. 297-305.

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Not for Resale

Wile, I., G. Miller, and S. Black. 1985. Design and Use of Artificial Wetlands. In P.J. Godfrey, E.R. Kaynor, and S. Pelczarski, (Eds.), *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters*. New York: Van Nostrand Reinhold. pp. 26-37.

Williams, R.B. 1982. Wastewater Reuse- An Assessment of the Potential and Technology. In E.J. Middlebrooks (Ed.), *Water Reuse*. Ann Arbor Science, Ann Arbor, MI. pp. 87-136.

Wilson, B.A., K.R. Townsend, and T.H. Anderson. 1987. Mosquito and Mosquitofish Responses to Loading of Water Hyacinth Wastewater Treatment Ponds. Abstract in K.R. Reddy and W.H. Smith, (Eds.), *Aquatic Plants for Water Treatment and Resource Recovery*. Magnolia Publishing, Inc., Orlando, FL. pp. 807-808.

Wisseman, R. and S. Cook, Jr. 1977. Heavy Metal Accumulation in the Sediments of a Washington Lake. *Bullet. of Environ. Contam. & Toxicol.* 18:77-82.

Wolverton, B.C., and M.M. McKnown. 1976. Water Hyacinths for Removal of Phenols from Polluted Waters. *Aquatic Botany*. 2:191-201.

Wolverton, B.C., and R.C. McDonald. 1981. Natural Processes for Treatment of Organic Chemical Waste. *The Environmental Professional*, 3:99-104.

Wolverton, B.C. 1987. Artificial Marshes for Wastewater Treatment. In K.R. Reddy and W.H. Smith (eds.). *Aquatic Plants for Water Treatment and Resource Recovery*. Magnolia Publishing, Inc., Orlando, FL. pp. 141-152.

Wood, A.W., L. Barjactarovic, C.J. Kennedy, A.P. Farrell and L.I. Bendell-Young. 1995. Fate of U-^{14}C-Palmitic Acid in Constructed Wetlands: a Microcosm Study. Poster presentation at SETAC World Congress, Oil Sands Session, Vancouver, B.C., Canada, November 5-9.

WPCF (Water Pollution Control Federation). 1990. *Natural Systems for Wastewater Treatment*. Manual of Practice FD-16. WPCF, Alexandria, VA., Washington, D.C.

Zander, M. 1980. Polycyclic Aromatic and Heteroaromatic Hydrocarbons. In O. Hutzinger (Ed.), *Handbook of Environmental Chemistry*. Springer Verlag, New York, NY.

Zhang, T., J.B. Ellis, D.M. Revitt, and R.B. Shutes. 1990. Metal Uptake and Associated Pollution Control by *Typha latifolia* in Urban Wetlands. In P.F. Cooper and B.C. Findlater (Eds.), *Proceedings of the International Conference on the Use of Constructed Wetlands in Water Pollution Control*. Cambridge, U.K. September 24-28, 1990. Pergamon Press, Oxford, U.K. pp. 451-459.

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APPENDIX A

Glossary of Terms

absorption The movement of a dissolved chemical through a semipermeable membrane into a living organism.

acid A chemical substance that can release excess protons (hydrogen ions).

activated sludge A complex variety of microorganisms growing in sludge in aerated wastewater treatment basins. Following settling, a portion of this microbial and sludge mixture is recycled to the influent of the treatment system, where microbes continue to grow. The remaining activated sludge is removed (wasted) from the treatment system and disposed of by different processes.

adsorption The adherence of a gas, liquid, or dissolved chemical to the surface of solid.

advanced wastewater treatment (AWT) Treatment of wastewater beyond the secondary treatment level. In some areas AWT represents treatment to less than 5 milligrams per liter (mg/L) of 5-day biochemical oxygen demand (BOD_5), 5 mg/L of total suspended solids (TSS), 3 mg/L of total nitrogen (TN), and 1 mg/L of total phosphorus (TP).

adventitious roots Roots that grow from the stems of some plants as a response to flooding. Adventitious roots develop on these plants when the plant's normal roots are in oxygen-deficient, flooded soils, and the adventitious roots are in the overlying, oxygen rich water column.

aeration The addition of air to water, usually for the purpose of providing higher oxygen concentrations for chemical and microbial treatment processes.

aerobic Pertaining to the presence of elemental oxygen.

algae A group of autotrophic plants that are unicellular or multicellular and typically grow in water or humid environments.

alkalinity A measure of the capacity of water to neutralize acids because of the presence of one or more of the following bases in the water: carbonates, bicarbonates, hydroxides, borates, silicates, or phosphates.

allocthonous Pertaining to substances (usually organic carbon) produced outside of and flowing into an aquatic or wetland ecosystem.

ammonification Bacterial decomposition of organic nitrogen to ammonia.

anaerobic Pertaining to the absence of free oxygen.

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anion A negatively charged ion.

annual Occurring over a 12-month period.

anoxic Pertaining to the absence of all oxygen (both free oxygen and chemically-bound oxygen).

aquaculture The propagation and maintenance of plants or animals by humans in aquatic and wetland environments.

aquatic Pertaining to flooded environments. Over a hydrologic gradient, the aquatic environment is the area waterward from emergent wetlands and is characterized by the growth of floating or submerged plant species.

arenchyma Porous tissues in vascular plants that have large air-filled spaces and thin cell walls. Arenchymous tissues allow gaseous diffusion between aboveground and belowground plant structures, thus permitting plants to grow in flooded conditions.

aspect ratio Ratio of wetland cell length to width.

autocthonous Pertaining to substances (usually organic carbon) produced internally in an aquatic or wetland ecosystem.

autotrophic The production of organic carbon from inorganic chemicals. Photosynthesis is an example of an autotrophic process.

bacteria Microscopic, unicellular organisms lacking chlorophyll. Most bacteria are heterotrophic (some are chemoautotrophs), and many species perform chemical transformations that are important in nutrient cycling and wastewater treatment.

benthic Pertaining to occurrence on or in the bottom sediments of wetland and aquatic ecosystems.

bioassay The use of plants or animals for testing water quality. Often refers to use of living organisms for testing toxicity of wastewaters.

biomass The total mass of living tissues (plant and animal).

BOD (biochemical oxygen demand) A measure of the oxygen consumed during degradation of organic and inorganic materials in water.

BOD_5 Five-day biochemical oxygen demand.

brackish water Pertaining to surface or groundwaters containing a salt content greater than 0.5 parts per thousand.

bulk density A measurement of the mass of soil occupying a given volume.

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carbonate An inorganic chemical compound containing one carbon atom and three oxygen atoms ($-CO_3$).

cation A positively-charged ion.

$CBOD_5$ Carbonaceous BOD_5.

CEC (cation exchange capacity) A measure of the ability of a soil to bind positively-charged ions.

channel A deeper portion of a water flowway that has faster current and water flow.

channelization The creation of a channel or channels resulting in faster water flow, a reduction in hydraulic residence time, and less contact between waters and solid surfaces within the water body.

chemosynthesis The use of chemically reduced energy for microbial growth.

chlorophyll A green organic compound produced by plants and used in photosynthesis.

clarifier A circular or rectangular sedimentation tank used to remove settled solids in water or wastewater.

