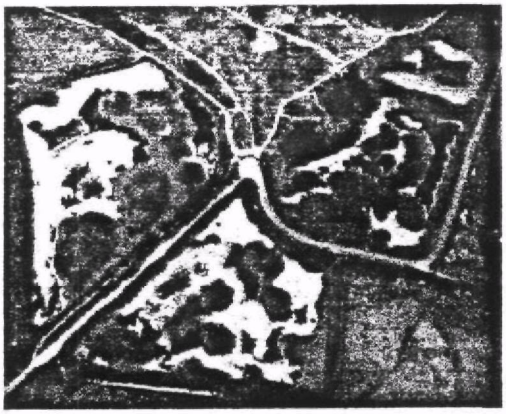


Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment

Prepared for

U.S. Environment Protection Agency,
Office of Wastewater Management
U.S. Bureau of Reclamation
City of Phoenix, Arizona

With funding from the

Environmental Technology Initiative Program

Prepared by

Environmental Resources Engineering Department
Humboldt State University
Arcata, California

CH2M-Hill
Gainesville, Florida

Wetland Management Services
Chelsea, Michigan

March 1999

FINAL DRAFT

Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment

Prepared for

U.S. Environmental Protection Agency,
Office of Wastewater Management
U.S. Bureau of Reclamation
City of Phoenix, Arizona

with funding from the
Environmental Technology Initiative Program

Prepared by

Environmental Resources Engineering Department
Humboldt State University
Arcata, CA 95521

CH2M-Hill
3011 Southwest Williston Rd.
Gainesville, FL 32608-3928

Wetland Management Services
Chelsea, MI

March 1999

Table of Contents

Table of Contents ..... **ii**

List of Tables vi
List of Figures vii
List of Equations x
List of Acronyms and Symbols xi

Acknowledgments ..... **xii**

Section 1 Introduction to Free Water Surface Treatment Wetlands **1-1**

Background 1-1
Introduction to the Technology 1-2
Types of Treatment Wetlands *1-2*
Other Benefits of Treatment Wetlands *1-4*
Historical Development of the Technology 1-6
Application of the Technology 1-9
Summary of Technology Issues 1-11
Organization of this Report 1-12

Section 2 Methods for Technology Assessment **2-1**

Data Sources 2-1
Technology Workshop and Peer Review 2-5
Data Quality and Validation 2-7

Section 3 Wetland Processes **3-1**

Wetland Hydrology 3-1
Water Balance *3-1*
Input Wastewater Flowrate 3-3
Precipitation 3-4
Evapotranspiration 3-4
Output Wastewater Flow 3-4
Percolation 3-4
Meteorological Effects on Wetland Water Budget *3-5*

Wetland Hydraulics 3-6
Wetland Hydraulic Definitions *3-6*
Water Depth 3-6
Surface Area 3-7
Volume 3-7
Wetland Porosity or Void Fraction 3-7
Hydraulic Detention Time 3-8
Hydraulic Loading Rate 3-8
Water Conveyance *3-9*

Aspect Ratio 3-9
Internal Flow Patterns Effects/Physical Facilities 3-10
Water Balance Effects on Wetland Hydraulics and Water Quality 3-11
Thermal Effects in Wetlands 3-11

Wetland Biogeochemistry 3-13
Total Suspended Solids 3-16
Processes 3-16
Settleable Solids Reduction-Anaerobic Decomposition 3-17
Biochemical Oxygen Demand 3-18
Nitrogen 3-19
Phosphorus 3-21
Chemical Oxygen Demand 3-23
Dissolved Oxygen 3-24
Hydrogen Ion 3-26

Constituent Characteristics 3-28

Aquatic Vegetation 3-29
Types of Wetland Vegetation 3-29
Vegetation Patterns 3-30
Role of Aquatic Plants in Controlling Treatment Processes 3-32

Section 4 Performance Expectations 4-1

Approach to Performance Evaluation 4-1
Data Base Evaluation (NADB and TADB) 4-1
Methodology 4-2

BOD Performance 4-4
Database Assessment 4-4
Temporal BOD Performance 4-5
BOD Permit Compliance 4-9

TSS Performance 4-10
Database Assessment 4-10
Temporal TSS Performance 4-12
TSS Permit Compliance 4-13

Nitrogen Performance 4-13
Organic Nitrogen Performance 4-14
Ammonia Nitrogen Performance 4-15
Total Kjeldahl Nitrogen Performance 4-17
Nitrate and TIN Performance 4-19
Total Nitrogen Performance 4-20
Nitrogen Permit Compliance 4-22
Ammonia Nitrogen 4-22
Total Nitrogen 4-22

Total Phosphorus Performance 4-23
Database Assessment 4-23
Temporal Phosphorus Performance 4-23
Total Phosphorus Permit Compliance 4-24

Fecal Coliform Performance 4-26
Database Assessment 4-26
Temporal Fecal Coliform Performance 4-28

Fecal Coliform Permit Compliance 4-28
Metals 4-28
Other Performance Considerations 4-30
Wetland Background Concentrations 4-30
Natural Variability 4-32

Section 5 System Planning and Design Considerations 5-1

Planning Considerations 5-1
Role of Wetlands in the Watershed 5-1
Additional Benefits/Habitat Considerations 5-4
Effluent Quality Considerations 5-5
Wetland Treatment System Objectives 5-5
Permitting 5-6
Public Access 5-8
Hydrological Considerations 5-8
Precipitation and Evapotranspiration 5-9
Groundwater 5-9
Ice and Snow 5-9
Engineering Considerations 5-10
Pre-Treatment Requirements 5-10
Soils, Slope and Subsurface Geology 5-10
Percolation and Use of Liners 5-10
Inlet/Outlet Types and Placement 5-11
Wildlife/HabitatConsideration 5-11
Environmental Impact 5-12
Land Use 5-12
Insect Vectors 5-12
Odors 5-12
Wildlife and Ecological Attractive Nuisances 5-13
Wetland Sizing 5-13
Approaches to Sizing 5-13
Assessment of Predictive Equations 5-14
Areal Loading Rate Method 5-16
Design Approach to Sizing 5-18

Section 6 Lessons Learned and Recommendations 6-1

Information Management 6-1
Planning 6-1
Multiple Benefits and Public Access 6-1
Environmental Education and Interpretation Centers 6-2
Open Water/Emergent Vegetation Ratio 6-3
Site Topography and Soils 6-4
Hydrology 6-4
Wetland Hydraulics 6-5
Inlet/Outlet Structures 6-5
Flow Measuring Devices 6-6
Internal Drainage 6-6

Internal Flow Pattern ... 6-7
Engineering ... 6-7
Berm Construction and Specifications ... 6-7
Wetland Configuration and Shape ... 6-8
Sediment Storage Zone at Inlet ... 6-9
Wetland Planting ... 6-9
Impermeable Barrier and Liner Materials ... 6-12
Operation and Maintenance ... 6-12
Management of FWS Constructed Wetlands ... 6-12
Potential Nuisance Conditions ... 6-13
Vegetation Management Implications ... 6-14
Mosquito Control ... 6-15
Process Control ... 6-15
Monitoring Requirements ... 6-16
Database Maintenance and Analysis ... 6-18
Considerations for Minimizing Variability in Effluent Quality ... 6-19
Research Studies ... 6-19
Critical Research Issues ... 6-20

Appendix A – References

List of Tables

TABLE 1-1 Additional benefits of NADB wetland wastewater treatment systems sorted by treatment objective. 1-6
TABLE 1-2 Timeline of selected events in wetland treatment technology (adapted from Kadlec and Knight 1996). 1-7
TABLE 1-3 Percentage distribution of NADB FWS treatment systems by wetland type and level of pretreatment. 1-10
TABLE 2-1 Listing of major treatment wetland conferences. 2-2
TABLE 2-2 EPA Publications on Free Water Surface Treatment Wetlands.......... 2-3
TABLE 2-3 Books with focus on Free Water Surface Treatment Wetlands - in chronological order.......... 2-3
TABLE 2-4 Journals that regularly publish articles dealing with treatment wetlands. 2-4
TABLE 2-5 Desired Minimum information/Criteria for FWS Wetland Systems. 2-4
TABLE 2-6 FWS Wetlands used for performance evaluation (Technology Assessment Sites).......... 2-6
TABLE 2-7 Panelists for the Mesa, Arizona, workshop held February 2 through 4, 1996. 2-7
TABLE 3-1 Mechanisms and factors that affect the potential for removal or addition of water quality constituents in FWS wetlands (Adapted from Stowell et al. 1980). 3-14
TABLE 3-2 Some common wetland plants and depths of occurrence used in FWS and floating aquatic constructed wetland. 3-30
TABLE 3-3 Submerged surface area of wetland vegetation, normalized for a depth of 0.5 m.......... 3-33
TABLE 4-1 Water quality constituent data availability for the FWS constructed wetland systems included in this assessment, as identified in Table 2-6.......... 4-3
TABLE 4-2 Summary of performance data and loadings for systems analyzed in this assessment (listed in Table 4-1). 4-4
TABLE 4-3 Metal removal data from free water surface treatment wetlands.......... 4-29
TABLE 4-4 Long-term average annual outflow concentrations for lightly loaded FWS wetlands in the NADB.......... 4-31
TABLE 4-5 Expected range of background concentrations for constituents of interest. 4-31
TABLE 5-1 Equations used to compute the performance of FWS constructed wetlands 5-15
TABLE 5-2 Range of areal loading rates for FWS constructed wetlands.......... 5-17
TABLE 6-1 Percent of dominant plant species areal coverage of the Enhancement Wetlands of the Arcata Marsh and Wildlife Sanctuary.......... 6-11
TABLE 6-2 Minimum monitoring requirements for a FWS constructed wetland. 6-17

List of Figures

FIGURE 1-1 Definition sketches for constructed wetlands: (a) free water surface constructed wetland with emergent vegetation, (b) free water surface wetland with an open water zone, and (c) constructed floating aquatic plant treatment system (adapted from Kadlec and Knight 1996). 1-3

FIGURE 1-2 Ecosystem and communities of a FWS (USEPA 1993b). 1-5

FIGURE 1-3 Percentage of all communities utilizing FWS constructed wetlands based upon community size (n = 135). 1-10

FIGURE 1-4 Distribution of FWS constructed wetlands utilized for treating wastewater by State – not including pilot projects or demonstration projects. 1-11

FIGURE 2-1 Influent BOD loading rates for FWS Wetland Systems in the NADB 2-9

FIGURE 3-1 Components of overall wetland water mass balance (Kadlec 1993). 3-3

FIGURE 3-2 Total annual losses (+) and gains (-) from evapotranspiration and precipitation in cm (ET-P) (Flach, 1973). 3-5

FIGURE 3-3 Monthly water budget for Arcata's wastewater treatment plant (Arcata, California) showing the effects of precipitation and evapotranspiration on the water budget. 3-6

FIGURE 3-4 Correlation between wetland water temperature and air temperatures. Both northern (Listowel) and southern (Orlando Easterly) systems show water temperatures that follow the mean daily air temperature during warm months from nearby weather stations (Kadlec and Knight 1996). 3-12

FIGURE 3-5 Conceptual partitioning of treatment processes through a FWS wetland. 3-16

FIGURE 3-6 Wetland TSS removal processes. 3-17

FIGURE 3-7 Simplified portrayal of wetland carbon processing. Incoming BOD_5 is reduced by deposition of particulate forms and by microbial processing in floating, epiphytic, and benthal litter layers. Decomposition processes create a return flux 3-19

FIGURE 3-8 Nitrogen transformation processes in wetlands (Gearheart 1998, unpublished data). 3-20

FIGURE 3-9 Influent and effluent phosphorus in the Arcata Pilot Project I FWS wetlands, Second Pilot Project, 1982. Cell 5 was loaded at 0.75 kg/ha·d, and Cell 3 at 0.15 kg/ha·d (Gearheart 1993). 3-22

FIGURE 3-10 Conceptual cycling of phosphorus forms in FWS constructed wetlands. SRP: Soluble reactive phosphorus; POP: particulate organic phosphorus; TSS-POP: form of POP in terms of a fraction of the total suspended solids. 3-22

FIGURE 3-11 BOD and COD effluent concentration before and during tap water loading to Arcata Pilot Project wetland. 3-23

FIGURE 3-12 Vertical distribution of DO in a submergent plant zone of the Arcata Enhancement Marsh 3-25

FIGURE 3-13 Vertical distribution of DO in an emergent plant zone of the Arcata Enhancement Marsh 3-25

FIGURE 3-14 Hydrogen ion (pH) buffering in system 3 at Listowel (Herskowitz 1986). 3-27

FIGURE 3-15 Metal sulfide burial processes in a wetland (Meyers 1998, personal communication). 3-28

FIGURE 3-16 Distribution of BOD and COD concentration by form (settleable, supracolloidal, or soluble) in oxidation pond effluent and treatment marsh effluent from Arcata, California (Gearheart 1992). 3-29

FIGURE 3-17 Coverage of plants during the startup period of the Arcata Pilot Project wetland 3-31

FIGURE 3-18 Stem, leaf and litter cumulative surface area for *Typha spp.* in Houghton Lake discharge zone wetland (Kadlec, 1997)........ 3-35
FIGURE 3-19 Stem and leaf surface area for *Scirpus acutis* (hardstem bulrush) and *Typha latifolia* (cattail) in Arcata Treatment Wetland (Gearheart et al., 1999, publication in progress)........ 3-35
FIGURE 4-1 Average BOD loading rate versus effluent BOD concentration for TADB sites........ 4-5
FIGURE 4-2 Monthly influent and effluent BOD values for Arcata's treatment wetland........ 4-5
FIGURE 4-3 Monthly influent and effluent BOD values for Arcata's enhancement wetland........ 4-6
FIGURE 4-4 Influent and effluent monthly BOD cumulative probability values for West Jackson County, MS........ 4-6
FIGURE 4-5 Influent and effluent monthly BOD for Lakeland, FL........ 4-7
FIGURE 4-6 Influent and effluent monthly BOD cumulative probability for Fort Deposit, AL........ 4-7
FIGURE 4-7 Monthly BOD loading rate versus BOD effluent concentration for Arcata Treatment Marsh........ 4-8
FIGURE 4-8 Cumulative monthly mass influent and effluent BOD for the Arcata Treatment Wetland........ 4-9
FIGURE 4-9 Monthy TSS loading versus effluent TSS concentration for TADB wetland systems........ 4-11
FIGURE 4-10 Cumulative probability distribution of monthly influent and effluent TSS concentration for Fort Deposit wetland........ 4-11
FIGURE 4-11 Weekly transect TSS concentration for Arcata's Cell 8 Pilot Project, with theoretical retention time of 6 days, receiving oxidation pond effluent........ 4-12
FIGURE 4-12 Weekly Influent and effluent TSS concentration for Arcata Enhancement Wetland........ 4-12
FIGURE 4-13 Cumulative yearly mass influent and effluent TSS for Arcata Treatment Wetland........ 4-13
FIGURE 4-14 Cumulative probability distribution of influent and effluent organic nitrogen for West Jackson County, Mississippi........ 4-15
FIGURE 4-15 Ammonia nitrogen loading versus effluent ammonia concentrations for TADB systems........ 4-15
FIGURE 4-16 Cumulative probability distribution of monthly influent and effluent ammonia nitrogen from Beaumont, Texas........ 4-16
FIGURE 4-17 Ammonia nitrogen removal for Beaumont, Texas through 8 cells with a total HRT of 17 days........ 4-17
FIGURE 4-18 Ammonia concentration transect through Arcata Pilot Project Wetland........ 4-17
FIGURE 4-19 Total Kjeldahl nitrogen loading versus effluent ammonia concentrations for the TADB........ 4-18
FIGURE 4-20 Cumulative probability distribution of monthly influent and effluent TKN from Central Slough, SC........ 4-18
FIGURE 4-21 Nitrate nitrogen loading versus effluent nitrate concentrations for the TADB........ 4-19
FIGURE 4-22 Cumulative probability distribution of monthly influent and effluent nitrate concentrations for Orange County, FL........ 4-20
FIGURE 4-23 Monthly influent and effluent of total inorganic nitrogen (TIN) for the Arcata Enhancement Wetland........ 4-20
FIGURE 4-24 Total nitrogen loading versus effluent total nitrogen concentrations for TADB wetland systems........ 4-21
FIGURE 4-25 Range of monthly inlet and outlet TN concentrations for cells 1 through 12 at the Iron Bridge FWS wetland near Orlando, Florida........ 4-21

FIGURE 4-26 Phosphorus pulsing, as illustrated in a pilot cell in Arcata, California. Marsh 1 received tap water (no phosphorus load), while Marsh 3 received oxidation pond effluent (Gearheart 1993). 4-24
FIGURE 4-27 Total phosphorus loading versus effluent phosphorus concentrations for the TADB FWS systems. 4-25
FIGURE 4-28 Cumulative probability distribution of monthly influent and effluent total phosphorus concentrations for Central Slough, SC. 4-25
FIGURE 4-29 Influent FC versus effluent FC for the TADB systems. 4-26
FIGURE 4-30 Cumulative probability distribution of influent and effluent fecal coliform from Arcata Pilot Project Cell 8, CA (Gearheart et al. 1986). 4-27
FIGURE 4-31 Cumulative probability distribution fecal coliform from Arcata Enhancement Wetland, CA (Gearheart 1998, unpublished data). 4-28
FIGURE 4-32 Variation in effluent BOD at the Arcata Enhancement Marsh 4-32
FIGURE 5-1 Diagram of a methodology for determining the appropriateness of the use of a constructed wetland and the factors necessary for the design of a multi-use constructed free surface wetland. 5-3
FIGURE 5-2 Annual average BOD concentration vs. annual average areal BOD loading rate for NADB systems 5-17
FIGURE 5-3 Tracer response curve for Sacramento Cell 7 (Nolte and Associates 1997). 5-19

List of Equations

(3-1) $\frac{dV}{dt} = Q_i - Q_o + Q_c - Q_b + Q_{sm} + (P - ET - I) * A$ 3-2

(3-2) $t = \frac{V\varepsilon}{Q}$ 3-8

(3-3) $Q_{avg} = \frac{Q_i + Q_o}{2}$ 3-8

(3-4) $q = \frac{Q}{A}$ 3-9

(4-1) $C_e = 3.42 + 0.262\ C_i$ 4-8

(5-1) $\frac{dC}{dt} = -k_{app}C$ 5-14

(5-2) $C_t = C_0 \exp^{-k_{app}t}$ 5-16

(5-3) $k_T = k_{20}\theta^{(T-20)}$ 5-16

List of Acronyms and Symbols

ADEM	Alabama Department of Environmental Management
ADEQ	Arizona Department of Environmental Quality
ASCE	American Society of Civil Engineers
BOD	Biochemical oxygen demand
CBOD	Carbonecous biochemical oxygen demand
CFU/100 mL	Colony-forming units per one hundred milliliters
CT	Crites, Tchobanoglous Model
d	Day
DO	Dissolved oxygen
EFF	Concentration reduction efficiency
ET	Evapotranspiration
FAC	Florida Administrative Code
FC	Fecal coliform
FWS	Free water surface
ha	Hectare
HRT	Hydraulic residence time
IAWQ	International Association on Water Quality
kg	Kilogram
kg/ha·d	Kilogram per hectare per day
L	Liter
m	Meter
mg/L	Milligram per liter
µg/L	Microgram per liter
mL	Milliliter
NADB	North American Wetland Database
NAWCC	North American Wetlands Conservation Council
NH_3-N	Ammonia nitrogen
NO_3-N	Nitrate nitrogen
NOD	Nitrogenous oxygen demand
PFR	Plug flow reactor
ppb	Part per billion
ppm	Part per million
RCM	Reed, Crites, Middlebrooks Model
RED	Mass reduction efficiency
SCDHEC	South Carolina Department of Health and Environmental Control
SFWMD	South Florida Water Management District
SRCSD	Sacramento Regional County Sanitation District
TADB	Technology Assessment Database
TIN	Total inorganic nitrogen
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
TVA	Tennessee Valley Authority
USEPA	U. S. Environmental Protection Agency
WEF	Water Environment Federation
WPCF	Water Pollution Control Federation
yr	Year

Acknowledgments

This report was prepared by the Environmental Resources Engineering Department of Humboldt State University, Arcata, California under a contract with the City of Phoenix, Arizona, CH2M-Hill, and Wetland Management Services. Material developed by Wetland Management Services and CH2M-Hill was utilized in the development of this report. Special acknowledgment goes to George Tchobanoglous for reviewing and editing the final draft report.

The following individuals reviewed the draft document and contributed constructively to the final report.