COD (chemical oxygen demand) A measure of the oxygen equivalent of the organic matter in water based on reaction with a strong chemical oxidant.

constructed wetland A wetland that is purposely constructed by humans in a non-wetland area.

consumer An animal that derives nutrition from other living organisms. Primary consumers feed on plants, and secondary and higher consumers feed on other animals.

degraded wetland A wetland altered by human action in a way that impairs the wetland's physical or chemical properties, resulting in reduced functions such as habitat value or flood storage.

delineation The process of determining boundaries. Wetlands delineation uses regulatory definitions based on hydrologic, soil, and vegetative indicators to identify these boundaries.

denitrification The anaerobic microbial reduction of oxidized nitrate nitrogen to nitrogen gas.

detritivore An animal that feeds on dead plant material and the associated mass of living bacteria and fungi.

detritus Dead plant material that is in the process of microbial decomposition.

diffusion The transfer of mass through a gas or liquid from a region of high concentration to a region of lower concentration.

disinfection The killing of the majority of microorganisms, including pathogenic bacteria, fungi, and viruses, by using a chemical or physical disinfectant. Disinfection is functionally defined by limits, such as achieving an effluent with no more than 200 colonies of fecal coliform bacteria in 100 milliliter (mL).

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dispersion Scattering and mixing within a water or gas volume.

disturbed wetland A wetland directly or indirectly altered by a perturbation, yet retaining some natural wetland characteristics; includes anthropogenic and natural perturbations.

diversity In ecology, diversity refers to the number of species of plants and animals within a defined area. Diversity is measured by a variety of indices that consider the number of species and, in some cases, the distribution of individuals among species.

diurnal Occurring on a daily basis or during the daylight period.

drained wetland A wetland in which the level or volume of ground or surface water has been reduced or eliminated by artificial means.

ecology The study of the interactions of organisms with their physical environment and with each other and of the results of such interactions.

ecosystem All organisms and the associated nonliving environmental factors with which they interact.

ecotone The boundary between adjacent ecosystem types. An ecotone can include environmental conditions that are common to both neighboring ecosystems and can have higher species diversity.

effluent A liquid or gas that flows out of a process or treatment system. Effluent can be synonymous with wastewater after any level of treatment.

Eh A measure of the reduction-oxidation (redox) potential of a soil based on a hydrogen scale.

emergent plant A rooted, vascular plant that grows in periodically or permanently flooded areas and has portions of the plant (stems and leaves) extending through and above the water plane.

enhanced wetland An existing wetland with certain functional values that have been increased or enhanced by human activity.

estuary An enclosed or open natural, transitional water body between a river and the ocean.

eutrophic Water with an excess of plant growth nutrients that typically result in algal blooms and extreme (high and low) dissolved oxygen concentrations.

evaporation The process by which water in a lake, river, wetland, or other water body becomes a gas.

evapotranspiration The combined processes of evaporation from the water or soil surface and transpiration of water by plants.

exotic species A plant or animal species that has been intentionally or accidentally introduced and that does not naturally occur in a region.

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facultative Having the ability to live under different conditions (for example, with or without free oxygen).

fecal Pertaining to feces.

fecal coliform Aerobic and facultative, Gram-negative, nonspore-forming, rod-shaped bacteria capable of growth at 44°C (112°F), and associated with fecal matter of warm-blooded animals.

fen A freshwater wetland occurring on low, poorly drained ground and dominated by herbaceous and shrubby vegetation. Soil is typically organic peat.

flash boards Removable boards used to control water levels.

floating aquatic plant A rooted or nonrooted vascular plant that is adapted to have some plant organs (generally the chlorophyll-bearing leaves) floating on the surface of the water in wetlands, lakes, and rivers.

floodplain Areas that are flooded periodically (usually annually) by the lateral overflow of rivers. In hydrology, the entire area that is flooded at a recurrence interval of 100 years.

food chain or web The interconnected group of plants and animals in an ecosystem. Food chain specifically refers to the progression of trophic levels (for example, primary producer, primary consumer, secondary consumer, tertiary consumer, etc.).

freshwater Water with a total dissolved solids (TDS) content less than 500 mg/L (0.5 parts per thousand TDS).

fungi Microscopic or small nonchlorophyll-bearing, heterotrophic, plant-like organisms that lack roots, stems, or leaves, and typically grow in dark and moist environments.

geomorphology The land and submarine relief features of the earth.

grazer An organism that feeds on plants or animals attached to surfaces.

greenway A strip or belt of vegetated land often used for recreation, as a land use buffer, or to provide a corridor and habitat for wildlife.

groundwater Water that is located below the ground surface.

habitat The environment occupied by individuals of a particular species, population, or community.

heavy metals Metallic elements that are above 21 atomic weight on the periodic table.

herbaceous Plant parts that contain chlorophyll and are non-woody.

herbivore An animal that feeds primarily on plant tissues.

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heterotrophic An organism that derives nutrition from organic carbon compounds.

hydraulic loading rate (HLR) A measure of the application of a volume of water to a land area with units of volume per area per time or simply reduced to applied water depth per time (for example, $m^3/[m^2/d]$ or cm/d).

hydraulic residence time (HRT) A measure of the average time that water occupies a given volume with units of time. The theoretical HRT is calculated as the volume divided by the flow (for example, $m^3/[m^2/d]$). The actual HRT is estimated based on tracer studies using conservative tracers such as lithium or dyes.

hydric soil A soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions. Hydric soils that occur in areas having indicators of hydrophytic vegetation and wetland hydrology are wetland soils.

hydrology A science dealing with the properties, distribution, and circulation of water on the land surface and in the soil, underlying rocks, and atmosphere.

hydrograph A record of the rise and fall of water levels during a given time period.

hydroperiod The period of wetland soil saturation or flooding. Hydroperiod is often expressed as a number of days or a percentage of time flooded during an annual period (for example, 25 days or 7 percent).

influent Water, wastewater, or other liquid flowing into a water body or treatment unit.

inorganic All chemicals that do not contain organic carbon.

invertebrate All animals that do not have backbones.

kinetics Pertaining to the rates at which changes occur in chemical, physical, and biological processes.

lacustrine The deepwater zone of a lake or reservoir.

lagoon Any large holding or detention pond, usually with earthen dikes, used to hold wastewater for sedimentation or biological oxidation.

leachate Liquid that has percolated through permeable solid waste and has extracted soluble dissolved or suspended materials from it.

lentic Pertaining to a lake or other non-flowing water body.

limnetic Relating to or inhabiting the open water portion of a freshwater body with a depth that light penetrates. The area of a wetland without emergent vegetation.

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littoral The shoreward zone of a lake or wetland. The area where water is shallow enough to allow the dominance of emergent vegetation.

lotic Pertaining to flowing water bodies such as streams and rivers.

macrophyte Macroscopic (visible to the unassisted eye) vascular plants.

marsh A wetland dominated by herbaceous, emergent plants.

mass loading The total amount, on a mass or mass per area basis, of a constituent entering a system.

mesotrophic Water quality characterized by an intermediate balance of plant growth nutrients.

metabolism The chemical oxidation of organic compounds resulting in the release of energy for maintenance and growth of living organisms.

micronutrient A chemical substance that is required for biological growth in relatively low quantities and in small proportion to the major growth nutrients. Some typical micronutrients include molybdenum, copper, boron, cobalt, iron, and iodine.

microorganism An animal or plant that can only be viewed with the aid of a microscope.

mitigation The replacement of functional values lost when an ecosystem is altered. Mitigation can include replacement, restoration, and enhancement of functional values.

natural wetland A wetland ecosystem that occurs without the aid of humans.

NH_4-N (ammonia nitrogen) A reduced form of nitrogen produced as a byproduct of organic matter decomposition and synthesized from oxidized nitrogen by biological and physical processes.

nitrification Biological transformation (oxidation) of ammonia nitrogen to nitrite and nitrate forms.

nitrogen fixation A microbial process in which atmospheric nitrogen gas is incorporated into the synthesis of organic nitrogen.

NO_3 + NO_2-N (nitrate plus nitrite nitrogen) Oxidized nitrogen.

nutrient A chemical substance that provides a raw material necessary for the growth of a plant or animal.

oligotrophic Water quality characterized by a deficiency of plant growth nutrients.

omnivore An animal that feeds on a mix of plant and animal foods.

organic Pertaining to chemical compounds that contain reduced carbon bonded with hydrogen, oxygen, and a variety of other elements. Organic compounds are typically volatile, combustible, or biodegradable and include proteins, carbohydrates, fats, and oils.

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Org-N (organic nitrogen) Nitrogen that is bound in organic compounds.

oxidation A chemical reaction in which the oxidation number (valence) of an element increases because of the loss of one or more electrons. Oxidation of an element is accompanied by the reduction of the other reactant and, in many cases, by the addition of oxygen to the compound.

oxygen sag The decrease in dissolved oxygen measured downstream of a relatively constant addition of an oxygen-consuming wastewater in a flowing water system.

palustrine All nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens, and all such tidal wetlands in areas where salinity from ocean-derived salts is below 0.5 parts per thousand.

parasite An organism that lives within or on another organism and derives its sustenance from that organism without providing a useful return to its host.

peat Partially decomposed but relatively stable organic matter formed from dead plants in flooded environments.

peatland An area where the soil is predominantly peat.

periphyton The community of microscopic plants and animals that grows on the surface of emergent and submergent plants in water bodies.

perennial Persisting for more than one year. Perennial plant species persist as woody vegetation from year to year or resprout from their rootstock on an annual basis.

photic zone The area of a water body receiving sunlight.

photosynthesis The biological synthesis of organic matter from inorganic matter in the presence of sunlight and chlorophyll.

phytoplankton Microscopic algae that are suspended in the water column and are not attached to surfaces.

piezometric surface The surface elevation of pressurized groundwater within a well or in a spring.

plant community All of the plant species and individuals occurring in a shared habitat or environment.

plug flow Linear flow along the length of a wetland cell.

pretreatment (or preliminary treatment) The initial treatment of wastewater to remove substances that might harm downstream treatment processes or to prepare wastewater for subsequent treatment.

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primary production The production of organic carbon compounds from inorganic nutrients. The energy source for this production is generally sunlight for chlorophyll-containing plants, but in some cases can be derived from reduced chemicals (chemoautotrophs).

primary treatment The first step in treatment of wastewaters. Primary treatment usually consists of screening and sedimentation of particulate solids. At petrochemical sites, primary treatment also includes free oil removal.

protozoa Small, one-celled animals including amoebae, ciliates, and flagellates.

receiving water A water body into which wastewater or treated effluent is discharged.

reclaimed wastewater Wastewater that has received treatment sufficient to allow beneficial reuse.

redox potential The potential of a soil to oxidize or reduce chemical substances.

reduction A chemical reaction in which the oxidation state (valence) of a chemical is lowered by the addition of electrons. Reduction of a chemical is simultaneous with the oxidation of another chemical and frequently involves the loss of oxygen.

respiration The intake of oxygen and the release of carbon dioxide as a result of metabolism (biological oxidation of organic carbon).

restoration The return of an ecosystem from a disturbed or altered condition to a previously existing natural condition as a result of human action (for example, by fill removal).

rhizosphere The chemical sphere of influence of plant roots growing in flooded soils. Depending on the overall oxygen balance (availability and consumption), the rhizosphere can be oxidized, resulting in the presence of aerobic soil properties in an otherwise anaerobic soil environment.

riparian Pertaining to a stream or river. Plant communities occurring in association with any spring, lake, river, stream, creek, wash, arroyo, or other body of water or channel having banks and a bed through which waters flow at least periodically.

riverine wetlands Wetlands associated with rivers.

salinity A measure of the total salt content of water. Salinity is usually reported as parts per thousand (ppt). The salinity of normal seawater is about 35 ppt.

saturated soil Soil in which the pore space is filled with water.

secondary production The production of biomass by consumer organisms by feeding on primary producers or lower trophic level consumers.

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secondary treatment Generally refers to wastewater treatment beyond initial sedimentation and oil removal. Secondary treatment typically includes biological reduction in concentrations of particulate and dissolved concentrations of oxygen-demanding pollutants.

sediment Mineral and organic particulate material that has settled from suspension in a liquid.

seed bank The accumulation of viable plant seeds occurring in soils and available for germination under favorable environmental conditions.

SF (surface flow) A treatment wetland category that is designed to have a free-water surface, above the ground level.

SSF (subsurface flow) A treatment wetland category that is designed to have the water surface below the level of the ground, with flow through a porous media.

sheet flow Water flow with a relatively thin and uniform depth.

short-circuit A faster, channelized water flow route that results in a lower actual hydraulic residence time than the theoretical hydraulic residence time.

slough A slow-moving creek or stream characterized by herbaceous and woody wetland vegetation.

sludge The accumulated solids separated from liquids, such as water or wastewater, during the treatment process.

soil The upper layer of the earth that can be dug or plowed and in which plants grow.

stabilization pond A type of treatment pond in which biological oxidation of organic matter results by natural or artificially enhanced transfer of oxygen from the atmosphere to the water.

stage-area curve The relationship between the depth of water and the surface area of a wetland or lake.

stage-discharge curve The relationship between water depth and outflow from a body of water.

stemflow Rainfall intercepted by plant leaves and branches and traveling to the ground via stems and the trunk.

submerged plants Aquatic vascular plants or plants that grow below the water surface for all or a majority of their life cycles.

substrate Substances used by organisms for growth in a liquid medium. Surface area of solids or soils used by organisms to attach.

subsurface flow (SSF) Flow of water or wastewater through a porous medium such as soil, sand, or gravel.

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succession The temporal changes of plant and animal populations and species in a given area following disturbance.

surface flow (SF) Flow of water or wastewater over the surface of the ground.

swamp A wetland dominated by woody plant species including trees and shrubs.

temperate zone The geographical area in the Northern Hemisphere between the Tropic of Cancer and the Arctic Circle and in the Southern Hemisphere between the Tropic of Capricorn and the Antarctic Circle. Temperate indicates that the climate is moderate and not extremely hot or cold.

terrestrial Living or growing on land that is not normally flooded or saturated.

tertiary treatment Wastewater treatment beyond secondary and often implying the removal of nutrients or heavy metals.

TKN (total Kjeldahl nitrogen) A measure of reduced nitrogen equal to the sum of Org-N and NH_4-N.

TN (total nitrogen) A measure of all organic and inorganic nitrogen forms in a water sample. Functionally, TN is equal to the sum of TKN and $NO_3 + NO_2$-N.

TOC (total organic carbon) A measure of the total reduced carbon in a water sample.

toxicity The adverse effect of a substance on the growth or reproduction of living organisms.

TP (total phosphorus) A measure of the total phosphorus in a water sample including organic and inorganic phosphorus in particulate and soluble forms.

transition zone The area between habitats or ecosystems (see ecotone). Frequently, transition zone is used to refer to the area between uplands and wetlands. In other cases, wetlands are referred to as transitional areas between uplands and aquatic ecosystems.

transpiration The transport of water vapor from the soil to the atmosphere through actively growing plants.

trickling filter A filter with coarse substrate or media to provide secondary treatment of wastewater. Microorganisms attached to the filter media use and reduce concentrations of soluble and particulate organic substances in the wastewater.

trophic level A level of biological organization characterized by a consistent feeding strategy (for example, all primary consumers are in the same trophic level in an ecosystem).

tropical The geographical area between the Tropic of Cancer and the Tropic of Capricorn. An area characterized by little variation in day length and temperature. Most tropical areas have high annual average temperatures. Tropical areas may or may not have seasonably variable rainfall patterns.