Robert Bastian	-	USEPA Washington, D.C.
Robert Kadlec	-	Wetland Management Services, Chelsea MI
Robert Knight	-	Gainesville, FL
Jim Kriessl	-	USEPA Cincinnati, OH
Eric Stiles	-	Bureau of Reclamation, Denver, CO

Principal funding for this work was provided by the U.S. Environmental Protection Agency, under an Environmental Technology Initiative (ETI) grant to the U.S. Bureau of Reclamation for support of technology development related to the Tres Rios multi-purpose constructed wetland project in Phoenix, Arizona. Project sponsors include Robert Bastian and Robert E. Lee of the U.S. Environmental Protection Agency Municipal Technology Branch, Marvin Murray of the U.S. Bureau of Reclamation, and Paul Kinshella of the City of Phoenix. A number of treatment wetland practitioners participated in a technology assessment workshop in Mesa, Arizona, in February 1996 and in March 1997, supplied information for this report, and provided a peer review of the final draft report.

Data summarized in this assessment were obtained from several sources. The North American Treatment Wetland Database provided an initial point of entry into selecting sites to be brought up to date and for systems which met the data quality criteria established for the report prepared by Robert Knight, Robert Kadlec, and Sherwood Reed under contract to the U.S. Environmental Protection Agency.

Project officers for the NADB project were Mary E. Kentula and Richard Olson at the Environmental Research Laboratory in Corvallis, Oregon, and Donald Brown at the Risk Assessment Engineering Laboratory in Cincinnati, Ohio. Considerable data were obtained from owners, consultants and researchers working on FWS constructed wetlands. Listed below are the wetland systems added to the database and individuals who provided data for this report.

Gustine, CA	Mac Walker – Walker & Assoc., Davis, CA
Ouray, CO	Tom Andrews – Southwest Wetlands, Santa Fe, NM
Hemet, CA	Stella Denison Eastern Munic. Wtr. Dist., Hemet, CA
Sacramento Regional, CA	Glen Dombeck, Nolte & Assoc., Sacramento, CA
Columbia, MO	Robert Kadlec – Wetland Mgmt. Services, Chelsea, MI

Minot, ND	Don Hammer, Norris, TN
Lakeland, FL	Robert Knight – CH2M-Hill, Gainesville, FL
Mount Angel, OR	John Yarnall, WesTech, Salem, OR
Arcata, CA	Robert Gearheart, Humboldt State Univ., Arcata, CA
Phoenix, AZ	Roland Wass, City of Phoenix, AZ
West Jackson Co. , MI	Bill Rackley, MGCRWA, MI
Manila, CA	Wiley Buck, Manila Community Serv. Dist., Manila, CA
Beaumont, TX	Bill Benner, Beaumont, TX

The principal authors of the final report were Robert Gearheart, Brad Finney, Margaret Lang, Jeffrey Anderson, and Sophie Lagacé.

SECTION 1

Introduction to Free Water Surface Treatment Wetlands

The purpose of *Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment* is to assess the application, performance, and scientific knowledge of free water surface (FWS) wetlands to treat municipal wastewater and to meet other societal and ecological needs. The objective of this assessment is to produce a document that public works engineers, consulting engineers, regulatory agency representatives, researchers and citizens can use to evaluate the feasibility of FWS treatment wetland technology. The scope of this document includes a summary of the treatment processes operating in FWS treatment wetlands, a summary and evaluation of FWS treatment wetland performance, and a brief discussion of important issues in the planning, design, and operation of FWS treatment wetlands.

Background

Free water surface wetlands have been engineered for water quality treatment in the United States since the early 1970s. Design information and operational performance data for these FWS treatment wetlands has been accumulating since that time. A number of efforts have been undertaken to summarize information from diverse data sources into a collection of performance descriptions. The most complete effort to date was the development of the North American Constructed Wetland Database (NADB) funded by the U.S. Environmental Protection Agency (EPA) (Knight et al. September 1993, NADB 1993, Brown and Waterman 1994).

The next step in assessing the performance of FWS treatment wetlands was to compile the assembled data into a summary of the state of knowledge. This technology assessment report serves that purpose by describing the current understanding of FWS wetland processes, and the performance of FWS treatment wetlands. Additionally, areas of inadequate understanding of this technology are identified in this report. The findings of this technology assessment have been incorporated into an update of the U.S. Environmental Protection Agency's (EPA's) FWS constructed wetland design manual (EPA 1988a) and the Water Environment Federation (WEF) Manual of Practice on Natural Systems (WEF, 1999), currently in preparation.

Three draft technical assessment documents have been prepared. A technical review team comprised of researchers, USEPA representatives, consultants, BOR representatives, COE representatives, and municipal representatives extensively reviewed each document. This final document, *Free Water Surface Wetlands for Wastewater Treatment: A Technology Assessment*, is a culmination of an extensive effort to create an accessible summary of the operating principles and performance expectations of FWS treatment wetlands for wastewater treatment.

Introduction to the Technology

Wastewater polishing systems utilizing wetland plants have proven to be very reliable. Wetland aquatic plants, through their canopy, biomass, and rhizosphere, create an environment that supports a wide range of physical, chemical, and microbial processes. These processes separately and in combination remove total suspended solids (TSS), reduce the influent biochemical oxygen demand (BOD), transform nitrogen forms, provide storage for metals, cycle phosphorus, and attenuate organisms of public health significance. The biogeochemical cycling of macro and micro nutrients within the wetland is the framework for the treatment capability of a wetland system. Valiela et al. (1976) describe the wastewater treatment capacity of natural wetlands as follows:

> ***"Wetlands seem to be better processors of wastes than estuaries and coastal waters. It might be feasible to safely dispose of effluents under carefully controlled conditions on marshlands rather than deeper coastal areas where the elimination of contaminants is not as effective and dispersal of contaminants is more likely. We would like to emphasize, however, that the wetland properties outlined above, and the consequent effects on nutrients, heavy metals, hydrocarbons, and pathogens are features of wetlands as they function naturally. They are in fact providing free waste treatment for contaminated waters already."***

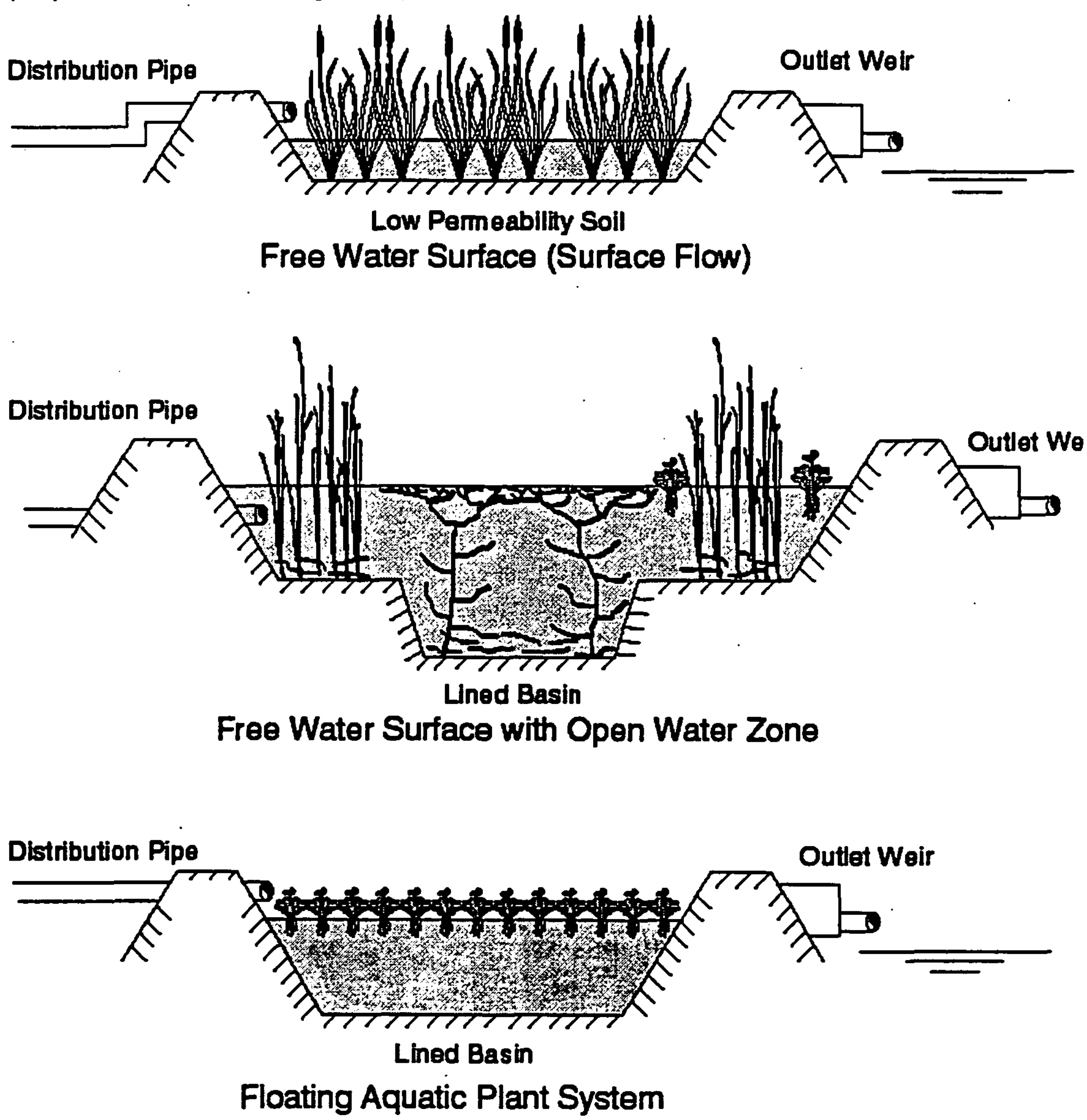
Natural wetlands are ecosystems that occur in areas that are intermediate between uplands and deep-water aquatic systems. Technical and regulatory definitions of wetlands focus on the dependence of wetland ecosystems on shallow water conditions which result in saturated soils, low dissolved oxygen (DO) levels or anaerobiosis in soils, and colonization by adapted plant and animal communities (Cowardin et al. 1979, Mitsch and Gosselink 1993). The ability of wetland ecosystems to improve water quality naturally has been recognized for more than 30 years. During this period, the use of constructed wetlands has evolved from a research concept to a relatively successful, and increasingly popular, pollution control technology (Tchobanoglous 1993).

Types of Treatment Wetlands

Three general types of shallow vegetated ecosystems are used for water quality treatment: (1) free water surface wetlands, (2) subsurface flow wetlands, and (3) floating aquatic plant treatment systems (Figure 1-1). All three of these vegetated treatment systems are operating in the U.S. for water quality improvement. Early performance information for all three system types has been published in a previous design manual (EPA 1988a). An update of the 1988 manual is due to be published by EPA in 1999. A subsurface flow technology assessment has already been completed (EPA 1993a). This present technology assessment report focuses only on the FWS treatment wetland technology.

In FWS treatment wetlands, water flows over the soil surface from an inlet point to an outlet point or, in rare cases, water is completely lost to evapotranspiration and infiltration within the wetland. The technology began with the ecological engineering of natural wetlands for wastewater treatment (Ewel and Odum 1984, Kadlec and Tilton 1979). Constructed FWS wetlands are designed to mimic the hydrologic regime of natural wetlands. Current application of FWS treatment wetland technology is almost exclusively through the construction of new FWS wetlands specifically for treatment and designed to enhance possible ancillary benefits.

FIGURE 1-1
Definition sketches for constructed wetlands: (a) free water surface constructed wetland with emergent vegetation, (b) free water surface wetland with an open water zone, and (c) constructed floating aquatic plant treatment system (adapted from Kadlec and Knight 1996).



This technology assessment includes performance data from both natural and constructed free water surface wetlands. These systems are similar in overall function with some important exceptions. The principal differences between natural and constructed treatment wetlands are structural: natural wetlands are more likely to have a forested plant community than constructed wetlands and to include a well-developed organic soil component. Natural wetlands generally have variable water depths and stagnant water zones outside the primary flow path. Natural wetlands can also have highly variable inflows.

Free water surface treatment wetlands function as land-intensive wastewater treatment 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 TSS) are trapped and tend to settle due to lowered flow velocities and sheltering from wind. The particulates contain BOD components, fixed forms of total nitrogen (TN) and total phosphorus (TP), and trace levels of metals and organics. These particulate pollutants enter the biogeochemical element cycles within the water column and surface soils of the wetland. Colloidal materials are subject to flocculation and are removed partially with the particulate fraction described above. At the same time, soils and active microbial and plant populations throughout the wetland environment sorb a fraction of the dissolved BOD, TN, TP, and trace elements. These dissolved constituents also enter the overall mineral cycles of the wetland ecosystem.

Free water surface treatment wetlands have some properties in common with facultative lagoons, but also have many important structural and functional differences. Water column processes in the open zones within FWS wetlands are nearly identical to similar zones within ponds. A surface autotrophic zone dominated by planktonic or filamentous algae or by floating or submerged aquatic macrophytes limits light to the deep zones. The absence of light in the deeper zones in both systems causes them to be dominated by anaerobic microbial processes. However, the shallow, emergent macrophyte zones present in FWS wetlands operate quite differently than any zone within a facultative lagoon. Emergent wetland plants tend to cool and shade the water surface reducing algae growth and limiting water reaeration processes that create dissolved oxygen. Secondary populations of duckweed covering the water surface and held in place by emergent plants may also hinder reaeration. Net carbon production in emergent wetlands tends to be high compared to facultative ponds because of much greater primary production of plant carbon. High production of plant carbon and the resistance of plant carbon to degradation combines with a low organic carbon decomposition rate in the oxygen deficient water column to create significant differences in biogeochemical cycling rates in wetlands compared to ponds and lagoons. Applications of floating plant systems (water hyacinths) have been documented by several studies (DeBusk et al. 1989, WPCF 1989).

Other Benefits of Treatment Wetlands

In addition to water quality benefits, wetland systems have also been designed and operated to provide wetland habitat for waterfowl and other wildlife (see Figure 1-2). Many FWS treatment wetland systems are operated as wildlife refuges or parks as well as part of wastewater treatment, reuse or disposal systems (Wilhem et al. 1989, Gearheart et al. 1989). In some cases, FWS constructed wetland systems provide an area for public education (interpretive center or informative displays) and outdoor recreation (walking, jogging, bird watching). The design of multiple purpose use FWS constructed wetlands has been significant. As shown in Table 1-1, over 40% of the NADB secondary and 36% of the NADB tertiary treatment applications identified one or more additional benefits with the system objectives. Some ecological benefits can be claimed for nearly all FWS constructed wetland systems regardless of their stated objectives. Benefits are often claimed for FWS constructed wetlands in areas where wetlands have been lost or degraded such as the facultative ponds in the north central United States (South Dakota and North Dakota) where existing degraded wetlands are used for seasonal storage.

FIGURE 1-2
Ecosystem and communities of a FWS (USEPA 1993b).

TABLE 1-1
Additional benefits of NADB wetland wastewater treatment systems sorted by treatment objective.

Wetland Treatment Application	Number	Research	Nature Study	Recreation	Hunting Fishing	Habitat	Other	Subtotal of Systems Additional Uses	Illustrative Example
Primary	6	1	2	0	1	1	1	6	Brookhaven; NY; Hay River, NWT
Secondary	45	4	5	1	3	4	1	18	Benton, KY; Iron Bridge, FL
Advanced Sec	11	1	1	0	1	1	0	4	Cannon Beach, OR; Tres Rios, AZ
Tertiary	4	0	1	0	1	0	0	2	Orange County, FL; Reedy Creek, FL
Ponds	45	0	1	0	0	1	0	2	Arcata, CA; Houghton Lake, MI
Other	4	0	0	0	1	0	0	1	
None	7	0	0	0	0	0	0	0	Armstrong Slough, FL; Des Plaines, IL
Unknown	13	1	1	0	1	0	0	3	
TOTAL	135	7	11	1	8	7	2	36	

Historical Development of the Technology

Free water surface treatment wetland technology has been under development, with varying success, for nearly 30 years in the United States (Table 1-2). In early laboratory studies in Germany, the effects of emergent plants on removal of organic compounds in industrial wastewater were examined (Seidel 1976). Constructed estuarine ponds with wetland vegetation were loaded with municipal wastewater during the 1960s and early 1970s in North Carolina (Odum 1985). Large-scale engineered natural wetland systems receiving pretreated municipal wastewater were studied in Michigan (Kadlec et al. 1993) and Florida (Ewel and Odum 1984) beginning in the early to mid-1970s. Constructed marsh-pond-meadow systems were under study at the same time in New York (Small and Wurm 1977). These research programs led to an increasing number of research and full-scale treatment wetland projects treating a variety of wastewater from municipal, industrial, and agricultural sources.

Many of the earliest treatment wetlands in Europe were subsurface flow systems designed to treat primary treated municipal wastewater. Soil and gravel-based subsurface flow wetlands are still the most prevalent application of this technology in Europe and the United Kingdom (Cooper 1990, Brix 1994a). Subsurface flow wetlands using gravel substrates have also been used extensively in the United States (Reed 1992). Subsurface flow wetland technology is not generally applicable to lagoon-pretreated wastewater because of clogging problems.

TABLE 1-2
Timeline of selected events in wetland treatment technology (adapted from Kadlec and Knight 1996).

Date	Location	Description
Selected Research Efforts		
1952-late 1970s	Plon, Germany	Removal of phenols and dairy wastewater treatment with bulrush plants by K. Seidel and R. Kickuth
1967-1972	Morehead City, NC	Constructed estuarine ponds and natural salt marsh studies of municipal effluent recycling by H.T. Odum and associates
1971-1975	Woods Hole, MA	Potential of natural salt marshes to remove nutrients, heavy metals, and organics was studied by I. Valiela, J.M. Teal and associates
1972-1977	Houghton Lake, MI	Natural wetland treatment of municipal wastewater by R.H. Kadlec and associates
1973-1974	Dulac, LA	Discharge of fish processing waste to a freshwater marsh by J.W. Day and coworkers
1973-1975	Seymour, WI	Pollutant removal in constructed marshes planted with bulrush by Spangler and coworkers
1973-1976	Brookhaven, NY	Meadow/marsh/pond systems by M.M. Small and associates
1973-1977	Gainesville, FL	Cypress wetlands for recycling of municipal wastewater by H.T. Odum, K. Ewel, and associates
1974-1975	Brillion, WI	Phosphorus removal in constructed and natural marsh wetlands by F.L. Spangler and associates
1975-1977	Trenton, NJ	Small enclosures in the Hamilton Marshes (freshwater tidal) were irrigated with treated sewage by Whigham and coworkers
1976-1979	Eagle Lake, IA	Assimilation of agricultural drainage and municipal wastewater nutrients in a natural marsh wetland by C.B. Davis, A.G. van der Valk, and coworkers
1976-1982	Southeast Florida	Nutrient removal in natural marsh wetlands receiving agricultural drainage waters by F.E. Davis, A.C. Federico, A.L. Goldstein, S.M. Davis, and coworkers
1979-1982	Humboldt, SK	Batch treatment of raw municipal sewage in lagoons and wetland trenches by Lakshman and coworkers
1980-1984	Listowel, Ontario	Constructed marsh wetlands were tested for treatment of municipal wastewater under a variety of design and operating conditions by Wile and associates
1979-1982	Arcata, CA	Pilot wetland treatment system for municipal wastewater treatment by Gearheart and coworkers
1979-1982	Humboldt, SK	Batch treatment of raw municipal sewage in lagoons and wetland trenches by Lakshman and coworkers
	NSTL Station	Wolverton's work on hyacinths
	Walt Disney World, FL	Pilot-scale wetland work on a variety of wetland plants
	Florida	Work on various aquatic plant in Florida by Ramesh Reddy, et al.
	San Diego, CA	1 mgd demonstration of treatment effectiveness of water hyacinths as a front end to the raw wastewater to potable water project
1981-1984	Santee, CA	Subsurface flow wetlands were tested for treatment of municipal wastewater by R.M. Gersberg and coworkers
1993	Hemet, CA	Effluent polishing, groundwater recharge

Date	Location	Description
1994	Tres Rios, AZ	Metals removal, effluent polishing, groundwater recharge
1995	Sacramento, CA	Metals removal
Selected Full-Scale Projects		
1972	Bellaire, MI	Natural forested wetland receiving municipal wastewater
1973	Mt. View, CA	Constructed wetlands for municipal wastewater treatment
1974	Othfresen, West Germany	Full-scale reed marsh facility treating municipal wastewater in an old quarry
1975	Mandan, ND	Constructed ponds and marshes to treat runoff and pretreated process wastewater from an oil refinery
1977	Lake Buena Vista, FL	Natural forested wetland was used for year-round advanced treatment and disposal of up to 27,700 cubic meters per day (m^3/d) of municipal wastewater
1978	Houghton Lake, MI	Natural peatland receiving summer flows of municipal wastewater
1979	Drummond, WI	Sphagnum bog receiving summer flows from a facultative lagoon
1979	Show Low, AZ	Constructed wetland ponds for municipal wastewater treatment and wildlife enhancement
1984	Incline Village, NV	Constructed wetlands for total assimilation (zero discharge) of municipal effluent
1986	Arcata, CA	Constructed marsh wetlands for municipal wastewater treatment, wetland creation, and wildlife enhancement
1987	Orlando and Lakeland, FL	Two large (> 480 ha) constructed wetlands for municipal treatment
1987	Myrtle Beach, SC	Natural Carolina bay wetlands for municipal wastewater treatment
1987-1988	Benton, Hardin, and Pembroke, KY	Constructed wetlands for municipal wastewater treatment designed by the Tennessee Valley Authority
1988	Hayward, CA	Five basin 70 ha wetland for wildlife enhancement
1988	Orange County, FL	Hybrid treatment system combining constructed and natural wetland units
1990	W. Jackson County, MS	Wildlife refuge linkage
1991	Columbus, MS	First full-scale constructed wetland for advanced treatment of pulp and paper mill wastewater
1991	Minot, ND	Northern surface flow wetland (51.2 ha) system for municipal treatment during 180-day discharge season
1993	Everglades, FL	Treatment of phosphorus in agricultural runoff in a 1,380-ha constructed filtering marsh
1993	Beaumont, TX	Large (263 ha) constructed marsh for municipal wastewater polishing and public use
1993	Ouray, CO	Effluent polishing
1995	Hidden Valley (Riverside), CA	Nitrogen removal, wetland restoration, wildlife habitat, groundwater recharge
1997	Cheney, WA	Wildlife enhancement, groundwater recharge

Free water surface constructed and natural wetlands providing treatment beyond the secondary level were built throughout the U.S. and Canada during the 1980s and 1990s. In addition to providing advanced treatment, an increasing number of these systems have been designed and operated to enhance wildlife habitat and provide public recreation. Free water surface treatment/habitat wetlands are typically much larger than subsurface flow wetlands, including several systems greater than 400 hectares (ha) in size. The largest application of FWS treatment wetland technology to date is the over 16,000 ha of FWS wetlands for the treatment of agricultural drainage in south Florida. Other large applications include the 89 ha wetland of Orange County, FL, for agricultural drainage and the 1200 ha Orlando, FL, wetland used to polish municipal effluent.