TSS (total suspended solids) A measure of the filterable matter in a water sample.

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upland Any area that is not an aquatic, wetland, or riparian habitat. An area that does not have the hydrologic regime necessary to support hydrophytic vegetation.

vegetation The accumulation of living plants within an area.

vertebrate An animal characterized by the presence of a spinal cord protected by vertebrae.

volatile Capable of being evaporated at relatively low temperatures.

watershed The entire surface drainage area that contributes runoff to a body of water.

water table The upper surface of the groundwater or saturated soil.

weir A device used to control and measure water or wastewater flow.

weir gate Water control device used to adjust water levels and measure flows simultaneously.

wetland An area that is inundated or saturated by surface or groundwater at a frequency, duration, and depth sufficient to support a predominance of emergent plant species adapted to growth in saturated soil conditions.

wetland function A physical, chemical, or biological process occurring in a wetland. Examples of wetland functions include primary production, water quality enhancement, groundwater recharge, organic export, wildlife production, and flood intensity reduction.

wetland mitigation bank A preserved, restored, constructed, or enhanced wetland that has been purposely set aside to provide compensation credits for losses of wetland functions caused by future human development activities as approved by regulatory agencies.

wetland structure The physical, chemical, and biological components of a wetland. Wetland structural components typically include wetland soils, macrophytes, surface water, detritus and microbes, and wetland animal populations.

wetland treatment system A wetland that has been engineered to receive water for the purpose of reducing concentrations of one or more pollutants.

wetland values Structural and functional attributes of wetlands that provide services to humans.

zonation The development of a visible progression of plant or animal communities in response to a gradient of water depth or some other environmental factor.

zooplankton Passively floating or weakly swimming, usually minute, animals that live suspended in the water column.

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APPENDIX B

Selected Petroleum Industry Treatment Wetland Case Histories

Treatment Wetland Pilot and Research Studies

Suncor, Inc., Oil Sands, Alberta, Canada

Project Description

The Suncor, Inc., Oil Sands Group operation near Fort McMurray, Alberta, employs the Clark Hot Water Process for the extraction of bitumen from oil sands. This process results in the generation of large volumes of waste fluids including fine tailings (sludge) and wastewaters (Gulley and Klym, 1992). By the end of mining operations at the current site, 135 million meters^3 of fine tailings will have to be treated as a part of Suncor's reclamation plan. Constructed surface flow wetlands to treat these wastewaters and tailings were built in 1991 on the Suncor mining land and planted in preparation for a long-term research program which started in 1992. The wetland design included three systems (two treatment systems and one reference system). The two treatment systems (Pond 1a and Dyke Drainage) each incorporated three replicated cells. The objectives of the design were to determine water quality characteristics of the effluent from each treatment wetland and assess the total ecological characteristics of the treatment wetlands including their chemical, toxicological, physical, and biological characteristics (Gulley *et al.*, 1995).

Wetland size design criteria were analyzed using data on T.E.H. (total extractable hydrocarbons) versus flow rate. The analysis resulted in the conclusion that both treatment systems were undersized and were overloaded in 1993. The original size of Pond 1A and Dyke Drainage systems were 0.04 hectare (ha) and both received approximately 6 liters per minute (L/min) of wastewater. The existing analysis suggests that Pond 1A should have been constructed at 0.11 ha or 84 percent larger than the designed size (Gulley *et al.*, 1995). Dyke Drainage was also undersized and should have been built at 0.05 ha or 60 percent larger than designed.

Operational Performance

Water quality results for outflow water met expectations for the Dyke Drainage treatment wetlands. The Pond 1A outflow water exceeded expectations in respect to water quality due to the high contaminant loading rates from the from the pond effluent (EVS Consultants, 1994). The following table (Table B-1) summarizes water quality data from the Dyke Drainage treatment system.

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TABLE B-1
Treatment Performance for the Dyke Drainage Wetland

Parameter	Influent (mg/L)	Effluent (mg/L)
Aluminum	0.2	0.38
Iron	1.31	1.21
Manganese	0.073	0.083
Zinc	0.021	0.011
Sodium	358	386

Source: Gulley *et al.*, 1995.

Neither wetland has the ability to reduce contaminants to the levels of the outflow of the control wetland. Overall treatment of both T.E.H. and ammonia-nitrogen for the two treatment systems combined was 21.6 and 72.2 percent, respectively (Gulley *et al.,* 1995). T.E.H. levels were reduced by approximately 30 percent in Pond 1A. The authors also found that ammonium nitrogen had elevated levels entering the treatment wetlands and that only limited reductions had occurred within the wetland systems. The hypothesized reasons include (1) a lack of available phosphorus (needed for biological treatment systems), (2) the availability of other organic compounds that may have competed with and/or inhibited the microbial oxidation of these contaminants, (3) and low levels of dissolved oxygen (EVS Consultants 1993, 1994). Both acute and sublethal toxicities were measured by using a common wetland zooplankter, *Daphnia magna*. Results from these tests indicate that reductions of toxicity within the treatment wetlands are occurring but outflow toxicity is sometimes present in the Dyke Drainage wetland outflows and is always present in the Pond 1A outflows (EVS Consultants, 1994). Other biological assay tests, including bacterial bioassays and standard trout LC_{50} bioassays, also indicated toxicity in the effluent waters from the wetlands.

Special Features/Issues

The researchers have identified several factors that have limited the effectiveness of treatment wetlands ability to reduce contaminants at Oil Sands. These factors include a lack of phosphorus, limiting the rate of mineralization of organic contaminants; the highly loaded (undersized) treatment cells with aspect ratios that may be too narrow; cool temperature effects due to the location of the site, which may inhibit the reduction of organic contaminants; and the excessive levels of contaminants, which may have overloaded the treatment capabilities of microbial communities (EVS Consultants, 1994).

DOE Oil and Gas Well Wastewaters

Project Description

In 1992, the University of Michigan initiated a project with funding from the Department of Energy to study the wetland treatment performance of oil and gas well wastewaters (Kadlec and Srinivasan, 1994;

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Srinivasan and Kadlec, 1995). The purpose of the study was to extend the knowledge base for treatment wetlands to include processes and substances of particular importance to small, on-site systems receiving oil and gas well wastewaters. The project was broken into the following four tasks:

- **Task 1**: Collection and critical evaluation of literature data on the sorption of heavy metals and the degradation of toxic organics commonly found in oil and gas wastewaters by typical wetland soil and biological assemblages.
- **Task 2**: Design, construction, and monitoring of laboratory-type wetland systems used to evaluate the treatment potential of various components of oil and gas well wastewaters and to investigate and develop the use of surfactant modified clays and algal adsorption systems as peripheral additives to the constructed treatment wetland for enhanced treatment.
- **Task 3**: Determination of the dynamics of uptake and fate of toxic organics and study of the physio-chemical immobilization potentials of the laboratory wetlands in reference to heavy metals.
- **Task 4**: Suggestion of guidelines for the design of a full scale wetland system for field implementation to treat oil and gas well wastewaters.

Results

The literature review (Task 1) encompassed the early efforts of the project. The investigators compiled and critically evaluated available data on treatment wetlands specifically used for oil and gas well wastewaters. The combination of literature and discussions with operators and researchers using this technology allowed the investigators to discover that the primary organic and inorganic target compounds for the study were phenol, Beta-naphthoic acid, copper (Cu)(II), and chromium (Cr)(VI).

The laboratory-type wetland system (LW) was constructed using 50-liter lysimeters planted with cattail (*Typha latifolia*). The study consisted of 90 lysimeters placed in a light-controlled laboratory at the University of Michigan. Because of problems with growth, all of the lysimeters were moved to the Botanical Gardens at the University of Michigan. Early results showed adsorption of heavy metals such as Cu(II) and Cr(VI) onto wetland soils.

The investigators also used an algal species, *Chlorella vulgaris*, as a potential additive to the treatment process. This species performed very well with respect to the removal of the target metal, cadmium (Cd)(II). However, the alga did not successfully treat the Cu(II) and Cr(VI) heavy metal constituents in the water. These results show that a combination of the alga and the modified clays have the potential to be low cost, effective additives to enhance the treatment wetland process.

The features and data collected from the LW systems allowed the investigators to determine first order removal kinetics for the various pollutants of concern. This information can be used to develop design guidelines for field-scale treatment wetland systems.

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BP Petroleum

Project Description

British Petroleum (BP) has many sites that historically have been used for handling and transferring petroleum hydrocarbons. Groundwater contamination has been noted at some of these sites. Some terminals are using standard mechanical treatment components such as mechanical separation and air stripping technologies (Rogozinski *et al.*, 1992). Because these technologies focus primarily on the volatile and nonvolatile organic petroleum associated contaminants, other associated pollutants are not receiving adequate treatment. A need for a passive biological treatment process has lead BP to begin using constructed treatment wetlands at one terminal facility (Rogozinski *et al.*, 1992).

The treatment wetland technology is used at the BP terminal at Port Everglades, Florida (Rogozinski *et al.*, 1992). Interim remedial action (IRA) is currently underway at the facility and includes mechanical separation and volatilization via air stripping. Since free product is being removed from the groundwater, several other pollutants have been identified in the waste stream. Some of these, including lead, ammonia-nitrogen, chemical oxygen demand (COD), and total organic carbon (TOC), may be associated with nonpetroleum associated contamination at the site. Also, complete treatment of the methyl tributyl ethylene (MTBE) and polycyclic aromatic hydrocarbon (PAH) contamination was not possible with the mechanical aspect of the IRA.

Implementation of the constructed wetland was divided into three phases to reduce cost. The first phase included the actual construction of the treatment wetland, the second phase included the purchase and installation of the liner for the wetland system on the sandy soil, and the third phase involved the purchase and planting of the wetland vegetation. The system was designed as a 70 square meter (m^2) surface flow treatment wetland. The system included a 30 mil polyethylene liner. The design flow was 5 gallons per minute (gpm), which provides an approximate 8-hour hydraulic retention time.

Operational Performance

The Port Everglades treatment wetland system exhibited excellent performance following the IRA treatment train. Many of the parameters measured were removed below detection limits (BDL). Table B-2 provides a brief list of the major parameters analyzed from the air stripper effluent and the wetland effluent as an indicator of how well the treatment wetland performed.

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TABLE B-2
Performance Data Summary for the BP Port Everglades Treatment Wetland

Parameter	Air Stripper Effluent	Wetland Effluent
Total VOAs	10(5-20)	BDL (BDL-31)
Total Naphthalenes	BDL (BDL-19)	BDL
Total PAHs excluding Naphthalenes	BDL (BDL-62)	BDL
Lead	65 (56-190)	16(5-26)

Note: All concentrations are in parts per billion (ppb).

VOAs volatile organic aromatics
() = range of detection

Source: Rogozinski *et al.*, 1992.

Special Features/Issues

Initial phase construction costs for the treatment wetland were approximately $10,300. The addition of the poly liner for $1,500 and $350 for the purchase and planting of the wetland vegetation added $1,850 to the final construction costs. Total construction cost for the 70-m^2 Port Everglades wetland system was $12,150.

On the basis of the results of Port Everglades project, BP Petroleum has evaluated the use of constructed wetlands to treat wastewaters generated at several refineries, processing facilities, and terminals.

Shell Oil Company

Project Description

A constructed pilot-scale wetland demonstration project has been implemented at the Shell NORCO refinery in St. Charles Parish, Louisiana (Hawkins *et al.*, 1997; Hawkins *et al.*, 1995; Dunn *et al.*, 1995). The primary goal of the project was to identify and test biological treatment options in anticipation of future restrictive National Pollutant Discharge Elimination System (NPDES) regulations. The purpose of the study was to demonstrate the ability of constructed wetlands to remove trace quantities of metals from refinery effluent while decreasing toxicity associated with these effluents. The testing of biological and, in particular, wetland treatment systems would allow the refinery to determine the treatment potential of a low cost, low maintenance treatment technology.

The primary research objectives were as follows:

- To design and construct a wetland for removal of trace quantities of metals and to subsequently decrease toxicity in the refinery effluent.

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- To evaluate the primary components of wetlands for their abilities to remove metals (primarily zinc) and for the toxicity of their effluents by using smaller scale systems (microcosms and pilot scale systems).
- To determine the chronic toxicity of zinc in laboratory and field-scale microcosm experiments.
- To collect fate and effects data for both laboratory and field microcosm systems in order to predict responses in pilot-scale exposures.

The researchers wanted to maintain the ability to emulate wetland structure and function in their systems. To achieve successful metals removal, the researchers identified the need for anaerobic, reducing conditions within the wetland soils of their systems. Careful attention was paid to hydroperiods, soil types, and vegetation during design, construction, and operation of the experimental wetland systems. To achieve high removal efficiencies, the constructed wetlands had to maintain a negative redox potential and basic pH value in the soils upon inundation (Hawkins *et al.,* 1995).

Two constructed wetland pilot-scale cells were each 30.5 meters long by 6.1 meters wide. The cells were lined with both clay (bentonite) and a high-density polyethylene liner. Each cell had 0.3 meter (m) of sediment added, and each was planted with giant bullrush, *Scirpus californicus*. Each cell had a 24-hour nominal hydraulic retention time (HRT) and the entire system could be run in parallel or in series. Each cell received between 19 and 190 L/min of refinery effluent.

The wetland microcosms used for zinc removal experiments were 570 L containers with a 190 L internal volume. The microcosms also had a 24-hour HRT. Soil depth was 0.3 meter, and the vegetation consisted of *Scirpus californicus*. The flow rate of the influent, which contained 1 to 2 mg/L of zinc, was 160 mL/min.

Operational Performance

The researchers found that the microcosm wetlands developed the ability to remove metals. These abilities included average daily zinc removal rates of more than 98 percent, 67 percent of the influent copper, and 89 percent of the lead found in the refinery effluent. The researchers also found that chronic toxicity was significantly decreased as evidenced by the positive results of bioassay tests using both *Hyalella azteca* and *Ceriodaphnia dubia*.

Research at the pilot cells was conducted for 250 days (Hawkins *et al.*, 1997). During this period, the two cells were operated in series with measured hydraulic retention time of about 23 days in each cell at a flow rate of 23 L/min and a water depth of 30 centimeters (cm). Sediment redox decreased from +90 mV to -165 mV during this period. Average inflow concentrations of total recoverable Cu, lead (Pb), and zinc (Zn) were reduced from 22.4, 10.5, and 565.9 micrograms per liter (µg/L) by 33, 79, and 85 percent, respectively (Table B-3).