Application of the Technology

Free water surface treatment wetlands can be characterized by either their origin (natural, constructed, hybrid) or by the level of pretreatment wastewater receives prior to entering the wetland. As can be seen in Table 1-3, about 28% of the NADB treatment systems utilize natural wetlands, 69% of the wetlands are constructed, and 3% are hybrid systems. About 65% of the natural wetland systems are receiving conventional secondary treated wastewater. More than 45% of the constructed wetland systems are treating pond effluent and 22% are treating conventional secondary effluent. Viewed from the perspective of pretreatment levels, one third of the wetland systems receive pond effluent, one third receive conventional secondary effluent, and the remaining third are distributed among primary, advanced secondary, tertiary, and other.

These treatment systems were designed to meet a wide range of discharge requirements including:

- NPDES secondary standards
- Total nitrogen
- Ammonia nitrogen
- Total phosphorus
- TMDL requirements
- Advanced secondary (BOD and TSS = 10 mg/L)
- Water reuse - groundwater discharge

Free water surface constructed wetlands have been applied to a wide variety of community sizes, however, nearly half of the existing systems are in communities with less than 1,000 people. The fraction of systems serving (or, in the case of pilot systems, located in) communities of different populations is summarized in Figure 1-3. About 30% of the FWS systems have been built in communities with 1,000 to 10,000 people. There are four full-scale wetland treatment systems serving communities with populations ranging from 100,000 to 1,000,000 (Beaumont, TX, Orlando, FL, Hayward, CA, and Riverside, CA). Demonstration projects operated by Phoenix, AZ, Albuquerque, NM, and the Sacramento, CA, Regional Wastewater Facility, are examples of locations for potential future large community applications.

The largest number of FWS treatment wetlands are located in the states of South Dakota and Florida (Figure 1-4). Most of the applications in these states utilize natural wetlands. California has the next largest number of projects. The majority of these applications are to meet effluent polishing and water reuse objectives.

TABLE 1-3
Percentage distribution of NADB FWS treatment systems by wetland type and level of pretreatment.

Wetland Treatment Application	Number	Natural (%)	Constructed (%)	Hybrid (%)	Other (%)	Unknown (%)
Primary	6	33	67	0	0	0
Secondary	45	53	44	0	2	0
Advanced Secondary	11	18	82	0	0	0
Tertiary	4	50	25	25	0	0
Ponds	45	2	96	2	0	0
Other	4	25	75	0	0	0
None	7	43	57	0	0	0
Unknown	13	15	69	0	0	15
Total Number	135	37	93	2	1	2

FIGURE 1-3
Percentage of all communities utilizing FWS constructed wetlands based upon community size (n = 135).

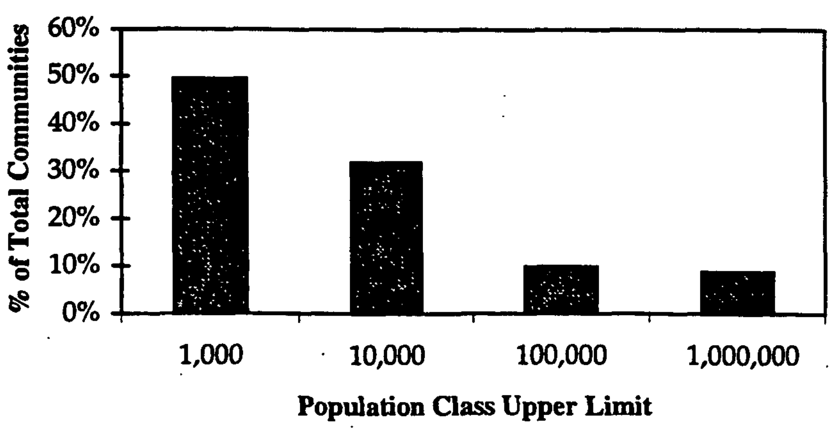
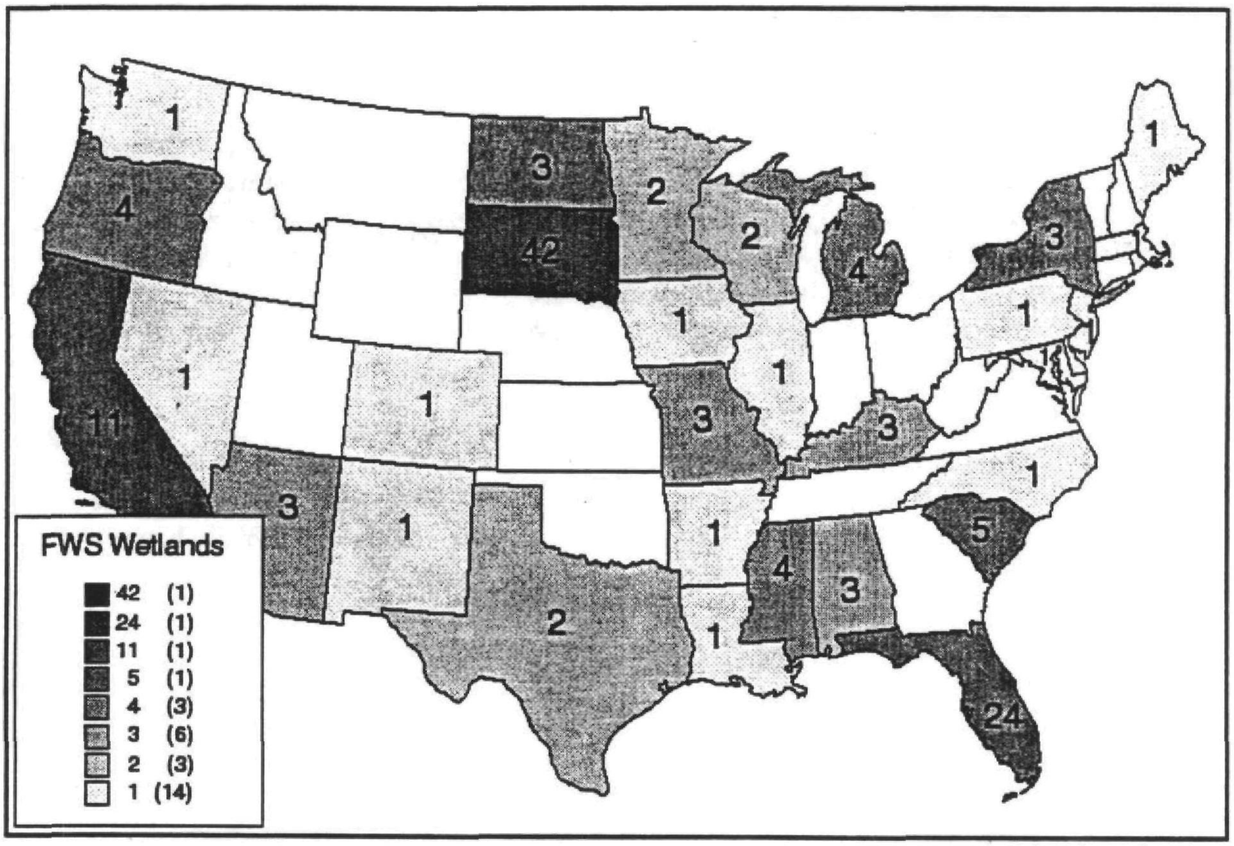


FIGURE 1-4
Distribution of FWS constructed wetlands utilized for treating wastewater by State – not including pilot projects or demonstration projects.



Summary of Technology Issues

The scope of this technology assessment is to present information necessary to determine whether FWS wetlands are appropriate for achieving specific water quality and treatment goals. The technical tasks of primary importance to applying this technology include the following:

- Estimate accurately the influent flows and pollutant loads to the FWS treatment wetland
- Estimate wetland performance and the area and volume required to meet the limiting water quality treatment goal(s)
- Design controls of the wetland hydrology and hydraulics to attain levels of performance comparable to the performance of the operating systems used to derive empirical rate constants
- Create and maintain the physical, chemical, and biological wetland system components necessary to achieve expected pollutant processing rates

The first of these tasks, the need to predict design loading, is a standard procedure for conventional wastewater treatment technologies and is not covered in this report. The remaining three tasks specific to the design and operation of FWS treatment wetland technology are covered in this report.

Numerous ancillary issues are also important in the design and operation of FWS treatment wetlands, but are not covered in detail in this technology assessment. These include conventional civil engineering design criteria for dikes and levees, water inlet and outlet control structures, and soil compaction and grading; mechanical design details for flow measurement devices; and architectural/landscape design details for operator and public access. Construction and operation issues are also important including: clearing and grubbing requirements, plant selection and plant maintenance techniques, water level control, avoidance of nuisance conditions from mosquitoes or odors, operator and public safety, and wildlife management.

These and other related issues for FWS treatment wetland technology are treated in greater detail in a number of sources related to FWS wetland design and operation (Arizona Department of Environmental Quality [ADEQ] 1995, Kadlec and Knight 1996, Reed et al. 1995, EPA 1988a and 1988b, and Water Pollution Control Federation [WPCF, now WEF] 1989). Both the EPA and WEF manuals are due to be reissued in 1999. This technology assessment report is not intended to provide detailed design guidance, but rather to present a summary of existing knowledge about FWS treatment wetland processes and performance.

Organization of this Report

The goal of this report is to summarize nearly 30 years of FWS treatment wetland information. Many of the volumes documenting the development of FWS treatment wetland technology are briefly described herein and are cited in the Reference Section.

The methods used to prepare this technology assessment report are discussed in Section 2. Data sources are described and information concerning data quality and validation are presented. A FWS treatment wetland technology assessment workshop convened in Mesa, Arizona, from February 2 to 4, 1996, to guide development of this report is also described.

Key components of the physical, chemical, and biological processes occurring in FWS treatment wetlands are summarized in Section 3. These fundamentals are essential for presenting and interpreting FWS wetland performance data. The subject areas covered in this section include: wetland hydrology, wetland hydraulics, wetland treatment processes, wetland vegetation and vegetation patterns, and wetland thermal effects.

The fundamentals necessary to evaluate and summarize FWS treatment wetland performance are presented and discussed in Section 4. Normal wetland background constituent concentrations, normal ranges of stochastic variability, and the general pattern of pollutant removal efficiencies are identified. Finally, wetland system performance is compared to permit limitations.

System planning and design considerations are presented in Section 5. The overall goals of a FWS constructed wetland and the role they play within a watershed in terms of wildlife habitat value and water quality are examined. Environmental impact and permit issues associated with constructed wetlands are also summarized in this section. Section 5 presents information concerning wetland system planning, design and sizing. Discussed are important issues concerning wetland system planning from a community level perspective. The current FWS constructed wetland design models and methods are introduced along with a discussion of their assumptions. Chapter 5 includes construction considerations, operation and maintenance considerations, and monitoring and management requirements.

Specific recommendations regarding the use and further development of a database for FWS constructed wetlands are presented in Section 6. A list of critical operational research issues is presented. Results from projects that address these critical issues would enhance the understanding and application of FWS constructed wetlands to treat domestic wastewater.

SECTION 2

Methods for Technology Assessment

Technology development is an incremental process, in which initial research, guided by information from related fields, provides a preliminary assortment of observations, speculation, and conclusions. Promising observations and conclusions become the basis for the design and scope of research efforts. As a technology develops, subsequent applications can typically be categorized as those that extend the experience with the technology or those that advance the state of knowledge about the technology. In the advancement of FWS treatment wetland technology, many efforts have been made towards data compilations and feasibility assessments rather than explicit experimental studies with clear questions, replicated design, and adequate controls. The two categories are not mutually exclusive; both applications contribute to the development and acceptance of FWS treatment wetland technology, but they differ in their contribution to the advancement of the technology. In this technology assessment, those treatment wetland applications that have been documented most thoroughly will be identified and emphasized. Further preference is given to research applications designed to advance the state of knowledge about FWS treatment wetland processes and performance.

Data Sources

Information concerning FWS treatment wetlands has been published in numerous locations including: agency-funded reports, wetland system design feasibility reports, system operational summaries, project case histories, technical research papers in refereed and non-refereed journals and books, conference proceedings, annotated bibliographies, design handbooks, electronic databases, and general wetland reference books. Primary sources are too numerous to include here, but citations for many of these references can be found in the documents listed in the Reference Section.

A sequence of treatment wetland conferences has been held in the U.S. and abroad beginning in the mid-1970s. A list of the major conferences and, when available, the literature citation for conference proceedings is provided in Table 2-1.

EPA has published a number of studies and summaries concerning FWS treatment wetlands. Titles and citations for these documents are summarized in Table 2-2. At least four states have published research syntheses and guidelines for consideration of treatment wetlands (Alabama Department of Environmental Management [ADEM] 1988, ADEQ 1995, Florida Administrative Code [FAC] 1989, South Carolina Department of Health and Environmental Control [SCDHEC] 1992). The reference section of this document also contains many detailed studies on FWS treatment wetlands.

Books dealing specifically with treatment wetlands are listed in Table 2-3. Journals that commonly publish articles about treatment wetlands are listed in Table 2-4.

TABLE 2-1
Listing of major treatment wetland conferences.

Date	Location	Description
May 1976	Ann Arbor, MI	Freshwater Wetland and Sewage Effluent Disposal (Tilton et al. 1976)
February 1978	Tallahassee, FL	Environmental Quality Through Wetlands Utilization (Drew 1978)
November 1978	Lake Buena Vista, FL	Wetland Functions and Values (Greeson et al. 1978)
July 1979	Higgins Lake, MI	Freshwater Wetland and Sanitary Wastewater Disposal (Sutherland and Kadlec 1979)
September 1979	Davis, CA	Aquaculture Systems for Wastewater Treatment (Bastian and Reed 1979)
June 1981	St. Paul, MN	Wetland Values and Management (Richardson 1981)
June 1982	Amherst, MA	Ecological Considerations in Wetlands Treatment of Municipal Wastewaters (Godfrey et al. 1985)
July 1986	Orlando, FL	Aquatic Plants for Water Treatment and Resource Recovery (Reddy and Smith 1987)
June 1988	Chattanooga, TN	Constructed Wetlands for Wastewater Treatment (Hammer 1989)
August 1988	Arcata, CA	Wetlands for Wastewater Treatment and Resource Enhancement (Allen and Gearheart 1988)
September 1989	Tampa, FL	Wetlands: Concerns and Successes (Fisk 1989)
September 1990	Cambridge, UK	Constructed Wetlands in Water Pollution Control IAWQ 2nd (Cooper and Findlater 1990)
September 1990	Show Low, AZ	Municipal Wetlands (City of Show Low Public Works Department)
June 1991	Arlington, VA	Created and Natural Wetlands in Controlling Non-Point Source Pollution (Olson 1992)
October 1991	Pensacola, FL	Constructed Wetlands for Water Quality Improvement (Moshiri 1993)
July 1992	Pinetop-Lakeside, AZ	Effluent Reuse and Constructed Wetlands (Arizona Hydrological Society Summer Seminar)
September 1992	Columbus, OH	INTECOL Wetlands Conference (Mitsch 1994)
December 1992	Sydney, Australia	Wetland Systems in Water Pollution Control IAWQ 3rd (Pilgram 1992)
November 1994	Guangzhou, China	4th International Conference on Wetland Systems for Water Pollution Control (International Association on Water Quality [IAWQ] 1994)
April 1994	Lafayette, IN	Constructed Wetlands for Animal Waste Management (DuBowy and Reaves 1994)
July 1995	Fayetteville, AR	Animal Waste and the Land-Water Interface (Steele 1995).
September 1995	Tampa, FL	Versatility of Wetlands in the Agricultural Landscape (Campbell 1995)
May 1996	Fort Worth, TX	Constructed Wetlands for Animal Waste Management (DuBowy, in preparation)
September 1996	Vienna, Austria	5th International Conference on Wetland Systems for Water Pollution Control (Perfler and Huberl, in preparation)

TABLE 2-2
EPA Publications on Free Water Surface Treatment Wetlands.

Aquaculture Systems for Wastewater Treatment. R.K. Bastian and S.C. Reed, eds. EPA 430/9-80-006. MCD 67.
University of California, Davis – Wetland Conference Proceedings. EPA,1979.
The Effects of Wastewater Treatment Facilities on Wetlands in the Midwest. EPA 905/3-83-002. 1983.
Freshwater Wetlands for Wastewater Management. Region IV Environmental Impact Statement. Phase 1 Report. EPA 904/9-83-107. 1983.
The Ecological Impacts of Wastewater on Wetlands: An Annotated Bibliography. EPA 905/3-84-002. 1984.
Freshwater Wetlands for Wastewater Management Handbook. EPA 904/9-85-135. 1985.
Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal. EPA 430/09-88-005. 1988.
Design Manual. Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. EPA 625/1-88/022. 1988.
Constructed Wetlands for Wastewater Treatment and Wildlife Habitat. 17 Case Studies. EPA 832-R-93-005. 1993.

TABLE 2-3
Books with focus on Free Water Surface Treatment Wetlands - in chronological order.

Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural, edited by Hammer, D. A., Lewis Publishers, Michigan, 1989.
Natural Systems for Wastewater Treatment - Manual of Practice, Water Environment Federation (formally Water Pollution Control Federation), 1989.
Constructed Wetlands for Water Quality Improvement, edited by Moshiri, G. A., Lewis Publishers, Boca Raton, 1993.
Wetlands, Second Edition, by Mitsch, W. J, and J. G. Gosselink, Van Nostrand Reinhold, New York, 1993.
Natural Systems for Waste Management and Treatment, Second Edition, by Reed, S. C., R. W. Crites, and E. J. Middlebrooks, McGraw-Hill Inc., New York, 1995.
Treatment Wetlands, by Kadlec, R. H., and R. L. Knight, Lewis Publishers, Boca Raton, 1996.
Creating Freshwater Wetlands, Second Edition, by Hammer, D. A., Lewis Publishers, Boca Raton, 1996.
Small and Decentralized Wastewater Management Systems, by R.W. Crites, and George Tchobanoglous, McGraw-Hill Inc., New York, 1998

TABLE 2-4
Journals that regularly publish articles dealing with treatment wetlands.

Aquatic Botany	American Water Resources Association (AWRA) Journal
Canadian Journal Fisheries and Aquatic Science	Ecological Applications
Ecological Engineering	Ecological Modeling
Hydrobiologia	Journal of Environmental Quality
Soil Science	Water Environment Research (formerly Journal of the Water Pollution Control Federation)
Water Environment Technology	Water Research
Water Resources Journal	Wetlands
Wetlands Journal	International Association for Water Quality

Free water surface treatment wetland data summaries exist in a number of locations and include various synthesis papers (North American Wetlands Conservation Council [NAWCC] 1995, Watson et al. 1989, WPCF 1989). The most widely used source of treatment wetland design and operational performance data is the North American Treatment Wetland Database (NADB) (Knight et al. 1993, Knight et al. September 1993, NADB 1993). This electronic database includes information from 203 treatment wetland systems at 176 sites in North America. Of these systems, 140 are FWS treatment wetlands of which 125 treat municipal wastewater, nine treat industrial wastewater, and six treat stormwater.

Many of these systems do not have detailed operational and performance data i.e., influent and effluent flow data, multiple cell water quality measurements, vegetation type and coverage, etc. To fully evaluate the performance of full-scale FWS wetlands treating municipal wastewater, the following data and operational information (Table 2-5) should be available:

TABLE 2-5
Desired Minimum information/Criteria for FWS Wetland Systems.