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TABLE B-3
Summary of Pilot Treatment Wetland Performance at Shell Oil Company's Norco, Louisiana Facility

Parameter	Symbol	Concentration		
		Inflow	West Cell Outflow	East Cell Outflow
Aluminum (µg/L)	Al	737.6	<110.1	<102.4
Arsenic (µg/L)	As	<4.6	<2.7	<2.5
Chromium (µg/L)	Cr	<9.0	<3.5	<3.1
Copper (µg/L)	Cu	<22.4	<15.0	<15.0
Iron (µg/L)	Fe	2.5	0.4	0.3
Lead (µg/L)	Pb	<10.5	<2.2	<2.2
Manganese (µg/L)	Mn	1208.1	102.9	97.6
Zinc (µg/L)	Zn	565.9	166.6	85.9
Total Petroleum Hydrocarbons-Extractable (mg/L)	TPH	18.9	1.4	<1.5
Ammonia (mg/L)	NH_4	0.7	0.4	0.3
BOD_5 (mg/L)	--	38.6	8.5	<8.1
Oil and Grease (mg/L)	O&G	<19.6	<5.0	<5.0
Total Dissolved Solids (mg/L)	TDS	1335.8	1397.5	1506.7
Total Organic Carbon (mg/L)	TOC	13.1	9.1	8.4
Total Suspended Solids (mg/L)	TSS	82.8	<4.8	<4.5
Total Phosphorus (mg/L)	TP	1.5	1.4	1.3
Total Kjeldahl Nitrogen (mg/L)	TKN	1.6	1.9	1.7

Notes: Means calculated using minimum detection limits as values for samples below detection limit. Wetland inflow was secondary wastewater pumped into the west cell; outflow from the west cell was inflow to the east cell.

Source: Hawkins *et al.*, 1997.

Mobil Oil AG Terminal, Bremen, Germany

Project Description

A wetland for treating oil-based effluents from a petroleum tank farm in Bremen Germany was studied by a number of researchers for 3 years (1985 to 1988) (Altman *et al.*, 1989). The biological phase of the treatment process, including a separator and bioreactor, was installed to increase the performance of the process to meet government permit regulations. These regulations mandated that hydrocarbon content be less than (<) 5 milligrams per liter (mg/L), COD < 100 mg/L, and 5-day biochemical oxygen demand (BOD_5) < 25 mg/L. The researchers found that preliminary tests resulted in influent concentrations of 60 mg/L hydrocarbon and 850 mg/L COD, respectively.

The treatment train consisted of three phases: pretreatment, biological treatment, and subsequent activated charcoal filtration. The pretreatment phase consisted of a separator, a parallel plate separation unit, an

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intermittent aeration basin, and an adsorption filter. The researchers noted that high COD and chloride loading to the system mandated the incorporation of a fourth pretreatment process — a percolating combined bioreactor (subsurface vertical flow wetland). This pretreatment phase was able to reduce the high COD levels (sometimes > 14,000 mg/L) and provided a reasonable influent wastewater quality to the treatment wetland phase.

The treatment wetland process followed a Seidel type design, incorporating both vertical and horizontal flow through cells that have a "cascading" flow distribution system. The treatment system consisted of two distinct systems, with System 1 composed of four treatment cells and System 2 composed of five treatment cells. The researchers also incorporated a vegetated treatment cell that did not receive effluent and was used as a control. The cell substrate consisted of a noncohesive gravel, which acted both as an aerobic and anaerobic substrate.

According to Altman *et al.* (1989), the aerobic/anaerobic treatment was achieved through active aeration from the bottom of each cell. Cells within each system were planted with either *Typha angustifolia*, *Scirpus lacustris*, *Phragmites communis,* or a specific combination of these species. Because COD concentrations were subsequently elevated after the treatment wetland process, the activated charcoal filter was used to reduce these levels to comply with government permit regulations.

Operation Performance

During the final phase of the study in 1988, System 1 received wastewater at a rate of 2 cubic meters per day (m^3/d), and System 2 received 3 m^3/d. Average hydraulic loading to the wetland was between 5 and 6 centimeters per day (cm/d). Higher loading rates influenced the viability of the macrophyte population. Reduction rates for COD, BOD_5, hydrocarbons, and other parameters ranged from 98 percent and above. Table B-4 includes some of the results achieved by the treatment wetland system.

TABLE B-4
Performance for a Vertical and Horizontal Flow Pilot Wetland in Bremen, Germany

Parameter	Influent (mg/L)	Effluent (mg/L)
COD	1,800	250
BOD_5	700	20
Hydrocarbons	5	0.2
Phenol Index	4	0.1
BTX Aromatics	0.1-1.6	0.01

Source: Altman *et al.*, 1989.

Substantial degradation of COD occurred only in the cells planted with *Typha,* and insignificant removals of COD were achieved in the cells planted with *Scirpus* or *Phragmites*. Once the macrophytes were

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established and the high peaks of COD were corrected, vigorous growth was achieved for all macrophyte species.

Special Features/Issues

From the preliminary test results, Altman *et al.* (1989) concluded the following:

- The treatment system was correctly designed and was able to achieve a 98 to 99 percent removal efficiency.
- Macrophyte-based treatment systems are suitable for the treatment of oily effluent from tank farms.
- Specific loading and sufficient buffering capacity must be available to achieve desired results, especially when these types of systems are subject to operational disturbances and surges of toxic effluent components.

Texaco Pilot Wetland

Project Description

A 0.04 ha, pilot-scale, free water surface constructed wetland was used to demonstrate tertiary treatment of a biologically treated refinery wastewater (Hall, 1996 [unpublished data]). The wastewater normally received pretreatment with an American Petroleum Institute (API) separator followed by a clarifier and a series of three oxidation lagoons. For this pilot study, the wastewater was collected from the clarifier before treatment in the final oxidation lagoons. The objective of this study was to determine if the wetland was capable of removing ammonia and suspended solids and reducing chronic toxicity to *Ceriodaphnia* and the fathead minnow (*Pimephales promelas*).

Table B-5 summarizes the average performance of the Pilot A wetland. The constructed wetland pilot unit removed ammonia and suspended solids while reducing chronic toxicity to both test species. Plant biomass increased by approximately 111 percent in the constructed wetland pilot unit.

A similar 0.04-ha pilot unit was used to demonstrate polishing of a refinery effluent, which had been subjected to treatment with an API separator followed by activated sludge. An 8-week pilot study was conducted to simulate tertiary treatment. The objective of this study was to determine if the wetland was capable of removing ammonia and reducing toxicity to the fathead minnow and *Ceriodaphnia*. Spiking experiments were also conducted with nontoxic effluent to simulate process unit upset conditions and to determine the point of breakthrough for ammonia.