	Informational/Data Category or Criteria
1)	Municipal wastewater treatment objective with NPDES or equivalent discharge permit for target contaminants,
2)	Wetland type – constructed, natural, or hybrid
3)	Systems have been in operation longer than 3 years and at least 2 years of operating data are available for the wetland,
4)	Spatial dimensions of the system are well characterized,
5)	Influent and effluent flow rates are available for independent wetland cells for a minimum time period of monthly averages,
6)	Influent and effluent constituent concentrations are available for independent wetland cells,
7)	Wetlands continuously discharge,

	Informational/Data Category or Criteria
8)	Minimize use of data from leaky or infiltrating (extraneous flows in or out) wetlands,
9)	Minimize use of multiple cell wetlands without intermediate flow rate and constituent concentration data,
10)	Particulate and soluble fractionated constituent data, and
11)	Surface mapping (vegetated vs. open area) characterization is available on a regular basis.

No full-scale FWS treatment wetland system has been identified for which all of the data and operational information listed above is available. Forty FWS treatment wetland systems were judged to meet enough of conditions 1 through 6 listed above to allow adequate evaluation of the system performance. These 40 systems also include FWS treatment wetlands operating across the range of feasible pollutant loading rates. The 40 systems meeting the minimum requirements for system evaluation are listed in Table 2-6, and are the principle sources of data used for this technology assessment. For the purposes of this document, these sites will be referred to as the Technology Assessment Sites, and the data associated with these sites will be referred to as the Technology Assessment Database (TADB). While most of these sites were represented in the NADB, several additional sites were added, and additional data from NADB sites were incorporated where available. Source information is given whenever necessary for data or information used in this report, and a listing of data used from the Table 2-6 FWS treatment wetlands is given in Appendix A.

Technology Workshop and Peer Review

An initial draft document was prepared by Sherwood C. Reed in cooperation with Parsons Engineering Science, Inc., under contract with EPA. An invited workshop was convened in Mesa, Arizona, from February 2 to 4, 1996, to provide additional input to the technology assessment process. This workshop consisted of presentations and discussions of 17 FWS treatment wetland technology issues by a group of panelists who are published practitioners in this field of expertise (Table 2-7). Not all of the FWS treatment wetland professionals with valuable information could be invited to participate on this panel. However, the panel consisted of a cross-section of the types of specialists who are active in the design and operation of this technology. These specialists brought a broad mix of experience related to different wastewater types, wetland configurations, wetland design, wetland data analysis and research, and science or engineering educational backgrounds. A revised document was prepared by Robert L. Knight and Robert H. Kadlec in cooperation with CH2M HILL, under contract with the City of Phoenix to complete tasks supported by a grant from EPA. This final report, prepared by Robert A. Gearheart and George Tchobanoglous with extensive input from numerous reviewers, reflects the data presented and discussed, and insights offered by panelists at the workshop.

TABLE 2-6
FWS Wetlands used for performance evaluation (Technology Assessment Sites).

System	State	Pretreatment	Seasonal	Origin	Area (ha)	Flow (m3/day)
Arcata Pilot I Cell 8	CA	Pond		Constructed	0.04	46
Arcata Pilot II	CA	Pond		Constructed	0.37	327
Arcata Treatment	CA	Pond		Constructed	1.87	6700
Arcata Enhancement Allen	CA	Pond		Constructed	4.40	5186
Arcata Enhancement	CA	Pond		Constructed	11.20	5186
Beaumont	TX	Pond		Constructed	222.00	79494
Benton Cattail	KY	Secondary		Constructed	1.50	815
Benton Woolgrass	KY	Secondary		Constructed	1.50	819
Brookhaven Meadow Marsh	NY	Primary		Constructed	0.32	48
Cannon Beach	OR	Adv Sec	x	Natural	7.00	1814
Central Slough	SC	Secondary		Natural	31.60	1788
Clermont Plot H	FL	Secondary		Natural	0.20	25
Columbia	MO	Adv Primary		Constructed	38.30	54287
Fort Deposit	AL	Pond		Constructed	6.00	584
Gustine (89-90) 1A	CA	Pond		Constructed	0.39	164
Gustine (89-90) 1B	CA	Pond		Constructed	0.39	82
Gustine (89-90) 1C	CA	Pond		Constructed	0.39	41
Gustine (89-90) 1D	CA	Pond		Constructed	0.39	164
Gustine (89-90) 2A	CA	Pond		Constructed	0.39	174
Gustine (89-90) 2B	CA	Pond		Constructed	0.39	164
Gustine (89-90) 6D	CA	Pond		Constructed	0.39	144
Gustine (94-97)	CA	Pond		Constructed	9.38	2563
Houghton Lake	MI	Pond	x	Natural	75.00	4378
Iron Bridge	FL	Secondary		Natural	494.00	45521
Lakeland	FL	Secondary		Constructed	498.00	26550
Listowel 4	ONT	Pond		Constructed	0.13	27
Manila	CA	Pond		Constructed	0.55	244
Minot	ND	Adv Sec	x	Constructed	50.18	16886
Mt. Angel	OR	Pond	x	Constructed	3.57	2320
Orange County	FL	Tertiary		Hybrid	89.00	6682
Ouray	CO	Pond		Constructed	0.89	718
Pembroke FWS 2	KY	Secondary		Constructed	0.93	287
Poinciana Boot	FL	Secondary		Natural	46.60	746
Reedy Creek WTS1	FL	Tertiary		Natural	35.00	12677
Reedy Creek OFWTS	FL	Tertiary		Natural	5.90	3719
Sacramento	CA	Secondary		Constructed	6.07	3975
Sea Pines Boggy Cut	SC	Secondary		Natural	20.00	6017
Tres Rios Hayfield	AZ	Adv Sec		Constructed	2.61	3477
Vereen Bear Bay	SC	Secondary		Natural	69.00	879
West Jackson County	MS	Pond		Constructed	22.70	6257

TABLE 2-7
Panelists for the Mesa, Arizona, workshop held February 2 through 4, 1996.

Andrews, Tom L.	Southwest Wetlands Group
Crites, Ron	Brown and Caldwell (formerly with Nolte and Associates)
DeBusk, Thomas A.	Azurea, Inc.
Dortch, Mark	U.S. Army Corps of Engineers
Gearheart, Robert A.	Humboldt State University
Hammer, Donald A.	Hammer Resources, Inc.
Kadlec, Robert H.	Wetlands Management Services
Knight, Robert L.	CH2M HILL
Mitsch, William J.	Ohio State University
Moore, James	Oregon State University
Payne, Victor W.E.	Payne Engineering
Reed, Sherwood C.	Environmental Engineering Consultants
Reddy, Ramesh	University of Florida
Schueler, Thomas R.	Center for Watershed Protection
Schwartz, Larry	Camp Dresser & McKee
Stiles, Eric	Bureau of Reclamation
Tchobanoglous, George	University of California, Davis

Data Quality and Validation

Data related to wetland design, operation, and performance have variable quality. Some design information is estimated from plans and specifications and has not been confirmed by as-built field measurements. Thus, wetland area estimates may be inaccurate because of difficult construction conditions, berm erosion during and following construction, or imprecise aerial photo interpretation. Similarly, water depths are rarely measured at more than a few points, and topography due to final grade variation or due to natural wetland conditions results in depth estimates that may be questionable.

Water flow rates can be measured with considerable accuracy, given state-of-the-art equipment and adequate calibration techniques. However, few facilities have a high level of instrument sophistication, and many only routinely estimate inflows or outflows, and not both. Internal flows are rarely measured. Considerable error has been observed in flow measurements from many treatment wetland facilities.

Numerous methods are available for analysis of water quality constituents. These methods tend to range from those requiring minimal sophistication to those methods employed in scientific research facilities. Significant variability exists in the accuracy of water quality data from different FWS treatment wetlands.

The NADB contains data with a wide range of quality, accuracy and precision. Some of the included data sets have large quantities of data collected from well-funded projects (i.e. large scale pilot projects), and the reported data is good quality and accurate. However, many data sets in the NADB have questionable flow rates and constituent concentration values, as is cautioned by the USEPA in the user instructions for the NADB. For this reason, greater or lesser reliance is warranted for conclusions formulated from different sites. When multiple data sets are included in an analysis, some of the uncertainty reflected in the results is likely due to measurement imprecision, while the rest is due to variables not included in the analysis.

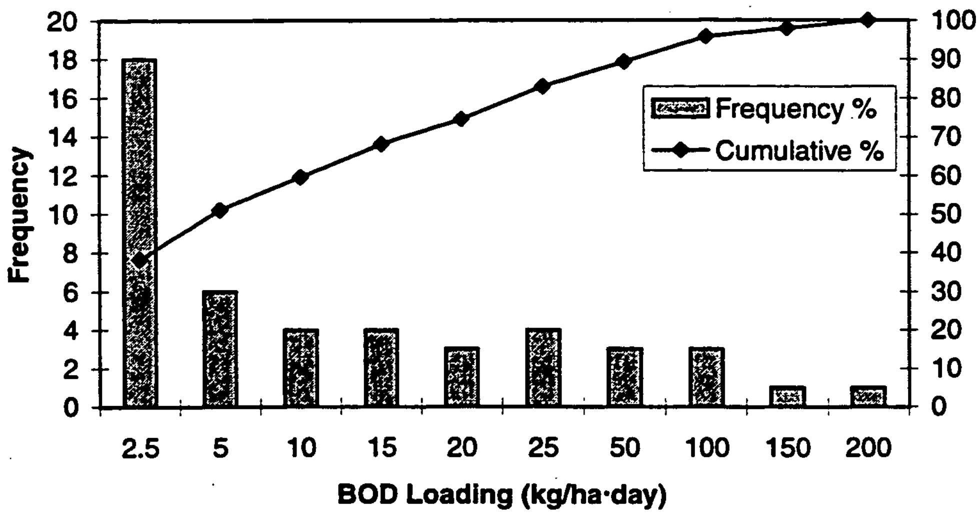
The NADB was developed to identify sites and was not an attempt to analyze data or assess data quality. The NADB provides cautionary information on data quality with no attempt to review and reject questionable data. Although recognized errors have been corrected for this technology assessment, it is inevitable, due to the large amount of data presented, that some of the results in this assessment will contain inaccuracies. The NADB operational data summary also disproportionately represents the southeastern US region and FWS treatment wetland systems with secondary or better quality influents. This situation needs to be considered carefully when attempting to draw conclusions regarding regional differences.

Additionally, the majority of the systems in the database are lightly loaded systems with relatively low influent BOD and TSS concentrations. In many of these systems, the effluent BOD is greater than the influent BOD. Figure 2-1 shows that as of 1993, 50% of the systems (and over 70% of the observations) documented in the NADB had average organic loads of less than 5 kg BOD/ha·d. Approximately 28% of the systems measured had organic loads less than 1 kg BOD/ha·d. Only 21% of the systems documented had loadings within the normally suggested range for secondary effluents from 12 to 50 kg/ha·d (calculated from hydraulic loading rate ranges suggested by Watson et al. in Hammer, 1989 for secondary and polishing treatment). The vast majority of the lightly loaded systems have effluent concentrations of BOD close to the influent concentration, and in some cases, the effluent BOD levels are higher than the influent. Over 44% of the influent BOD measurements for FWS wetlands in the NADB were less than 10 mg/L (32% less than 5 mg/L). Nearly 60 percent of these systems had effluent BOD values less than 5 mg/L. Some of these systems with low effluent BOD were moderately loaded systems, but most were very lightly loaded.

Because of legitimate concerns about data quality or relevance, it is important to examine information from multiple systems; to look for consistent trends among systems and over time; and to question and understand conflicting results. It is also prudent to look to multiple, independent data sets to validate apparent trends and conclusions. The level of confidence in the conclusions stated in this report is proportional to the availability of corroborating evidence and is indicated, when appropriate, throughout the text.

In summary the NADB was viewed as an overview inventory of wetland technology but not sufficient in itself to provide loading data and discharge data to be statistically analyzed. Individual sites and entries do provide data that can be used to predict performance and to extrapolate performance to other sites.

FIGURE 2-1
Influent BOD loading rates for FWS Wetland Systems in the NADB.



SECTION 3

Wetland Processes

Free water surface (FWS) treatment wetlands are typically shallow vegetated basins. They are designed and constructed to exploit physical, chemical and biological processes naturally occurring in wetlands to provide for the reduction of organic material, total suspended solids, nutrients, and pathogenic organisms. FWS treatment wetlands take advantage of these natural treatment processes by providing ample time for settling and for the wastewater to react with the many different reactive surfaces found in wetlands. Wastewater normally has higher nutrient concentrations than natural wetland influents, thus, many of the wetland processes and constituent reductions proceed at increased rates in FWS constructed wetlands. These increased nutrient loadings generally result in higher levels of biological production in FWS constructed wetlands receiving wastewater than in natural wetlands.

Important wetland processes, as they relate to FWS constructed wetlands, are summarized briefly in this chapter. Topics discussed include wetland hydrology, hydraulics, biogeochemistry, aquatic vegetation, and thermal effects. The intent of this section is to provide the reader with a brief introduction to wetland processes. For a more detailed discussion of wetland processes, the reader may refer to many of the books available on wetlands (see Table 2-3).

Wetland Hydrology

The hydrology of FWS wetlands, both natural and constructed, is often considered the most important factor in maintaining wetland structure and function, determining species composition, and developing a successful wetlands project (Mitsch and Gosselink, 1993; Hammer, 1992). Wetland hydrology directly influences and controls abiotic factors such as water and nutrient availability, aerobic and anaerobic conditions in both the soil and water columns, water chemistry, soil salinity, soil conditions (e.g. peat building), and water depth and velocity. In turn, biotic components of a wetland (primarily vegetation) directly influence wetland hydrology through processes such as transpiration, interception of precipitation, peat building, shading, wind blocks, and development of microclimates within the wetland. The development of a water balance or budget, the standard method for characterizing wetland hydrology, is described below.

Water Balance

The wetland water balance is used to quantify the hydrologic balance between inflows and outflows of water to and from the wetland, and the wetland volume or storage capabilities. The flows and storage volume control the length of time water spends in the wetland, and thus the opportunity for interactions between waterborne substances and the wetland ecosystem. A thorough understanding of the dynamic nature of the wetland water balance, and how this balance affects pollutants, is necessary for the planning and design of FWS constructed wetlands.

Water enters natural wetlands via stream inflow, runoff, groundwater discharge and precipitation, and water is lost through stream outflow, groundwater recharge (infiltration), and evapotranspiration (Figure 3-1). These flows are extremely variable and stochastic in nature, which can cause large water level fluctuations to occur in natural wetlands. In contrast, FWS constructed wetlands are isolated from stream inflow, and their primary sources of water are wastewater inflow, precipitation and runoff; water losses are via infiltration entry into the outlet, evapotranspiration, and possibly percolation (if the wetland bottom and sides are unlined and/or permeable). The steady inflow associated with FWS constructed wetlands represents an important feature that distinguishes them from many natural wetlands. A dominant steady inflow, with little variation in water levels drives the ecosystem toward an ecological condition that is somewhat different from a stochastically driven system. Dryout does not normally occur in FWS constructed wetlands, and only plants that can withstand continuous flooding will survive.

Although FWS constructed wetlands experience more constant inflows, seasonally variable wastewater flows can combine with seasonally variable precipitation and evapotranspiration to cause large differences in seasonal hydrologic functions. An overall water balance is required to perform the contaminant mass balance analyses necessary to predict or evaluate wetland functioning. The averaging time period over which the water balance components are determined must be short enough (weekly to monthly) to capture seasonal effects. In addition, the averaging time period must also be compatible with the frequency of water quality sampling. For instance, weekly water quality results would normally be combined with weekly average flows to determine mass removal rates. At a minimum, a detailed monthly or seasonal water balance, in which all potential water losses and gains are considered, should be conducted for any proposed FWS treatment wetland. An annual water budget will miss important seasonal wetland water gains or losses, such as heavy periods of winter precipitation or high summer evapotranspiration rates.

The overall dynamic water budget for a FWS constructed wetland can be stated as:

$$\frac{dV}{dt} = Q_i - Q_o + Q_c - Q_b + Q_{sm} + (P - ET - I) * A \quad (3\text{-}1)$$

where:

dV/dt = rate of change in water volume (V) in wetlan with time (t) (L^3/t),

Q_i = input wastewater flow rate (L^3/t),

Q_o = output wastewater flow rate (L^3/t),

Q_c = catchment runoff rate (L^3/t),

Q_b = bank loss rate (L^3/t),

Q_{sm} = snowmelt rate (L^3/t),

P = precipitation rate (L/t),

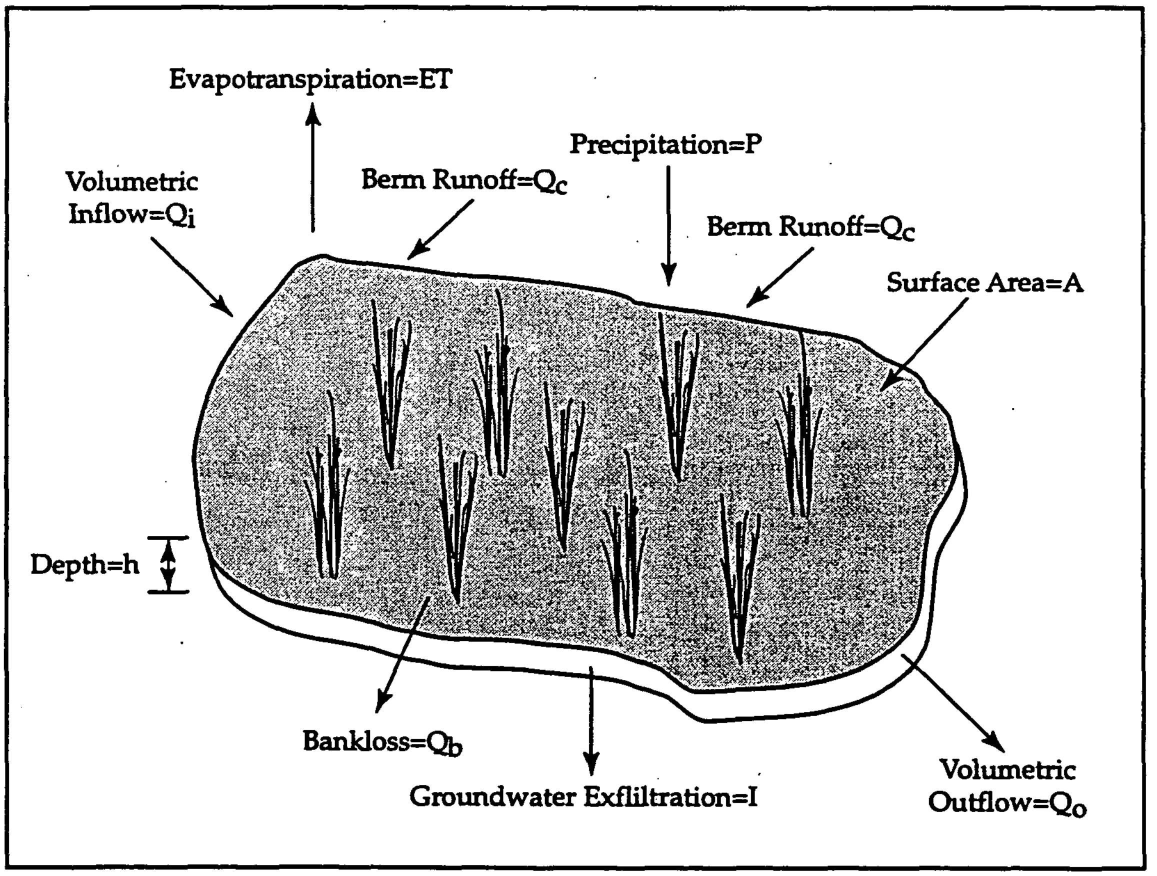
ET = evapotranspiration rate, meters per day (L/t),

I = exfiltration to groundwater (L/t),

A = wetland top surface area, square meters (L^2),

Each term in this water budget may be important for a given constructed wetland, but rarely do all terms contribute significantly. The importance of the primary components of Equation 3-1 will need to be determined prior to the preparation of the wetland water budget. Some of the terms may be deemed insignificant and can be neglected from the water budget equation (e.g., Q_b, Q_c, Q_{sm}, are generally ignored). In addition, groundwater exfiltration (I) can be neglected if the wetland is lined with some type of impermeable barrier.

FIGURE 3-1
Components of overall wetland water mass balance (Kadlec 1993).



Input Wastewater Flowrate

The daily influent wastewater flow (Q_i) will typically be the controlling inflow into a FWS treatment wetland. If wastewater flowrates are not known, they can be estimated using conventional engineering methods for predicting wastewater flows, such as water usage records, or user numbers and typical wastewater per capita flowrates found in the literature. The variability of wastewater flowrates may need to be considered when conducting wetland water balances, especially for small to medium size FWS treatment wetlands. Variable wastewater flows include seasonal peaks from vacation communities and high infiltration and inflow rates into collection systems, the latter being a condition which should be studied and minimized prior to treatment system design.