The wetland was operated on a 6-day HRT. Table B-6 summarizes the average performance of the Pilot Unit B wetland. The wetland successfully removed ammonia while reducing toxicity to both species. Levels of ammonia as high as 9,450 parts per million (ppm) were successfully reduced to nontoxic concentrations before breakthrough occurred and toxicity was observed. This study showed that a

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TABLE B-5

Pilot Unit A: Summary of Constructed Wetland Test Parameters

	Constructed Wetland	
Parameter	**Influent Average**	**Effluent Average**
BOD	103.7 mg/L	2.1 mg/L
COD	332.7 mg/L	9.7 mg/L
TSS	14.5 mg/L	2.4 mg/L
O&G	2.0 mg/L	0.8 mg/L
pH	7.6	7.9
Conductivity	2969 mg/L	32.7 mg/L
Sulfate	350 mg/L	5.4 mg/L
Carbon (C)		
TC	65.2 mg/L	3.7 mg/L
TOC	48.8 mg/L	2.3 mg/L
TIC	16.4 mg/L	1.5 mg/L
Nitrogen (N)		
TKN	8.1 mg/L	0.05 mg/L
NH_4-N	6.3 mg/L	nd
NO_3	nd	nd
Phosphorus (P)		
Total	5.9 mg/L	1.1 mg/L
Ortho	3.4 mg/L	nd
C:N:P Ratio	88:1:9	46:1:22

NH4-N ammonia-nitrogen
NO_3 nitrate
TC total carbon
TIC total inorganic carbon
Source: Hall, 1996.

constructed wetland could easily treat short-term ammonia upsets (Table B-7). The wastewater did not appear to impact the health of the plants, as plant biomass increased by an average of 105 percent over the course of the 8-week study.

A seed-bank pilot study was conducted to determine the optimum seed soil for establishment of a full-scale constructed wetland. Tanks were prepared by using seed soil from three different sites. Two of the sites were existing bodies of water, while the third site was an agricultural field in a bottomland area. Tanks were approximately 3 meters in diameter by 1.2 meters deep. A common base substrate of topsoil was overlaid by 0.6 cm of the designated seed soil. Elevations in each pilot unit varied from simulated upland fringes with infrequent inundation to typical wetland elevation with continuous inundation. Clarifier water was applied to each pilot unit on an as-needed basis. After 9 months of growth, each seed bank pilot unit was evaluated for biomass and species composition to determine which site contained the most appropriate seed bank for use in wetland construction. Seed soil collected from one of the two existing bodies of water was determined to be the most appropriate seed bank soil for development of a full-scale constructed wetland.

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TABLE B-6
Pilot Unit B: Summary of Constructed Wetland Test Parameters

Parameter	Constructed Wetland	
	Influent Average	Effluent Average
BOD	1.9 mg/L	1.8 mg/L
COD	41.7 mg/L	4.4 mg/L
TSS	1.3 mg/L	6.0 mg/L
O&G	2.5 mg/L	2.2 mg/L
pH	7.6	6.7
Conductivity	1853 μmhos/cm	48 μmhos/cm
Sulfate	266 mg/L	< 1.0 mg/L
Carbon		
TC	73 mg/L	7 mg/L
TOC	57 mg/L	6 mg/L
TIC	17 mg/L	1.3 mg/L
Nitrogen		
TKN	4.2 mg/L	0.1 mg/L
NH_4-N	0.2 mg/L	< 0.1 mg/L
NO_3	1.1 mg/L	0.1 mg/L
Phosphorus		
total	5.9 mg/L	1.3 mg/L
ortho	1.5 mg/L	< 0.1 mg/L
C:N:P Ratio	88:1:9	32:1:7

μmhos/cm micromhos (siemens) per centimeter

Source: Hall, 1996.

TABLE B-7
Pilot Unit B: Constructed Wetland Response to Ammonia Upset

Week No.	Constructed Wetlands		Ranges
	Influent Average	Effluent Average	
1-4	0.07 mg/L	ND	ND - 0.09 mg/L
5-6	44.8 mg/L	ND	ND - 46.6 mg/L
7-8	9,450 mg/L	25 mg/L	ND - 9,890 mg/L

nd - nondetectable by method

Source: Hall, 1996.

Full-Scale Treatment Wetland Projects

Amoco's Mandan, North Dakota Facility

Project Description

A stringent National Pollutant Discharge Elimination System (NPDES) permit required Amoco's Mandan, North Dakota, refinery to examine options for improving their wastewater treatment process (Litchfield and Schatz, 1990; Litchfield, 1993). The refinery staff reviewed a number of mechanical and biological treatment options as enhancements to Amoco's existing biooxidation system. Availability of land, past

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successes with the existing system, and economics guided the decision to enhance the existing biooxidation treatment system. The refinery itself covers 122 ha of a 389-ha tract of land north of Mandan, North Dakota, along the west bank of the Missouri River (Litchfield, 1993).

The Mandan refinery has the capacity to process about 7,592 metric tons of crude oil per day and uses about 5,700 m^3/d of water from the Missouri River (Litchfield, 1993). Process water is directed to an API separator for primary treatment and then passed through the oxidation lagoon for secondary treatment. Process wastewater and stormwater are then directed through an 0.8 kilometer (km) earthen canal to 6 of the 11 cascading ponds (16.6 ha) before eventual discharge from Dam 4 to the river. The remaining five ponds (19.1 ha) are reserved for wildlife management or can be used for diversion or additional holding capacity during high stormwater runoff conditions or plant upsets. The biooxidation ponds were constructed by damming existing drainages and resulted in average water depths between 1.2 and 1.8 meters. Shallower areas along the shorelines, in the earthen canal, and especially in the downstream ponds naturally colonized with emergent wetland plants including cattail, bulrush, and other species.

Operational Performance

The following average mass removals occurred in the biooxidation pond system during a 3-year period:

Parameter	Percent Removal
BOD_5,	88 %
COD	77 %
NH_4-N	78 %
TSS	88 %
Sulfides	100 %
Phenols	97 %
Oil and grease	97 %
Hexavalent chromium	93 %
Total chromium	86 %

This performance has resulted in permit compliance for an extended period. The few violations that have occurred were apparently in response to high rainfall or snowmelt events (Litchfield, 1993).

Special Features/Issues

After construction of the biooxidation pond-wetland system, wildlife usage of the site increased. A total of 192 bird species have been observed nearby, with about 60 species nesting in the area. Nesting habitat was increased by creating islands within the ponds and planting about 50,000 trees and shrubs. In addition, upland areas are planted in wildlife food crops such as alfalfa, millet, flax, and corn. The ponds were stocked with rainbow trout, largemouth bass, and bluegill. Since 1977, about 1,246 giant Canada geese have fledged at the Amoco Mandan site. Amoco's Mandan wetland project has received significant recognition for its contributions to wildlife conservation, including the 1980 Citizen Participation Award

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from the U.S. Environmental Protection Agency (EPA), the 1986 Blue Heron Award from the National Wildlife Federation, and the Environmental Achievement Award from the Renew America Organization.

Chevron Richmond Refinery Wetland

Project Description

The Chevron Richmond Refinery Wetland (RRW) originated in 1988 as a pilot study marsh in the Number Two oxidation pond at Chevron's Richmond Refinery in Point Richmond, California. The pond was used as a polishing pond for refinery effluent between 1963 and 1985. However, water flow to this pond was reduced during this period, and by 1985, the pond no longer provided any positive benefit (Chevron, 1996). The intent of this study was to demonstrate the feasibility of enhancing the effluent water quality by allowing it to pass through a "created" but "natural" overland flow wetland (Chevron, 1996). The pond was dewatered and allowed to dry, serving as a storage basin for stormwater. The mud bottom of the pond became dry and cracked, creating an eyesore. Management at Chevron requested that the visual appearance of the pond be enhanced, so in 1986, the soils were tilled, sampled, and found to be capable of supporting a variety of vegetation. A two-stage revegetation program for the pond was implemented with the approval of the California Regional Water Quality Control Board and the help of the California Department of Fish and Game and the National Audubon Society. By 1989, the first stage (12.14 ha) was planted in the pond, and the RRW became operational. The second stage of planting followed with an additional 12.14 of wetland plants. The 12.14 ha were kept as a mud flat for shorebird habitat.