Precipitation

Depending on the time scale of the water budget, precipitation (P) data may be required in daily, weekly, monthly, seasonal or annual quantities. Precipitation inflows into a wetland come from direct precipitation onto the wetland surface area, and runoff from the wetland catchment (i.e. berms and roads). The effects of precipitation on the wetland water balance can be significant, especially in areas of high rainfall or snowfall rates. High seasonal precipitation can dilute wetland pollutant concentrations, and the resulting effects may need to be considered in a wetland pollutant mass balance.

Evapotranspiration

Evapotranspiration in a FWS constructed wetland is the combined water loss due to evaporation from the water surface and transpiration from wetland vegetation. Many FWS wetlands operate with small hydraulic loading rates. For the 100 surface flow wetlands in North America, a hydraulic loading of 10.0 mm/d is found to be the 40th percentile (Knight et al. September 1993). Evapotranspiration (ET) losses approach a daily average of 5.0 mm/d in summer in the southern U.S.; consequently, more than half the water added daily may be lost to ET under these circumstances. Because ET follows a diurnal cycle, with a maximum during early afternoon and a minimum in the late nighttime hours, outflow from a FWS constructed wetland can cease during the day in areas of high ET rates. As shown in Figure 3-2, with the exception of the non-coastal, western U.S., annual water loss due to ET is largely replaced by precipitation.

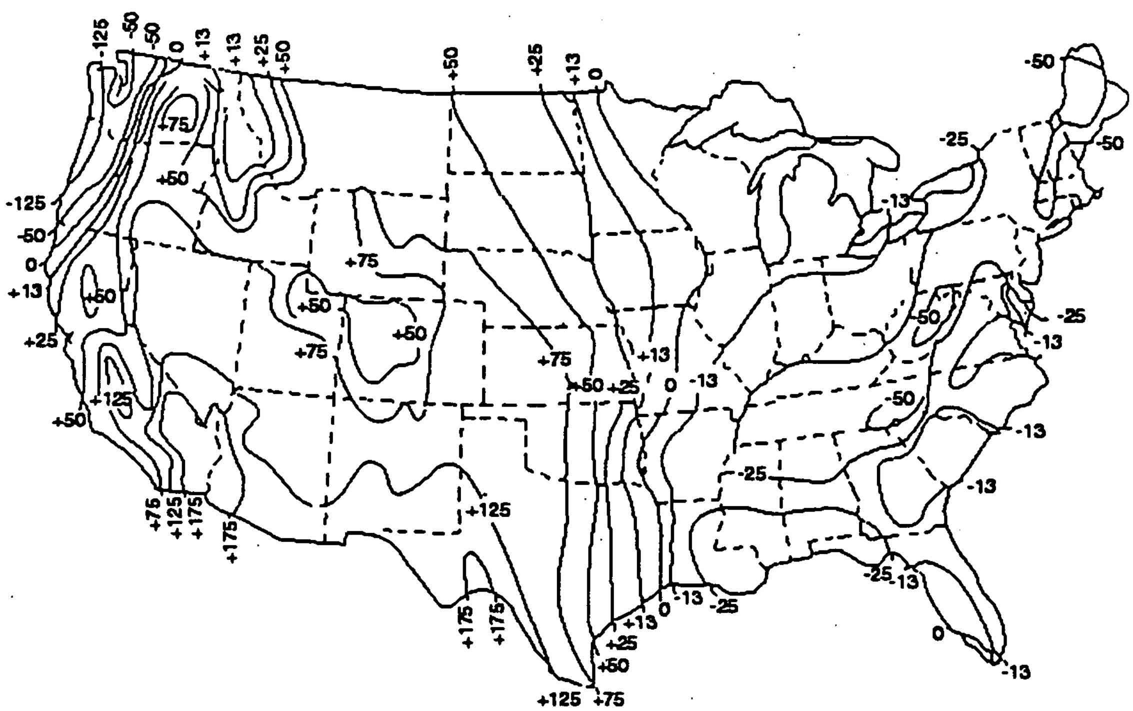
Output Wastewater Flow

The output wastewater flow corresponds to the amount of treated wastewater (effluent) leaving the FWS constructed wetland. The outlet in a FWS constructed wetland generally consists of some type of control structure that can be used to regulate water depth. Increasing or decreasing the water level also changes the wetland volume, which can influence the wetland water budget by providing more or less water storage potential to offset the effects of high seasonal precipitation or evapotranspiration.

Percolation

In a FWS constructed wetland, percolation is the loss of water that occurs into the bottom soils or berms. The effect of percolation is to reduce the water remaining in a wetland and change the potential for each constituent transformation. The hydraulic load reduction is further changed by the loss of certain soluble constituents as the water percolates from the system and infiltrates into the soil. If the FWS constructed wetland is lined with some type of impermeable barrier, percolation can be neglected in the water balance.

FIGURE 3-2
Total annual losses (+) and gains (-) from evapotranspiration and precipitation in cm (ET-P) (Flach, 1973).

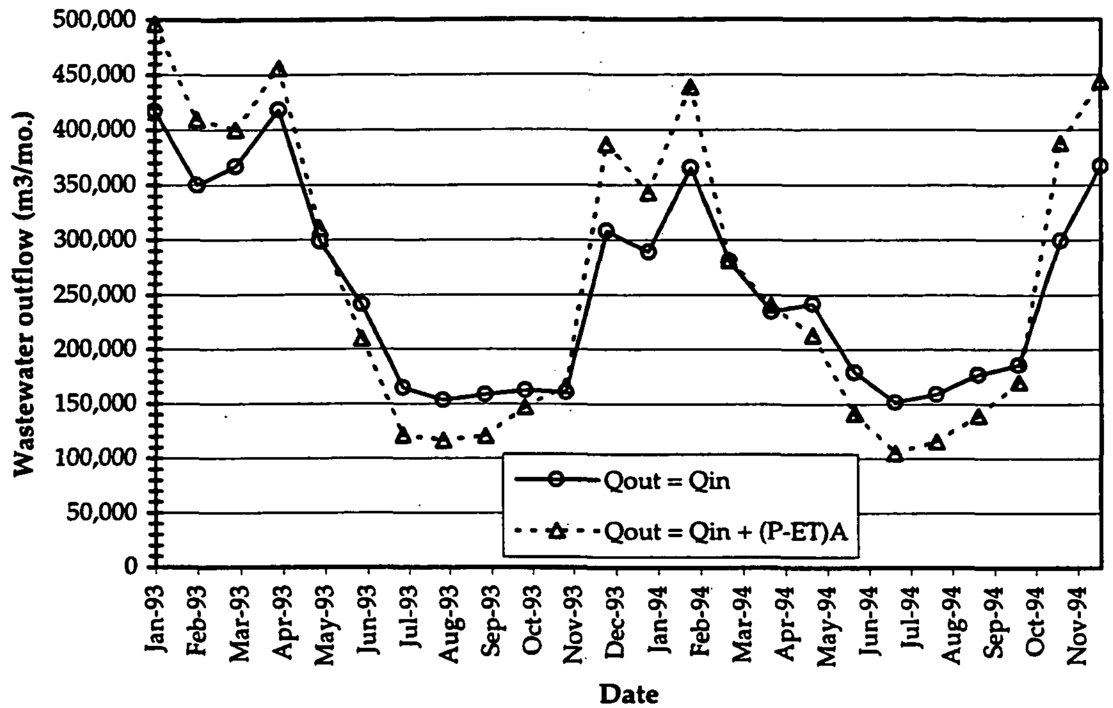


Meteorological Effects on Wetland Water Budget

FWS constructed wetlands generally have a more consistent hydrology than natural wetlands. However the variability of wastewater inflows, and the seasonal and stochastic nature of precipitation and ET can produce a variable seasonal hydrology in these wetlands.

The effects of precipitation and ET on monthly outflows from the Arcata, CA, FWS constructed wetland system are shown in Figure 3-3. The solid line is the wastewater outflow neglecting the effects of precipitation and ET ($Q_o = Q_i$). Note the increase and variable nature of wastewater inflows for the months of December through April, which is caused by seasonal infiltration and inflow into the collection system. The dashed line indicates the wastewater outflow when monthly precipitation and ET are included in the water budget. Precipitation increases wastewater outflows during the wet weather season (November through April) whereas ET reduces wastewater outflows during the warmer months of the year (May through October).

FIGURE 3-3
Monthly water budget for Arcata's wastewater treatment plant (Arcata, California) showing the effects of precipitation and evapotranspiration on the water budget.



Wetland Hydraulics

Wetland hydraulics is the term applied to the movement of water through the wetland. An improper hydraulic design can cause problems with water conveyance, water quality, odors, and vector nuisances. For example, in a few instances FWS constructed wetland design has failed to account properly for head loss, with inlet over-flooding as the result. Important wetland hydraulic definitions and basic wetland hydraulic principles are presented and discussed below.

Wetland Hydraulic Definitions

Water Depth

Compared to other aquatic treatment systems (lagoons for example), a wetland can be operated over a wide range of depths varying between 0.5 and 1.5 m (20 in. to 5 ft). Depending on the bottom topography and slope of the water surface, water depth will not be equal at all locations in a constructed wetland. For natural wetlands and some large FWS constructed wetlands, accurate determinations of water depth may be difficult due to lack of survey data. However, many FWS constructed wetlands are designed and constructed with strict engineering grade control and detailed surveys. Consequently, the elevations of the bottom, berms, islands, and inlet and outlet structures are known with some degree of accuracy. With detailed elevations, accurate estimates of average water depth can be obtained. Water depth in FWS constructed wetlands should be considered an operational characteristic as well as a design characteristic. The effective depth of a wetland will change with time. Litterfall below the water surface and detrital buildup on the bottom begin to reduce the depth therefore reducing the effective hydraulic volume.

Surface Area

The surface area (A) of a FWS constructed wetland is the area of the wetland water surface. For many FWS constructed wetlands, an accurate surface area can be obtained from construction drawings or as-built surveys. If construction or as-built information are not available, a survey of the wetland water surface perimeter is necessary to determine surface area. The area may also be estimated from an aerial photo. For most situations, the surface area or the wetland footprint at the surface is a good estimate of the wetland bottom area.

Volume

The volume (V) of a FWS treatment wetland is the potential quantity of water (neglecting vegetation, litter and peat) found in the wetland basin. As indicated under the depth discussion, the volume changes with time for a given outlet weir setting.

Wetland Porosity or Void Fraction

In a natural or constructed wetland, the vegetation, litter and peat occupy a portion of the water column, thereby reducing the space available for water. The porosity of the wetland (ε), or void fraction, is the ratio of the actual volume available for water to occupy in a wetland. Wetland porosity can be difficult to determine as it varies in the x-y (horizontal) dimension due to plant species composition and distribution, and in the vertical direction with lesser values near the bottom in the litter layer. As a result, wetland porosity values listed in the literature can be highly variable and not in good agreement. For example, Reed et al. (1995) give wetland porosity values ranging from 0.65 to 0.75 for vegetated wetlands, with lower numbers for dense, mature wetlands. However, Kadlec and Knight (1996) report that average wetland porosity values are usually greater than 0.95, and $\varepsilon = 1.0$ can be used as a good approximation.

The overall effect of porosity is to reduce the wetland volume available for water flow and storage. In turn, this reduction in volume reduces the amount of time water remains in the wetland, and the potential for constituent removal to occur. Lower wetland porosity values correspond to a lower fraction of the wetland volume available for water, shorter hydraulic detention times, lower removal efficiencies, and result in larger required wetland areas to achieve desired treatment goals. To be conservative, a porosity (ε) value of 0.7 to 0.9 is recommended in FWS constructed wetland design calculations, with lower ε values for densely vegetated wetlands, and higher ε values for wetlands with more open water areas.

Volume is not the only factor affected by vegetation density and porosity, headloss is equally important. The friction coefficient that controls headloss through the wetland depends on the vegetation density. Highly vegetated areas will have a greater headloss than open areas, and this increased headloss may cause a significant backwater effect and can lead to the development of preferential flow paths. If this potential backwater is not accounted for in the FWS wetland design, inlet flooding may occur as the wetland vegetation density increases or the porosity decreases.

Hydraulic Detention Time

The theoretical (or nominal) hydraulic detention time (t) is the ratio between flowrate and the wetland volume available for water flow, and includes the volume reducing effects of vegetation (porosity). The theoretical hydraulic detention time can be calculated as:

$$t = \frac{V\varepsilon}{Q} \tag{3-2}$$

where:

- t = hydraulic detention time (d),
- V = volume of wetland basin (m^3),
- ε = wetland porosity, and
- Q = flowrate (m^3/d).

The flowrate (Q) value used in the hydraulic detention time calculation is generally one of two values: input wastewater flowrate (Q_i), or average flowrate (Q_{ave}). The use of input wastewater flowrate (Q_i) in Equation 3-2, results in the inlet hydraulic detention time. The inlet hydraulic detention time neglects the effects of precipitation, evapotranspiration and percolation, and assumes $Q_i = Q_o$. The input wastewater flowrate (Q_i) should only be used for preliminary calculations, or when no measurement or estimate (i.e. water balance) of the output wastewater flowrate (Q_o) exists.

A more realistic measure of detention time can be computed using the average flowrate (Q_{avg}) in Equation 3-2 to account for the effects of water gains and losses (precipitation, evapotranspiration and infiltration) that occur in a wetland. The average flowrate can be estimated by:

$$Q_{avg} = \frac{Q_i + Q_o}{2} \tag{3-3}$$

The accuracy of the theoretical hydraulic detention time calculation is dependent on the measurements of depth, surface area, and the estimate of porosity. As mentioned earlier, the theoretical detention time may also be a very poor estimate of the actual hydraulic detention time due to hydraulic short circuiting. The modal detention time, which can be determined by a tracer study, will always be shorter than the theoretical value (sometimes less than half).

Hydraulic Loading Rate

The hydraulic loading rate (q) is the rainfall equivalent of whatever flowrate is under consideration; however, it does not imply the physical distribution of water uniformly over the wetland surface.. The hydraulic loading rate is defined as:

$$q = \frac{Q}{A} \tag{3-4}$$

where:
- q = inlet hydraulic loading rate (m/d),
- Q = flowrate (m^3/d), and
- A = wetland surface area (m^2).

When the input wastewater flowrate (Qi) is used in Equation 3-4, the resulting calculation is for the inlet hydraulic detention time, which neglects the effects of precipitation, evapotranspiration and infiltration. Like hydraulic detention time, the average flowrate (Q_{avg}) can also be used in Equation 3-4, resulting in the average hydraulic loading rate, accounting for water losses and gains in the wetland.

Water Conveyance

Water conveyance in FWS wetlands is complex hydraulically, varying in both space and time due to changing inflow conditions and the stochastic nature of hydrologic events. Water moves through FWS wetlands in response to a surface water gradient from inlet to outlet, impeded by the friction created from submerged plants, litter, peat, and the bottom and sides of the wetland. Some type of outflow structure, such as an adjustable weir typically is used to control the water depth. The hydraulic profile of the water surface is dictated by these factors, combined with the bottom slope and length-to-width ratio of the wetland.

It is important to consider wetland hydraulics when designing a FWS constructed wetland. The primary concern is to ensure that the wetland can handle all potential flows without creating significant backwater problems, such as flooding the inlet structures or overtopping of berms. In some cases, FWS wetlands were constructed without sufficient consideration of headloss from submerged wetland vegetation, peat, and litter, resulting in systems that are constrained hydraulically and cannot carry a range of flows without overtopping the berms.

Assessment of the headloss from inlet to outlet can usually be done using Manning's equation. When a more detailed headloss calculation is required, or the effects of precipitation, evapotranspiration and infiltration need to be considered in water conveyance calculations, then the simplified one-dimensional flow procedure presented by Kadlec and Knight (1996) can be used. In the case of complex geometry or irregular boundaries more detailed hydraulic modeling approaches may be required, such as the one-dimensional HEC2 or HECRAS (U.S. Army Corps of Engineers Hydraulic Engineering Center), or the two-dimensional Surface Water Modeling System (Engineering Computer Graphics Laboratory, Brigham Young University).

Aspect Ratio

The aspect ratio is defined as the quotient of the average length of the major axis and the average width of a wetland. Because the footprint of a wetland can have a variety of shapes, it is the effective aspect ratio between inlets and outlets that is important. In general, FWS treatment wetlands with high length to width ratios are of greatest concern with respect to headloss. However, some early researchers reported that the treatment performance of FWS constructed wetlands is better at higher aspect ratios (Wile et al. 1985). For wetland systems with high length to width ratios, careful consideration needs to be given to headloss and internal flow through the wetland. The weir overflow rate, location of inlets and outlets, and elevation of berms is as important as or more important than the influence of the aspect ratio on wetland performance.

Internal Flow Patterns Effects/Physical Facilities

The low gradients found in FWS treatment wetlands result in very low water velocities, approaching laminar flow in highly vegetated areas. This type of flow regime produces quiescent conditions, an ideal situation for many of the physical, chemical and biological processes that occur in FWS wetlands.

Water does not flow through a FWS wetland in one flow direction or path. Instead, water flows through a complex maze of submerged vegetation, litter, peat and other obstructions (e.g., islands); forcing the water velocity to increase and decrease and continually change direction. Water in open areas located away from submerged vegetation or accumulated bottom material is less subject to friction and generally moves at faster velocities than water located in densely vegetated areas. Open water zones are subject to wind-driven surface flows, which can move at higher velocities than water below the surface, and cause mixing to occur at different depths. Some areas of a FWS constructed wetland, such as corners and behind islands, may become isolated from the main flow path, creating pockets of dead space for which no or little water exchange occurs. The bottom topography may also form deeper pockets or pools, creating more dead space zones, resulting in a constantly changing internal flow pattern intermediate between the ideal extremes of plug flow and complete mixing.

All of these processes combined cause water to flow through a FWS wetland in a shorter time period than defined by the theoretical hydraulic detention time. In many cases, water can flow at high velocities through a small portion of the total wetland volume, significantly lowering the hydraulic detention time, as a result of short-circuiting. For example, the theoretical detention time for the Boggy Gut treatment wetland was estimated to be 19 days; however, the measured value using tracer studies was approximately 2 days (Knight and Ferda 1989). Careful consideration of the site characteristics showed that this difference was due to large zones (both spatial and vertical) of wetland (dead zones) that were not incorporated effectively in the treatment of the influent flow.

The placement, size, and orientation of inlet and outlet works is an important factor in determining the hydraulic response of a FWS constructed wetland to wastewater inputs and process withdrawals. There have been no studies conducted to test these factors experimentally. Experience to date has been to distribute the influent over a large portion of the inlet region and to place relatively narrow (0.6 to 1 m) rectangular adjustable weirs along the discharge region of the cells. Several strategies exist in terms of the collection volume at the terminus region of the wetland (Kadlec and Knight 1996). In one approach, a deeper zone is created in the outlet zone with the outlet weir control structure placed away from the bank into the collection volumes. Other approaches have been to collect the influent in shallower depths through vegetated fenced to minimize fish and amphibian entrapment in the effluent. Square non-adjustable weir structures have been experimented with to increase weir overflow rates 225 to 500 L/m ·min (Gearheart, 1998, Unpublished data).

Water Balance Effects on Wetland Hydraulics and Water Quality

The variability inherent in wastewater flowrates and the stochastic nature of meteorological events controls wetland hydraulics, which in turn affects wetland water quality. The impacts to wetland hydraulics can best be described by noting the increases and decreases to the wetland hydraulic detention time caused by water gains and losses in the wetlands water balance. Likewise, the wetland hydraulic detention time can also be used to explain water balance impacts to wetland water quality.

Precipitation to a wetland increases inflow, which impacts wetland hydraulics by decreasing the hydraulic detention time, and affects water quality by diluting constituent concentrations. The combination of these two influences can provide either poorer or better performance of the wetland with regard to water. In systems receiving low influent constituent concentrations, concentration reduction is likely to be poorer with precipitation additions; in heavily loaded systems concentration reductions may be higher. Evapotranspiration has the effect of increasing hydraulic detention time and increasing constituent concentrations. The combination of precipitation and evapotranspiration can improve concentration reduction in very lightly loaded systems, but generally decreases concentration reduction in heavily loaded systems. The effect of exfiltration is similar to evapotranspiration by increasing the hydraulic detention time and increasing the potential for constituent removal. Constituent load reduction can further be enhanced by the loss of constituents with the water as it infiltrates into the soil.

Thermal Effects in Wetlands

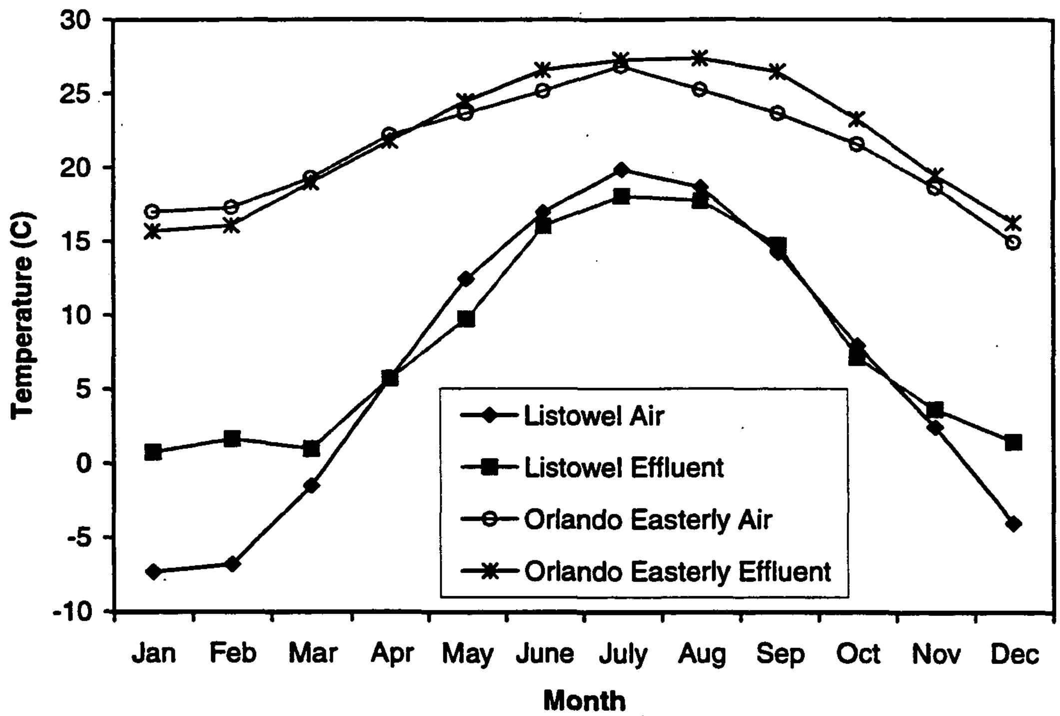
The temperature of wetland waters influences both the physical and biological processes within a FWS constructed wetland. Under winter conditions, ice formation may also alter wetland hydraulics and limit oxygen transfer. Under severe conditions, freezing may even result in system failure. Decreased temperatures are known to reduce the rates of biological reactions. The extent of temperature effects, however, varies with the constituent. In FWS constructed wetlands, BOD removal does not always appear to exhibit a temperature dependence. Temperature dependent BOD removal may be masked by other processes such as internal loads due to decomposition that are also temperature dependent, or the removal may be primarily due to non-biological mechanisms. Nitrogen removal has consistently been observed to decrease with temperature, indicating that it is controlled by biological mechanisms.

Predicting and understanding the influence of water temperature within a FWS wetland is an essential step in identifying the limits of its operation. Temperatures can be estimated using an energy balance which accounts for the gains and losses of energy to the wetland over time and space. The important gains and losses in the energy balance will vary seasonally. At minimum, a winter and summer energy balance will be needed to predict the range of operating water temperatures, and thus the corresponding range in temperature dependent pollutant removal rates.

In summer, large amounts of energy are supplied by solar radiation. A small portion of this recharges the soil energy storage, but most is lost via evaporation and transpiration. In winter, energy gains are from soil storage, and loss is to the cold ambient air. If snow or ice is present, radiation, convection, and sublimation create a balance that dictates the snow surface temperature.

When ice cover is absent, the energy balance is typically such that the gains and losses of energy are balanced, and the water temperature approaches equilibrium with the mean monthly temperature, T (Figure 3-4).

FIGURE 3-4
Correlation between wetland water temperature and air temperatures. Both northern (Listowel) and southern (Orlando Easterly) systems show water temperatures that follow the mean daily air temperature during warm months from nearby weather stations (Kadlec and Knight 1996).



If a frozen season is present, insulating layers of snow and ice can change the application of the energy balance considerably. There is no longer a large radiation input to the water, and energy gains are now solely from deep soil storage. Losses are by heat conduction through the snow and ice to the cold air above and to ice formation. Incoming sensible heat is typically dissipated because losses are generally greater than gains. Evaporation from the water layer is prevented by the ice cap. As a consequence, gains and losses do not balance as in summer, and temperature decline will typically proceed throughout the flow path.

The amount of ice formation is determined by climatological conditions that vary greatly from one winter to another. Wetland vegetation is effective in trapping snow to greater extents than unvegetated areas. Therefore, ice thickness in wetlands may be much less than in adjacent lakes or frost depths in nearby uplands. The Listowel, Ontario, wetlands experienced ice thickness on the order of 100 to 150 mm during flow conditions for a climate typified by a mean January air temperature of -9°C (16° F). Ice or frost depths in the Houghton Lake, Michigan, wetland range from zero (for copious early snow) to 200 mm for unvegetated pond zones with little snow. The mean January temperature is -8°C (18°F), and there is no winter water flow. Kadlec and Knight (1996) and Reed et al. (1995) provide a thorough discussion of FWS wetland temperature and ice formation prediction.

Wetland Biogeochemistry

Free water surface treatment wetlands support a variety of sequential and often complimentary treatment processes. The predominant physical, chemical, and biological processes operative in FWS treatment wetlands are summarized in Table 3-1. These interrelated biological, chemical, and physical treatment processes control the transport and transformation of constituents through FWS wetlands. The specific processes controlling biological oxygen demand, total suspended solids, nitrogen, dissolved organic phosphorus, chemical oxygen demand, dissolved oxygen, pH, organic pollutants, and metals within FWS wetlands are more explicitly described in subsections below.

A hypothetical partitioning of treatment processes throughout the wetland volume is shown in Figure 3-5. Wetland treatment processes are generally associated with vertically and horizontally differentiated zones within the wetland volume. These zones are linked both hydrodynamically and through sequential physical, chemical and biological reactions. In the inlet zone, the physical process of sedimentation dominates treatment and quickly removes the easily settleable solids and their associated constituent. Finer particulates are removed slowly by flocculent settling further into the wetland.

The location of various aerobic biological processes operating within the wetland is partially determined by the dissolved oxygen concentration. The oxygen demand from degradable carbon compounds is met near the surface of the open water zones of the wetland where oxygen transfer from the atmosphere and released to the water column by photosynthesis is greatest. Reduction of the ammonia nitrogen (nitrification) in a wetland occurs where carbonaceous BOD has been generally satisfied, and sufficient dissolved oxygen is present in the water column. The zone where net removal of total inorganic nitrogen occurs follows the open water zone where aerobic nitrification occurs.

Denitrification has been shown to be a significant process in FWS constructed wetlands. The combination of anoxic conditions, a physical substrate for the bacteria films, and an internal carbon supply provide ideal conditions for nitrate conversion to nitrogen gas. The dissolved organic carbon produced as a by-product of detrital decomposition supplies the carbon for this microbial process. Because denitrifiers are obligate anaerobes, oxygen must be suppressed to less than 0.5 mg/L in the water column. Both nitrification and denitrification processes are temperature dependent, and enzymatically shut down at temperatures less than 5-7 °C.

This brief introduction illustrates how FWS constructed wetlands incorporate a similar sequence of treatment processes to those commonly employed in conventional wastewater treatment. FWS constructed wetlands can be designed to emphasize some treatment processes over others by altering the geometry, hydraulics, and plant types or locations. A more detailed discussion of the role of unique features of FWS constructed wetlands and the processes controlling specific constituents of interest follows.

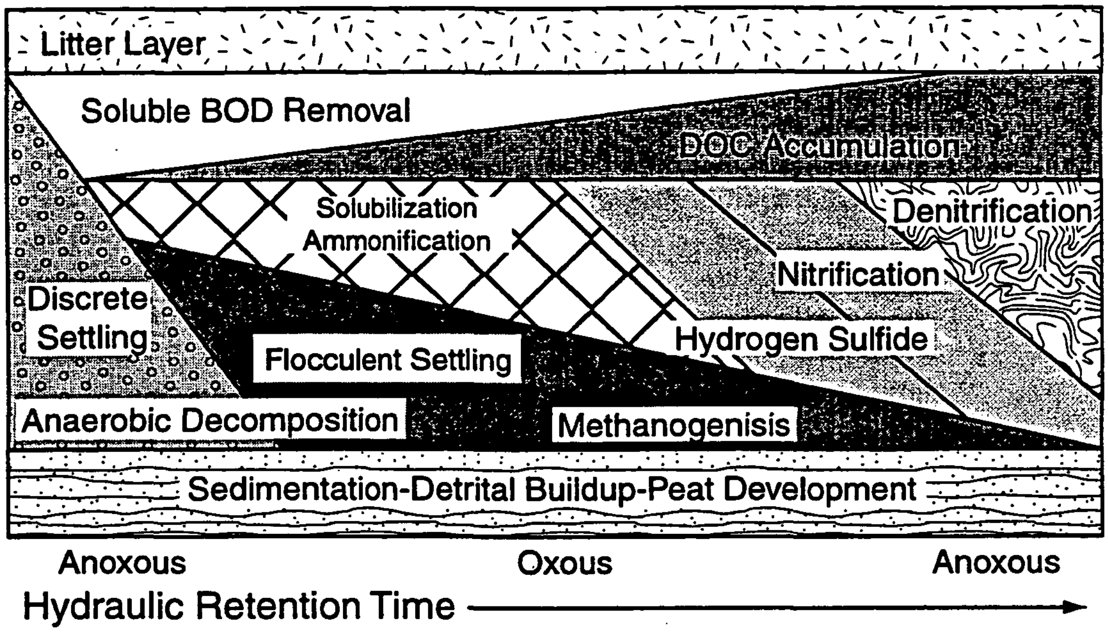
TABLE 3-1
Mechanisms and factors that affect the potential for removal or addition of water quality constituents in FWS wetlands (Adapted from Stowell et al. 1980).

Mechanism	Water Quality Constituent*							Description
	BOD	TSS	N	P	DO	Bacteria Virus	Heavy Metals	
Physical								
Absorption			S		P/S			Gas transfer to and from water surface
Adsorption/ desorption	I	S				P	I	Interparticle attractive force (van de Waals force); hydrophylic interaction
Emulsification		S					S	Suspension of low solubility chemicals
Evaporation						I	S	Volatilization and aerosol formation; thermal moderation
Filtration Impaction	I	S					I	Particulates filtered mechanically as water passes through substrate and plants
Flocculation	P	P				P	S	Interparticle attractive force (van de Waals force); hydrophylic interaction
Photochemical reactions								Solar radiation is known to trigger a number of chemical reactions. Radiation in the near-ultraviolet (UV) and visible range is known to cause the breakdown of a variety of organic compounds. Pathogenic bacteria and virus attenuation.
Sedimentation	P	P	I	I	I	S	P	Gravitational settling of larger particles and contaminants
Thermal	I		P	S				Autoflocculation; natural coagulants
Volatilization			P					Similar process to gas absorption, except that the net flux is out of the water surface.
Chemical								
Adsorption				P		S	S	On substrate and plate surfaces
Chelation				S			P	Formation of complexed metal compounds through ligands
Chemical reactions								Hydrolysis, for example, is an important chemical reaction that occurs in the environment, by which proteins are converted into amino acids and other soluble compounds. Organic nitrogen can also be converted to ammonium.
Decomposition						P		Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation, hydrolysis
Oxidation/ reduction reactions	P	S					P	Anoxic condition; metal speciation; organic acid production

Mechanism	BOD	TSS	N	P	DO	Bacteria Virus	Heavy Metals	Description
			Water Quality Constituent*					
Precipitation				P			P	Formation of co-precipitates with insoluble compounds
Biological								
Algal synthesis			S	S				The synthesis of algal cell tissue using the nutrients in wastewater.
Assimilation, plant	C	C	S	P/S	I/C	I	S	Uptake and metabolism by plants; root excretions may be toxic to enteric organisms; transpiration concentrates effluent; dissolved oxygen supply
Bacteria/ Metabolism								Removal of colloidal solids and soluble organics by suspended, benthic and plant supported bacteria; bacterial nitrification, denitrification; microbial mediated oxidation
Aerobic	P/C	S	I	I	P	P		
Anaerobic		P/C	C	C				
Plant adsorption			S	S	C		S	Under proper conditions, significant quantities of contaminants will be taken up by plants.
Predation		P				S		Zooplankton and aquatic insect larva particles; odonata and fish-aquatic insect

Notes: *P = primary processes, S = secondary processes, I = incidental effect (occurring with removal of other constituent), C = contributory effect, S/P = depends on influent and design conditions, N = negative.

FIGURE 3-5
Conceptual partitioning of treatment processes through a FWS wetland.



Total Suspended Solids

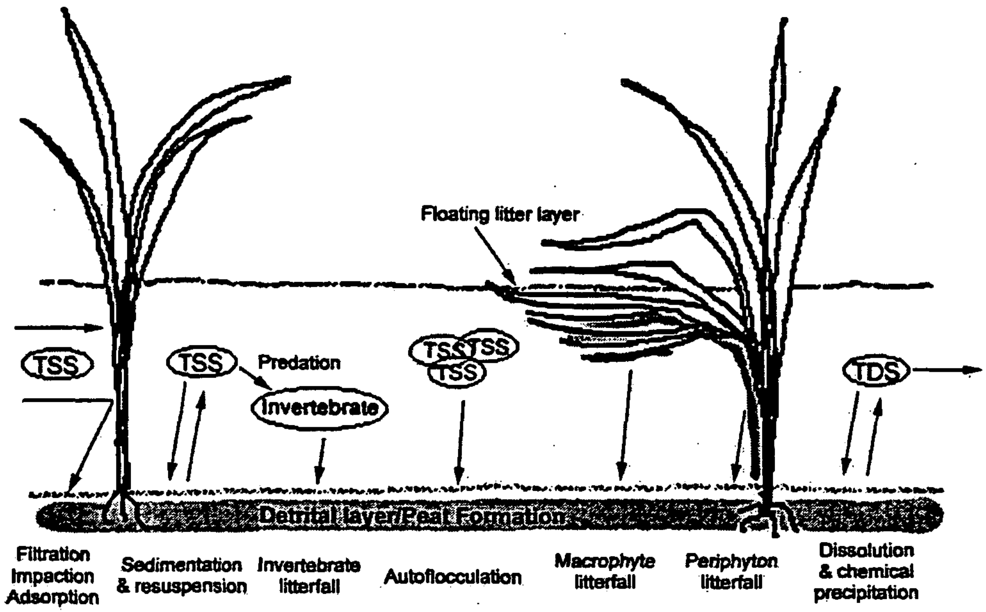
Processes

Total suspended solids (TSS) are both removed and produced by natural wetland processes. During treatment, settleable incoming particulate matter usually has ample time to settle and become trapped in litter or dead zones. Total suspended solids settle in the inlet zone as colloidal solids flocculated as they pass through vegetated zones. Anaerobic conditions produce sulfides that assist in binding metals as acid volatile sulfides. Soluble organic constituents are reduced to carbon dioxide and low molecular weight organic acids. This combination of removal processes is generally referred to as filtration by wetland scientists, although stem and litter densities are not typically high enough to act as a filter mat. As shown in Figure 3-6, in addition to trapping incoming TSS, a number of wetland processes produce particulate matter including: death of invertebrates, fragmentation of detritus from plants and algae, and the formation of chemical precipitates such as iron sulfide. Bacteria and fungi can colonize these materials and add to their mass.

The dominant TSS removal process is sedimentation, although all of the above processes contribute to TSS reduction. In wetlands, velocity-induced resuspension is minimal, but gas lift and bioturbation can reintroduce solids into the water column. Wetland sediments and micro-detritus are typically near neutral buoyancy, flocculant, and easily disturbed. Bioturbation by fish, mammals, and birds can resuspend these materials and lead to additional TSS in the wetland effluent. The oxygen generated by algal photosynthesis or methane formed in anaerobic processes can cause flotation of floc assemblages.

Resuspension due to fluid shear forces on bed solids is not usually a significant process except in the vicinity of a point discharge into the treatment wetland.

FIGURE 3-6
Wetland TSS removal processes.



The magnitude of wetland particulate cycling is large, with high internal levels of gross sedimentation and resuspension, and almost always overshadows TSS influent loadings. TSS effluent concentrations rarely result from an irreducible fraction of the TSS influent, and are often dictated by the wetland processes that generate TSS within the wetland. Most FWS constructed wetland designs are determined by an effluent limitation other than TSS and are sufficiently large that effluent TSS approaches background levels. Large expanses of open water not followed by vegetation can however lead to excessive algal growth and subsequent high effluent TSS.

High incoming TSS or high nutrient loadings that stimulate high TSS production may eventually lead to a measurable increase 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 non-volatile solids, a settling basin can be designed to intercept a large portion of the solids, thus providing for easier cleanout and extending the life of the inlet region of the wetland.

Settleable Solids Reduction-Anaerobic Decomposition

The benthal decomposition of accumulated solids from the influent and from the plant litter produced in the wetland has a delayed effect on the oxygen budget and biochemical oxygen demand (BOD) concentrations in a FWS treatment wetland. The accumulated material compacts and densifies as anaerobic processes release aerobically degradable by-products to the sediment and organic layer pore water. These aerobically degradable by-products subsequently diffuse into the overlying water column and contribute to the BOD.

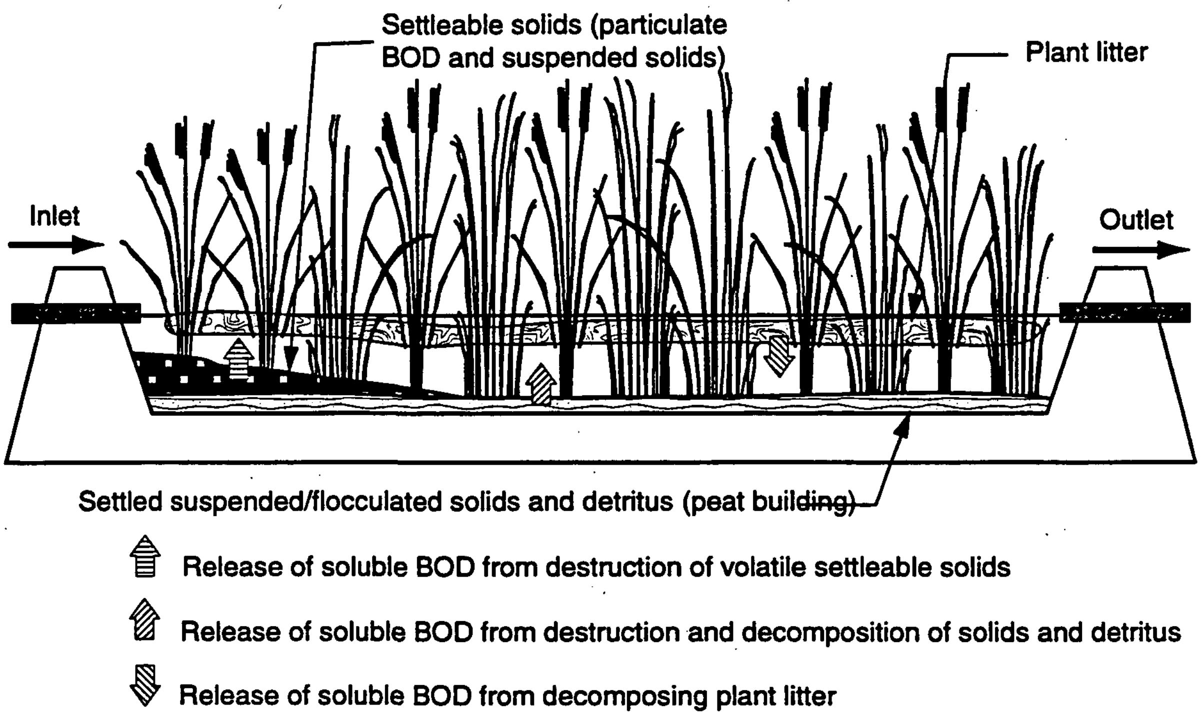
The accumulated organic debris degrades at different rates depending on the source and composition of the organic material. As the degradability of the material decreases, the decomposition rates slow and the nature of the soluble by-products change. The implication of this degradation rate and its relationship with the BOD in the water column is significant. For example, the half-life of soluble BOD is approximately 3 days while the half-life of organic sediment, which is temperature-dependent, is more on the order of 4 months. Earlier observations by sanitary engineers of the role that benthic organic deposits played in the oxygen budget in streams is analogous in many ways to conditions in a FWS wetland. The oxygen requirements of benthal organic deposits are limited by the rate at which production of diffusible degradable material enters the overlying water column and not by the rate at which anaerobic breakdown occurs (Phelps 1944). For a given solids accumulation rate and temperature regime, a steady-state condition of organic sediment decay and release of soluble BOD to the water column should develop. This release of soluble BOD from the litter layer is one component contributing to the background BOD.