Operational Performance

The RRW began operating in 1989 and successfully serves many functions, including water polishing treatment, stormwater storage, habitat for various waterfowl and shorebirds, and design and water quality performance data for the RRW. From 1989 to 1992, vegetation and sediments were sampled annually for accumulation of heavy metals. Bird use and reproduction have been conducted at the RRW since its inception. A study of the aquatic invertebrate population living in the RRW was conducted in 1991, and a detailed study of shorebird use of the RRW was conducted in 1994 and 1995.

Operation of the RRW from 1988 through 1991 resulted in a reduction in several water quality parameters, including:

- BOD by 51 percent
- Ammonia by 76 percent
- TSS by 45 percent
- Nitrates by 69 percent

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TABLE B-8
Summary of Design and Performance of Richmond Refinery Wetland

Operation Start Date: 1988
Constructed Wetland Area
Total: 36.42 ha
Pass 1: ~12.14 ha
Pass 2: ~12.14 ha
Pass 3: ~12.14 ha

Typical Flow: 9,500 m^3/day
Wastewater Source: Refinery effluent

Influent Quality (average)		Effluent Quality (average)	
BOD	12.2 mg/L	BOD	7.1 mg/L
TSS	35.9 mg/L	TSS	34.1 mg/L
TDS	2.6 mg/L	TDS	2.9 mg/L
TP	89.8 mg/L	TP	73.3 mg/L
TN	5.5 mg/L	TN	1.9 mg/L

Source: Chevron, 1996.

A total of 8 orders and 53 families of invertebrates contributing to the food chain at the RRW were identified during the invertebrate survey (Chevron, 1996). The wetland has demonstrated the ability to improve water quality while providing significant habitat for numerous waterfowl.

Special Features/Issues

The success of the RRW centers around the design, implementation, and operation of the wetland (including monitoring), all under the control of one responsible organization. The single most important design factor contributing to the physical success of the RRW is the ability to control water flow rates and levels. Proper water management is key to optimizing plant propagation, water quality, and habitat use.

Yanshan Petrochemical Corporation, China

Pilot Project

Dong and Lin (1994) report data and models for a research facility polishing secondarily treated petrochemical wastewater in six wetlands and six ponds composing a 1.5-ha test unit. This research facility tested a variety of plants and soil substrates over the seasons. No large effect was found for any variable except hydraulic loading rate (Tables B-9 and B-10).

A linear COD removal efficiency regression with hydraulic loading rate was found to fit quite well, as follows:

$$\text{Percent Reduction} = 48.2 - 27.1*\text{HLR(m/d)} \quad (R^2 = 0.90) \qquad \text{(B-1)}$$

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Full-Scale Project

Dong and Lin (1994) describe a full-scale facility, built in 1990 and consisting of 50 ha of wetlands (ca. 50 percent) and ponds treating 100,000 m^3/d. The facility is configured with concentric rings of wetlands draining inward to oxidation ponds. The full-scale facility reduces BOD, COD, TSS, nutrients, metals, phenols, and oil (Table B-11).

TABLE B-9
Removal Efficiencies of Various Vegetation Types, Yanshan Pilot Project

	Vegetation Type			
Pollutant	*Phalaris arundinacea*	*Phragmites australis*	*Festuca arundinacea*	Mixed "Weeds"
COD	33	42	29	29
BOD	59	53	41	43
Mineral Oil	46	42	36	37
TN	24	18	21	21
Phenol	38	35	32	32
TSS	59	50	43	41
TP	42	39	35	31

Source: Dong and Lin, 1994.

Jinling Petroleum, Beijing, China

Project Description

The Jinling Petrochemical Company reported reductions in several parameters, including phenol, COD, metals, nutrients and oil in water hyacinth wetlands (Tang and Lu, 1993). Two wetlands (25 meters x 150 meters x 1 meter deep) received wastewater at detention times ranging from 2 to 12 days. One channel was 80 percent covered by *Eichhornia crassipes*; the other was unvegetated. Pretreatment included oil separation, flotation, and aeration.

Pollutant removals were achieved for all constituents, with a trend toward better removal at longer detention times. The data were used to generate estimates of areal removal rate constants (Table B-12). The vegetated channel had higher rate constants than the unvegetated channel. Rate constants were typically somewhat higher than for freshwater systems (FWS) or subsurface flow wetlands as reported by Kadlec and Knight (1996).

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At COD levels less than about 260 mg/L, the vegetation suffered no toxic effects. Metals were selectively concentrated in leaves in preference to roots. The diversity and number of microorganisms were greater in the hyacinth channel than in the control channel, and diversity increased with increasing detention time.

TABLE B-10
Performance of the Yanshan Research Wetlands at Niukouyu, P.R. China, near Beijin, 1991-93

Parameter	Season	Percent Reduction in Wetland
COD, mg/L	Spring	38.9
	Summer	47.7
	Fall	30.9
	Winter	32.5
TSS, mg/L	Spring	44.6
	Summer	42.1
	Fall	55.6
	Winter	27.8
Phenols, μg/L	Spring	34.2
	Summer	36.7
	Fall	29.2
	Winter	27.8

Source: Dong and Lin, 1994.

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TABLE B-11
Performance of the Yanshan Wetland-Pond System (Doug and Lin, 1994).

Pollutant	Influent (mg/L)	Effluent (mg/L)	Concentration Efficiency (%)	Rate Constant (m/yr)
COD	170	47.5	72	104
BOD	38	15.3	63	81
TP	1.51	0.43	68	94
TN	9.86	5.76	41	43
Ammonia N	5.81	3.47	34	35
Mineral Oil	0.84	0.29	67	91
Phenol	0.027	0.010	70	98
TSS	180.9	41.2	74	110
Hg	0.00082	0.00008	90	189
Cd	0.0033	0.003	11	10
DO	4.28	7.83		
pH	7.8	7.9		

Notes: Hydraulic loading = 0.2 - 0.25 m/day.
Detention time = 5 days.

m/yr meters per year

Source: Dong and Lin, 1994.

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TABLE B-12
Pollutant Removals in Hyacinth and Control Wetlands.

			Hyacinth		Control	
Retention Time Days	Pollutant	Inlet (mg/L)	Outlet (mg/L)	k (m/yr)	Outlet (mg/L)	k (m/yr)
2	Phenol	0.2	0.1	152	0.1	88
2	Oil	11.0	5.3	135	6.1	107
2	COD	245.5	129.8	116	170.2	60
2	N	46.7	32.5	66	43.8	12
2	P	3.5	3.2	18	3.3	11
2	Cu	20	0.1	287	0.4	287
2	Zn	0.3	0.2	32	0.2	32
2	Fe	1.6	0.9	47	1.2	47
2	Mn	1.8	0.1	228	0.5	228
2	Mg	51.0	27.6	36	41.9	36
4	Phenol	0.1	0.0	97	0.1	59
4	Oil	6.7	4.1	45	5.0	27
4	COD	119.6	89.4	24	98.9	17
4	N	46.7	33.9	29	39.6	15
4	P	3.3	1.3	84	1.7	58
4	Cu	6.7	1.4	144	4.9	27
4	Zn	0.5	0.3	66	0.3	44
4	Fe	2.4	1.8	24	2.2	6
4	Mn	2.8	0.1	283	0.6	139
4	Mg	57.6	31.9	54	48.4	16
6	Phenol	0.1	0.0	169	0.0	80
6	COD	122.6	95.9	15	117.7	2

Note: Rate consultants are for presumed zero background.

Source: Tang and Lu, 1993.

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