Biochemical Oxygen Demand

For FWS treatment wetlands receiving municipal wastewaters, some fraction of the influent carbon compounds are dissolved while the rest enters in the form of particulates. Particulate settling provides one removal mechanism, and typically occurs in the inlet region of the wetland (Figure 3-7). Microbial communities process the dissolved carbon compounds. Microbial removal processes include oxidation in the aerobic regions of the wetland and methanogenesis in the anaerobic regions. The active microorganisms are usually associated with solid surfaces, such as litter, sediments, and submerged plant parts.

In addition to microbial decomposition, dissolved carbon is fixed into new biomass during photosynthesis, and decomposition of plant litter returns a significant fraction of this carbon back to the water column. The decomposition of litter and sediments produces a return flux of BOD_5 to the water column. The balance between removal of influent BOD_5 and the decomposition processes contributing BOD_5 determines the wetland effluent BOD_5 concentration.

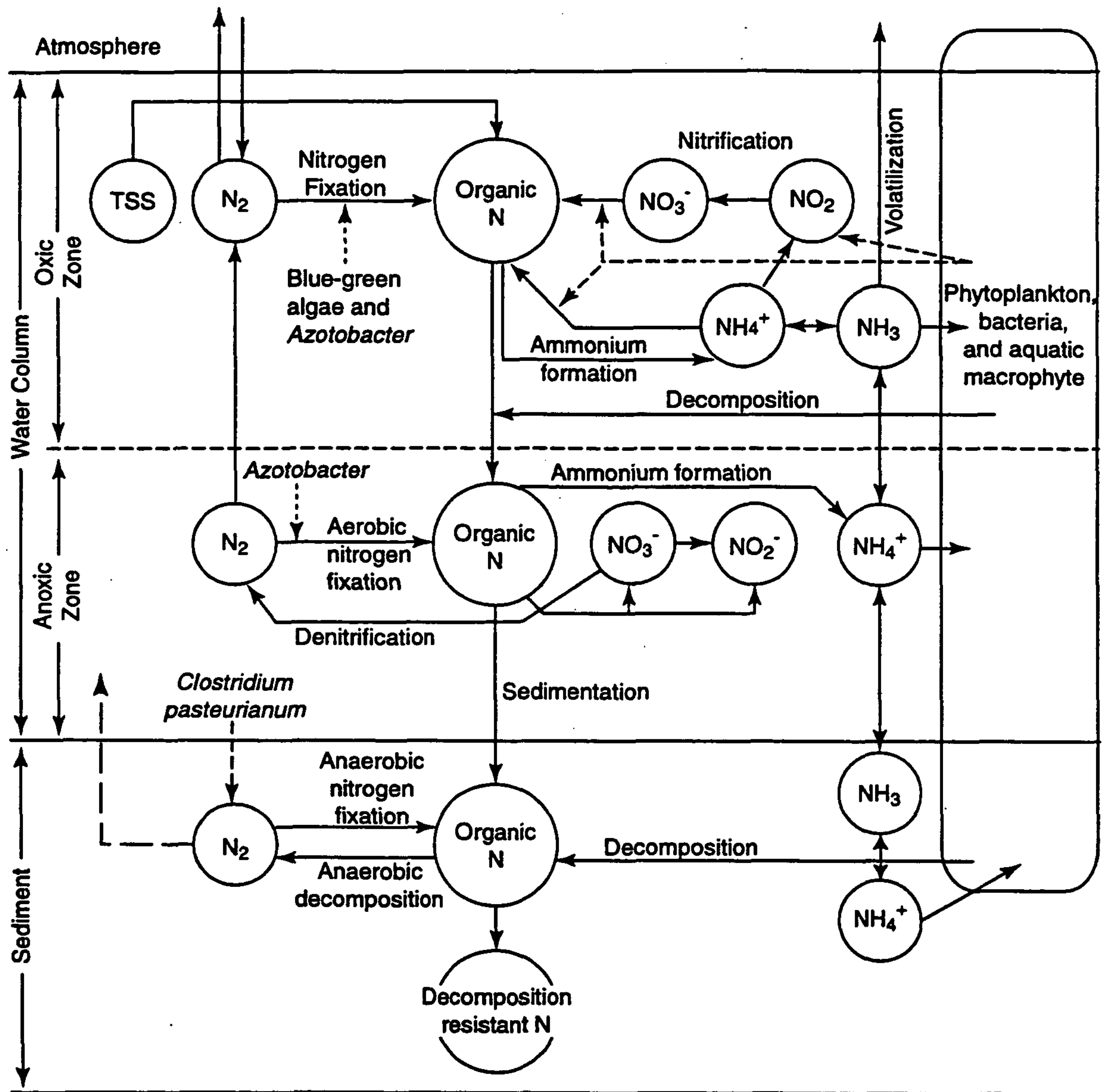
FIGURE 3-7
Simplified portrayal of wetland carbon processing. Incoming BOD_5 is reduced by deposition of particulate forms and by microbial processing in floating, epiphytic, and benthal litter layers. Decomposition processes create a return flux.



Nitrogen

Nitrogen is a key element in biogeochemical cycles and occurs in a number of different oxidation states in wastewater and treatment wetlands. Numerous biological and physio-chemical processes can transform nitrogen between its various oxidation states (Figure 3-8). The dominant nitrogen species in FWS treatment wetlands depends on the level and type of wastewater pretreatment, but may include organic, ammonia, nitrate, and nitrite nitrogen, and nitrogen gases (di-nitrogen gas [N_2] and di-nitrogen oxide [N_20]). A fraction of the organic nitrogen is readily mineralized to ammonia nitrogen in aquatic and wetland environments. Ammonia nitrogen is distributed between the ionized form (ammonium, NH_4^+) and a smaller percentage as un-ionized ammonia (NH_3). The distribution of total ammonia between NH_4^+ and NH_3 depends on water temperature and pH. Un-ionized ammonia is volatile and may be lost directly to the atmosphere.

FIGURE 3-8
Nitrogen transformation processes in wetlands (Gearheart 1998, unpublished data).



Ammonium nitrogen can be oxidized in open, aerobic zones 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 nitrogen in the plants, or may be removed from the water column by adsorption to solid surfaces, such as wetland sediments. Adsorbed ammonium is readily released back to the dissolved ammonia 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 by the anaerobic process, denitrification. Denitrification occurs most readily in wetland sediments and in the water column below fully vegetated growth where dissolved oxygen concentrations are low and available organic carbon is high. Organic carbon is consumed in this microbial process and alkalinity is produced. To complete the cycle, atmospheric di-nitrogen gas can be microbially fixed in open zones as organic N and reintroduced into the wetland through nitrogen fixation. However, this transformation is not normally a significant contribution of organic N to FWS treatment wetlands. Because of the complex transformations affecting nitrogen species in wetlands, a sequential series of reactions must be considered to describe adequately treatment performance, even on the most elementary level.

Phosphorus

New constructed and natural wetlands are capable of adsorpting and absorbing phosphorus (P) loadings until the capacity of the soils and new plant growth are saturated. Phosphorus interacts strongly with wetland soils and biota, which provide short-term removal and long-term storage (Reddy 1984, Reddy and D'Angelo 1994). The potential for P removal is most easily illustrated by the seasonal uptake and release by plants of soluble reactive phosphorus. The effects of two different phosphorus loadings on the effluent soluble reactive phosphorus during the growing season (Figure 3-9) were evaluated in Arcata's Pilot Project I. The difference between the lower phosphorus loading (Cell 3) and the saturated phosphorus loading (Cell 5) represents the mass of phosphorus taken up by macrophytes and epiphytes. The majority of the phosphorus taken up by the wetland plants is released as soluble reactive phosphorus in the late summer and fall as the plants senesce and decompose.

In FWS constructed wetlands, soil sorption can initially provide phosphorus removal, but this partly reversible storage eventually becomes buried with organic solids from the influent TSS and the accumulated detrital materials. For some antecedent soil conditions, there may be an initial release of P. This new source of P acts to fertilize the wetland, and some P is utilized in establishing a larger standing crop of vegetation.

Sustainable P removal processes involve accretion and burial of phosphorus in wetland sediments. Uptake by small organisms, including bacteria, algae, and duckweed, acts as a rapid-action, partly reversible removal mechanism (Figure 3-10). Cycling through growth, death, and decomposition returns most of the microbiotic uptake back to the water column, but a significant residual is lost to long-term accretion in newly formed sediments and soils. Macrophytes, such as cattails and bulrushes, perform a similar function, but on a longer time scale of months to 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 also contribute to the accretion process (Reckhow and Qian 1994). There can also be 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.

U.S. EPA Headquarters Library
Mail code 3201
1200 Pennsylvania Avenue NW
Washington DC 20460

FIGURE 3-9
Influent and effluent phosphorus in the Arcata Pilot Project I FWS wetlands, Second Pilot Project, 1982. Cell 5 was loaded at 0.75 kg/ha·d, and Cell 3 at 0.15 kg/ha·d (Gearheart 1993).

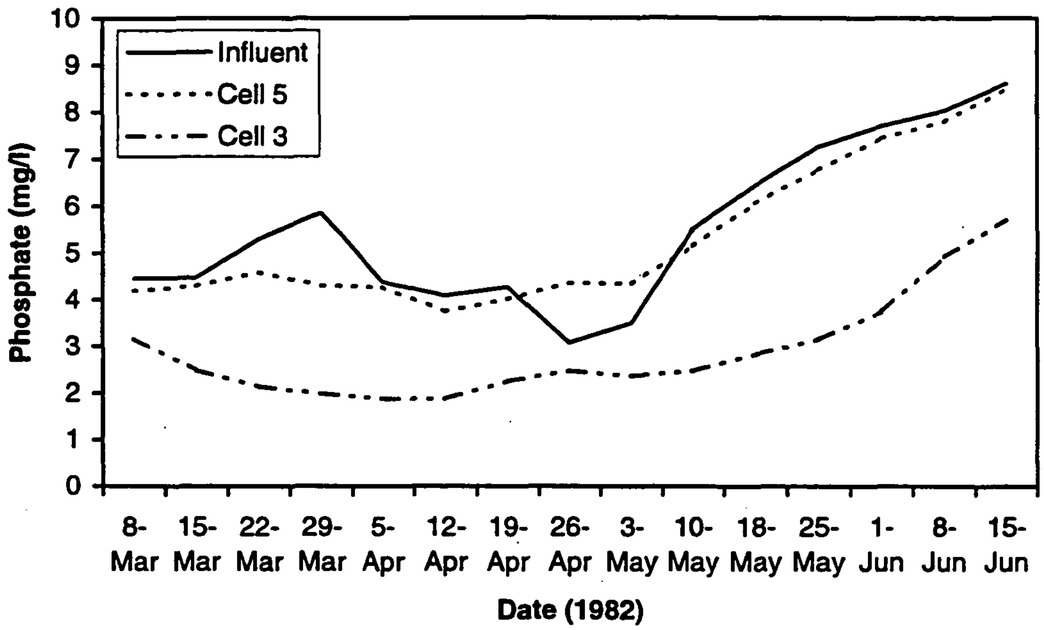
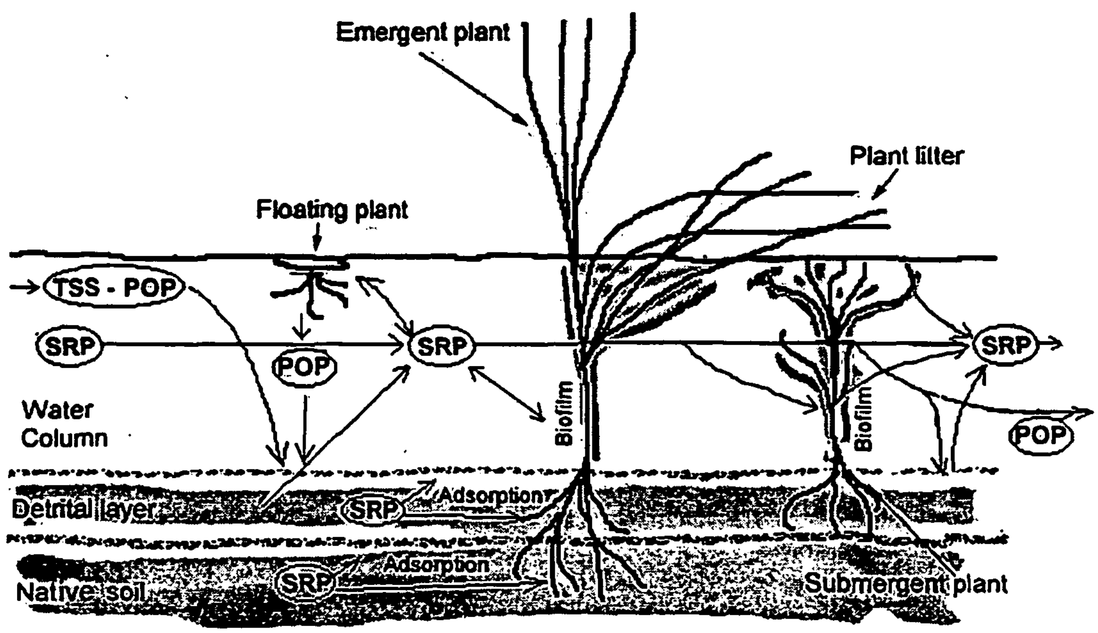


FIGURE 3-10
Conceptual cycling of phosphorus forms in FWS constructed wetlands. SRP: Soluble reactive phosphorus; POP: particulate organic phosphorus; TSS-POP: form of POP in terms of a fraction of the total suspended solids.



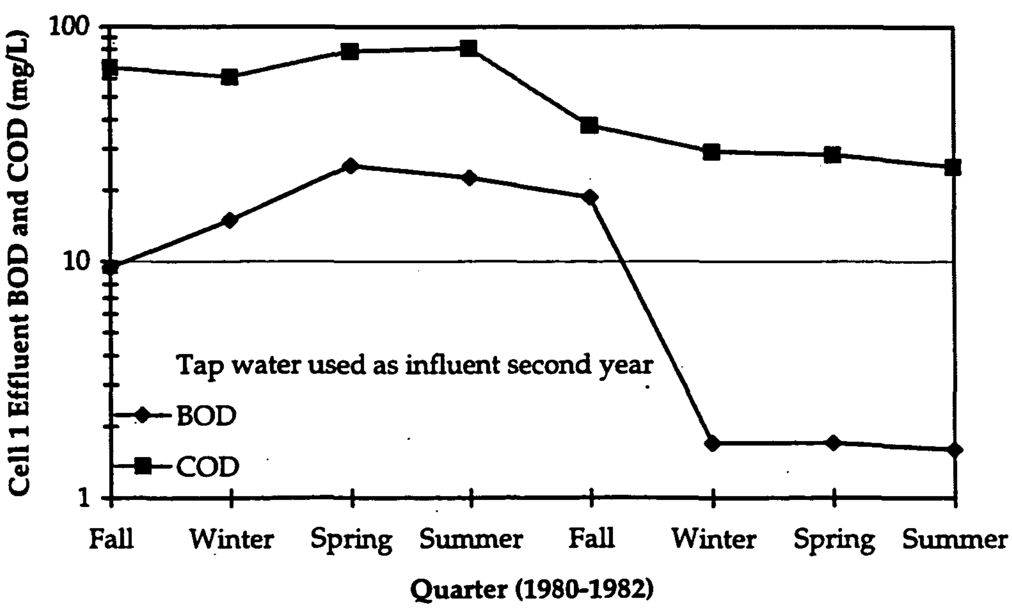
Chemical Oxygen Demand

The chemical oxygen demand (COD) measures the concentration of oxidizable organic carbon compounds using a strong chemical oxidant. Thus, the COD test measures the sum concentration of two distinct fractions of oxidizable compounds: easily biodegradable compounds and oxidizable but not easily biodegradable compounds. The concentration of easily biodegradable compounds is assumed equal to the BOD_5 with the difference between the COD and BOD_5 representing the concentration of compounds that is not easily biodegradable. Some of these non-BOD compounds are degradable under anoxic conditions through anaerobic decomposition, or under aerobic conditions in periods of longer than 5 days.

In the Arcata pilot cells, the effluent COD of wetland cells only varied from 60 to 66 mg/L while the influent BOD ranged from 45 to 92 mg/L (Gearheart et al., 1983). From the consistent COD effluent concentrations from the pilot wetland cells even with a ten fold range in hydraulic/organic loading, it can be concluded that the effluent concentrations are more closely associated with the amount and type of aquatic plants within the wetland. The influent COD/BOD ratio averaged 3.7 for the FWS constructed wetland influent (oxidation pond effluent) and the effluent COD/BOD ratio varied from 3.1 at the beginning of the study to 28 at the end of the study. Physical and microbial processes remove COD while other processes produce COD in FWS constructed wetlands.

A study was performed at Arcata, California where a pilot cell was loaded at 50 kg/ha·d for 15 months after which the influent was switched to tap water for 9 months. The concentration of BOD and COD before and after the addition of tap water (no addition of influent BOD) is shown in Figure 3-11. The COD/BOD ratio was 3.9 during the BOD loading period.

FIGURE 3-11
BOD and COD effluent concentration before and during tap water loading to Arcata Pilot Project wetland.



After the addition of freshwater to the system, the COD/BOD ratio increased to 17 with COD and BOD concentrations of 30 and 1.7 mg/L, respectively. It appears, based on these observations, that the detrital material contributes about 1.7 mg/L of BOD at the wetland cell hydraulic loading rate of 240 mm/day.

Dissolved Oxygen

Dissolved oxygen is depleted to meet wetland oxygen requirements in four major categories: sediment/litter oxygen demand, respiration requirements, dissolved carbonaceous BOD, and dissolved nitrogenous oxygen demand NOD. The sediment oxygen demand is the result of decomposing detritus generated by carbon fixation in the wetland, as well as the decomposition of precipitated organic solids that entered with the wastewater. The NOD is exerted primarily by ammonium nitrogen, but ammonium may also be contributed by the mineralization of organic nitrogen. Decomposition processes in the wetland also contribute to NOD and BOD, further increasing the oxygen demand and reducing the dissolved oxygen in the wetland.

Plant roots also require oxygen, which is normally transported downward through passages (aerenchyma) in stems and roots. Some surplus of oxygen may be released from small roots into their immediate environs, but it is quickly consumed in the reduction of local oxygen demand (Brix 1994a). Wetland soils are typically anoxic or anaerobic (Reddy and D'Angelo 1994).

Wetland open-area surface waters are aerated by oxygen transfer from the atmosphere, through the air-water interface. Reaeration mechanisms include dissolution and diffusion (O'Connor and Dobbins 1958), as well as turbulent transfer associated with rainfall and wind induced surface mixing (South Florida Water Management District [SFWMD] unpublished data). In unshaded, open water areas, photosynthesis by algae within the water column produces oxygen, sometimes creating dissolved oxygen concentrations in excess of the saturation limit (Schwegler 1978). However, in vegetated regions of the wetland, shading prevents high algae concentrations and DO levels are typically low near the surface and anaerobic conditions persist throughout most of the water column. The effect of vegetation on DO level in the Arcata Enhancement Marsh is shown in Figure 3-12 and Figure 3-13, with the DO in the non-vegetated zones (Figure 3-12) significantly higher than that in the vegetated zone (Figure 3-13).

Photosynthesis stops at night, and respiration, which consumes oxygen, dominates. The result is a strong diurnal variation in water column DO for lightly loaded, algae-rich, open water wetlands.

FIGURE 3-12
Vertical distribution of DO in a submergent plant zone of the Arcata Enhancement Marsh.

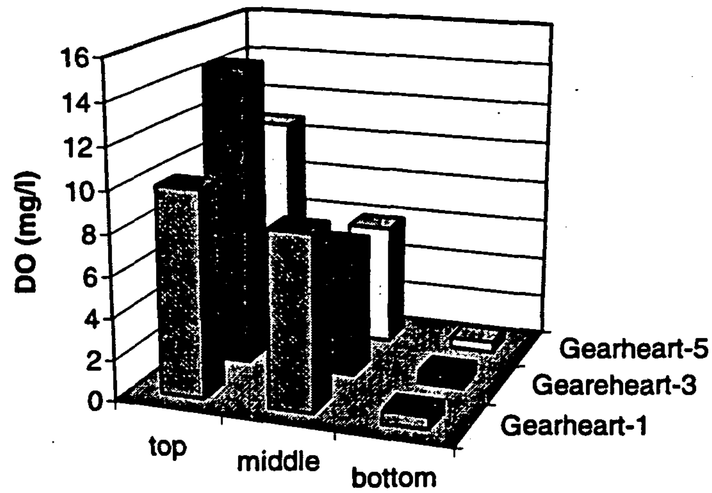
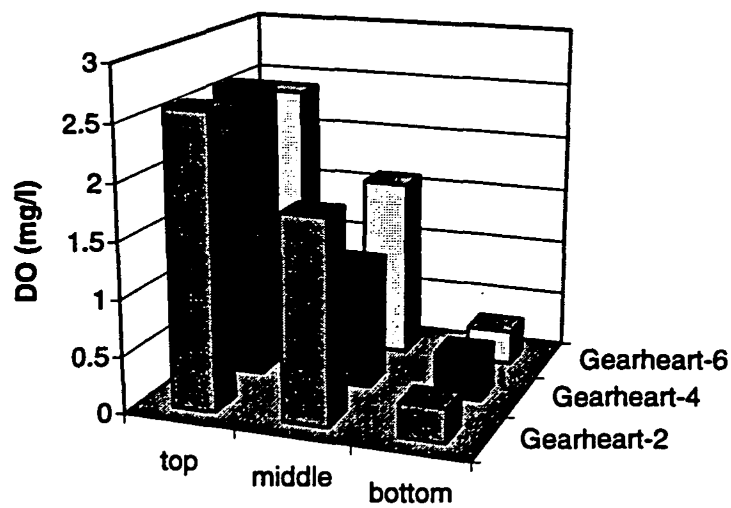


FIGURE 3-13
Vertical distribution of DO in an emergent plant zone of the Arcata Enhancement Marsh.



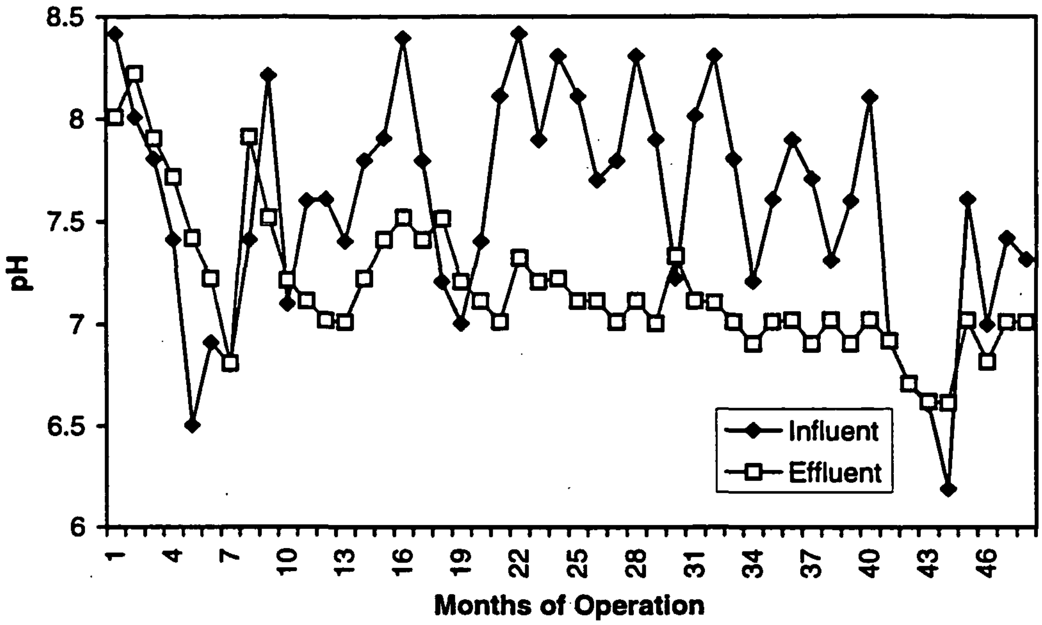
Hydrogen Ion

Natural wetlands exhibit pH values ranging from slightly basic in alkaline fens (pH = 7 to 8) to quite acidic in sphagnum bogs (pH = 3 to 4) (Mitsch and Gosselink 1993). Natural freshwater marsh pH values are generally slightly acidic (pH = 6 to 7). Treatment wetland effluent hydrogen ion concentrations are typically neutral to slightly acidic. Open water zones within wetlands can develop high levels of algal and submergent plant activity, which in turn create a high pH environment. Data on an open water, unvegetated treatment "wetland" displayed high pH during some summer periods (pH > 9), with circumneutral influent (7.0 < pH < 7.4) (Bavor et al. 1988). Algal photosynthetic processes peak during the daytime hours, creating high pH during the day, followed by a nighttime sag with low pH as respiration replaces photosynthesis.

The organic substances generated within a wetland via growth, death, and decomposition cycles are a source of natural acidity. The resulting humic substances are large complex molecules with multiple carboxylate and phenolate groups. The protonated forms have a tendency to be less soluble in water and precipitate under acidic conditions. As a consequence, wetland soil/water systems are buffered against incoming basic substances. They are less well buffered against incoming acidic substances as the water column contains a limited amount of soluble humics.

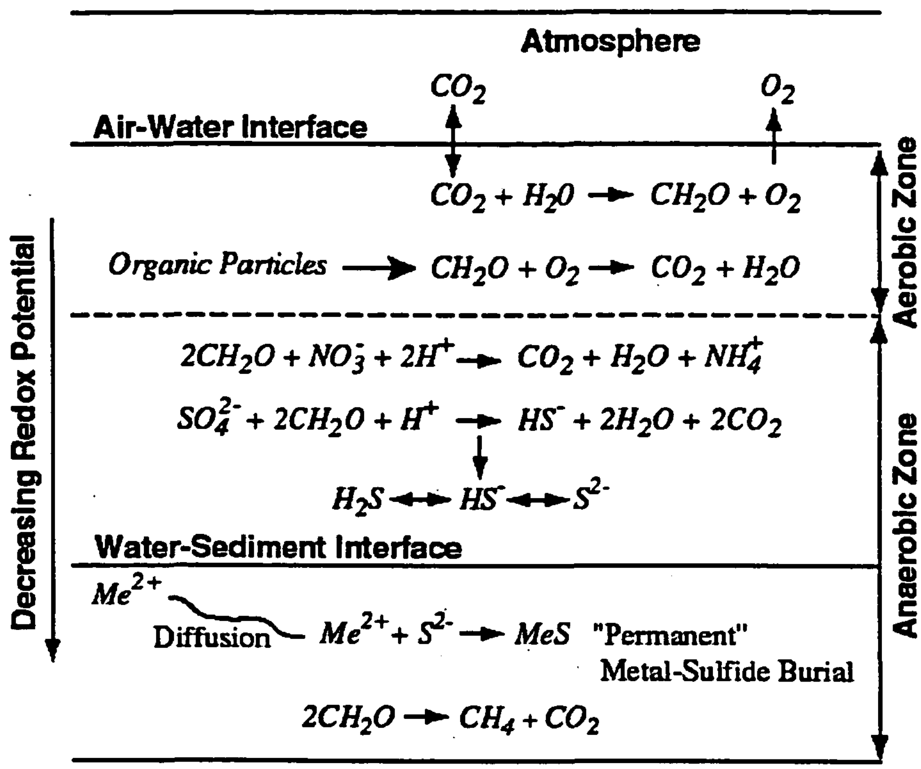
The net result of the processes described above is that treatment wetlands can maintain their effluent pH at approximately pH 7 (Gearheart et al., 1983). Listowel constructed treatment wetland 3 received lagoon water, which periodically exhibited high pH due to algal activity in the lagoon (Figure 3-14). During the first year of operation, little or no buffer capacity was evident. As the vegetation spread to cover the wetland and litter formation and decomposition became operative, high incoming pH values were neutralized effectively by the wetland. In the Arcata's Pilot project, it was found that wetland cells receiving oxidation pond effluent consistently produced a pH between 6.5 and 7.0 (alkalinity of 90 mg/L), regardless of the organic loading or the pH variation in the influent. This neutral effluent pH was attributed to the organic acids produced in the decomposition process and to the ammonia and sulfide production and disassociation that offered some buffer capacity

FIGURE 3-14
Hydrogen ion (pH) buffering in system 3 at Listowel (Herskowitz 1986).



The metals removed from the water column by settling are bound to particles and may eventually be buried in the anoxic sediments where sulfides are predominant. As shown in Figure 3-15, in the sediments below open water zones, most metals of concern are bound to acid volatile sulfides which minimize their biological mobilization. If sediments are disturbed or resuspended and moved into oxic regions of the wetland, sequestered metals may revert to dissolved forms and be released. Metals are also incorporated into the biomass via the primary production processes in a wetland. For macrophytes, metals are taken up via the roots and distributed throughout the plant. The extent of uptake and distribution within the plant depends on the metal species and plant type. Metal actions in sediments below vegetated zones behave similarly, except that the aerobic zone is extremely shallow and gaseous discharge is generally impeded at the air/water interface by duckweed.

FIGURE 3-15
Metal sulfide burial processes in a wetland (Meyers 1998, personal communication).



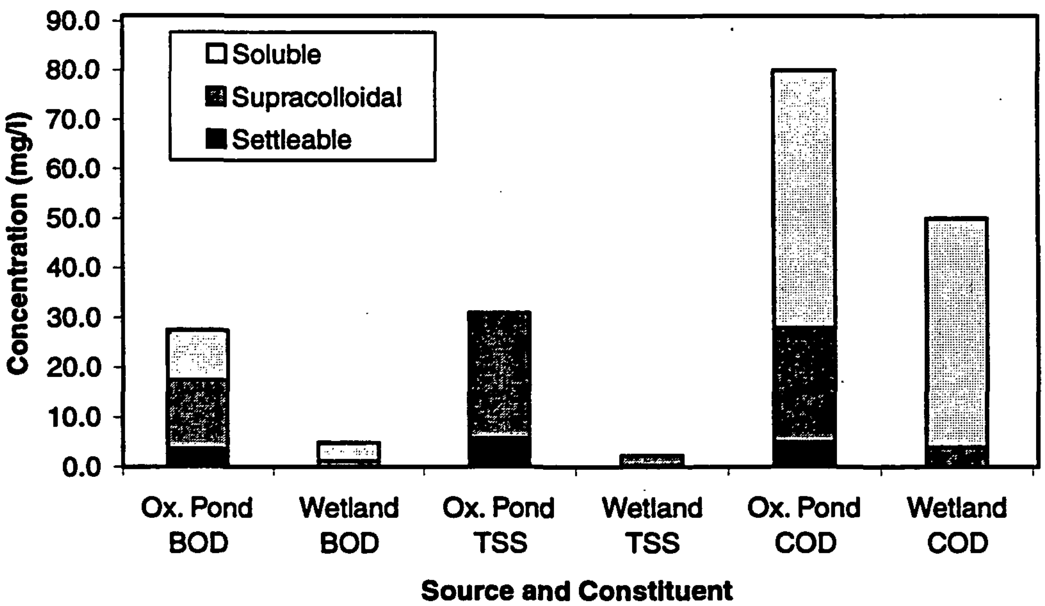
Constituent Characteristics

The characteristics of the wastewater constituents are of major importance in analyzing the performance of any wastewater treatment processes. These characteristics change as the wastewater proceeds through various processes in wastewater treatment systems. This is best illustrated by determining the solids characteristic through a system. Large particulate organic solids predominate in raw wastewater. These are measured as either flotable solids, settleable solids or suspended solids, and dissolved solids. Smaller organic colloidal solids are usually not removed in primary treatment, for example; wetland solubilization can play a role in the separation, paticulization, and solubilization of these various wastewater constituents. In effect, a FWS constructed wetland replicates a full wastewater treatment train in terms of types and linkages of the physical, chemical, and biological processes. It is important in the design and operation of a FWS wetland to determine the particulate/soluble distribution of the constituents. Settleable organic solids which are separated by settling process will serve as an internal load of dissolved and colloidal solids upon anaerobic decomposition. Biodegradable dissolved organic solids (VSS) are broken down, releasing ammonia, soluble reactive phosphorus, dissolved organic carbon, and gases (CO_2 and CH_4). upon anaerobic decomposition of these settled solids. Colloidal solids are also released in the decomposition process which includes the heterotrophic bacteria responsible for the decomposition as well as organism and/or viruses of public health significance. The latter two particle types are adsorbed or impacted in the settleable solids, and are released to the water column upon decomposition.

As FWS constructed wetlands are placed further into conventional treatment trains, i.e., secondary and tertiary applications as opposed to primary and/or advance primary applications, the physical characteristics (size, density, etc.) of the constituents must be taken into consideration.

Soluble forms of COD and BOD dominate in the effluent from a wetland. An example of the partitioning of the various particle size of the constituents can be seen in Figure 3-16. In the case of an oxidation pond effluent, the majority of the BOD for example is supracolloidal. In the case of the wetland effluent, the majority of the BOD is soluble. It is the removal of the settleable and supracolloidal BOD through the wetland which accounts for the majority of the BOD removed in the wetland. The soluble BOD removed is also significant and represents a net removal since the decay of the settled solids and plant detritus add to the soluble BOD in the system. This can be seen in the COD values in the oxidation pond and wetland effluent. The COD values are about the same for both systems. The BOD/COD ratio has changed significantly through the system as refractory and more complex organic compounds are formed in the decomposition of the plant material.

FIGURE 3-16
Distribution of BOD and COD concentration by form (settleable, supracolloidal, or soluble) in oxidation pond effluent and treatment marsh effluent from Arcata, California (Gearheart 1992).



Aquatic Vegetation

Types of Wetland Vegetation

Of the thousands of vascular plants on earth, only a relatively limited number are adapted to the conditions of continual submergence and waterlogged soils. FWS wetlands may consist of a variety of different emergent, submerged, and floating aquatic vegetation species, distributed primarily based on water depths. In general, emergent species are found in shallow water depths, while submerged species occupy deeper water zones; floating species of vegetation can occur in both shallow and deeper water areas.

In FWS constructed wetlands, the most common vegetation species have typically been emergent species such as bulrush, cattails, rushes, and reeds (Pullin and Hammer 1989, Reddy and Smith 1987). In the past, general practice was to use either a mono-culture of one species, or a combination of two or more species in FWS constructed wetlands used primarily for the treatment of wastewater. Constructed FWS wetlands that are used as habitat or enhancement wetlands, will typically be planted with a variety of emergent, submerged, and floating species. Some of the more common wetland plants used in FWS constructed wetlands, either for treatment or enhancement, and the species type and typical water depths of occurrence are listed in Table 3-2.

TABLE 3-2
Some common wetland plants and depths of occurrence used in FWS and floating aquatic constructed wetland.

Plant type	Species name	Common name	Range of depths (m)
Emergent	*Typha* spp.	Cattail	> 0.1 to < 1
	Scirpus spp.	Bulrush	> 0.1 to < 1
	Juncus spp.	Rushes	> 0.1 to < 0.3
	Carex spp.	Sedges	> 0.1 to < 0.3
	Phragmites spp.	Reeds	> 0.1 to < 1
Submerged	*Potamogeton* spp.	Pond weeds	> 0.5
	Vallisneria spp.	Tapegrass, wild celery	> 0.5
	Ruppia spp.	Widgeongrass	> 0.5
	Nuphar spp.	Spatterdock	> 0.5
	Elodea spp.	Waterweed	> 0.5
Floating	*Lemna* spp.	Duckweed	Flooded
	Eichhornia crassipes	Water hyacinth	Flooded
	Hydrocotlye umbellata	Water pennywort	Flooded
	Azolla spp.	Water fern	Flooded
	Wolffia spp.	Watermeal	Flooded

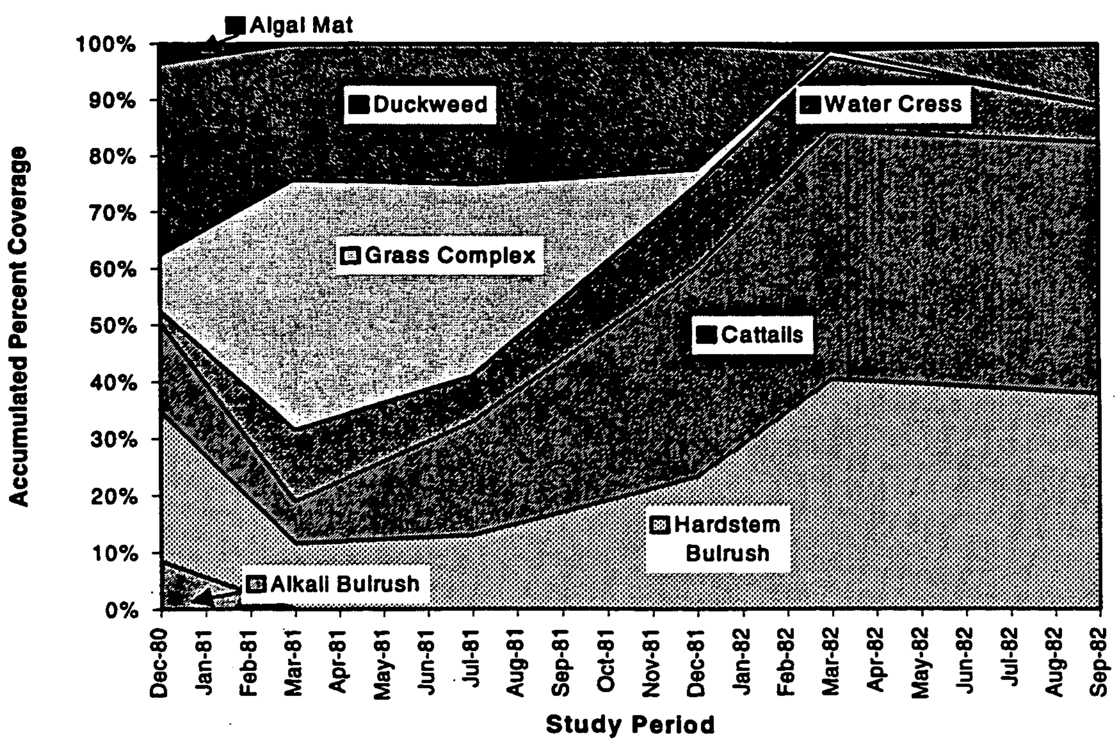
Vegetation Patterns

When constructed or natural FWS wetlands are used for treating wastewater, they become one of the more highly productive types of wetlands, primarily due to the high level of nutrients found in the wastewater. Nutrient cycling proceeds at a rapid rate, creating high density standing crops of vegetation, especially emergent species. The amount of biomass is both species and climate dependent, as is the stem density. Cattail has a relatively large basal diameter, and can occur at about 30 to 50 stems per square meter in treatment wetlands. In contrast, bulrush have smaller diameter stems, and may occur at hundreds of stems per square meter. Stem density is additionally constrained by the growth requirements of the plant in question.

Above-ground macrophyte biomass may be separated into three compartments: live (green), standing dead (brown, upright), and litter (brown, broken, prostrate). Different compartments dominate the aboveground vegetation structure during different seasons. In northern climates, the end-of-season standing live crop converts to standing dead, and subsequently to litter and peat. In warmer climates, such phases are shorter and less pronounced, but there are dormant periods at all latitudes.

Because FWS constructed wetlands need to be planted, they do not initially possess all vegetative compartments; typically a startup period of many months to a few years is required for the vegetation compartment to develop fully. The percent coverage of various plant species during the first two years following planting of the Arcata Pilot Project wetland is presented in Figure 3-17. The grass and duckweed that were predominant during the first year were relatively uncommon in the second year as the cattail and hardstem bulrush grew taller and either shaded or filled in the open water areas. During this startup period, wetland treatment processes may not be functioning at their full potential or may be performing at an unsustainably high level of nutrient uptake, nitrification, etc.

FIGURE 3-17
Coverage of plants during the startup period of the Arcata Pilot Project wetland.



Role of Aquatic Plants in Controlling Treatment Processes

Aquatic macrophytes play an important role in the treatment processes active within FWS constructed wetlands. The plants, unique to the wetland environment, both control the pollutant removal processes and act as sources and sinks of certain dissolved and particulate water quality constituents. Wetland plants also play an important role in preventing incoming radiation from entering the water column. Interception of incoming radiation significantly reduces algae growth, which can add carbon back to the system via photosynthesis. The shading of the water surface also moderates the water temperature of a wetland. A distinguishing characteristic of FWS constructed wetlands is that the water temperature profile is buffered from the changes in the ambient temperature. The cooling potential for any one site is dependent upon the range of temperatures found at that site, the ET rate, and the extent of the canopy. While the magnitude of thermal buffering is unique to a site, in certain locations this effect can be taken advantage of to meet instream temperature standards.

Well-developed stands of vegetation also reduce the natural reaeration process by controlling the micrometeorology within the wetland and limiting wind induced turbulent mixing. Lower rates of oxygen transfer, combined with low algal concentrations and the dissolved oxygen consumed within the water column to satisfy BOD, usually results in low dissolved oxygen concentrations in FWS constructed wetlands. Surface level dissolved oxygen concentrations at 20 to 40 percent of saturation are commonly observed. Low dissolved oxygen concentrations are mitigated somewhat by the contribution of oxygen to the water column by common wetland plants.

While debate surrounds the potential for in-situ reaeration via emergent macrophytes, no debate exists concerning the ability of submergent plants to contribute dissolved oxygen. In most cases, emergent and submergent plants are not found in the same wetland zones. Submergent aquatic macrophytes thrive in the unshaded regions of FWS constructed wetlands. These plants contribute dissolved oxygen directly to the water column while affording a physical substrate for periphytic bacteria and algae. Plants such as *Potamogeton pectinatus*, sago pondweed, are commonly planted in FWS constructed wetlands to support the nitrification of ammonia and serve as a food source for aquatic waterfowl. Floating aquatic macrophytes are subject to being moved by the wind over the surface of the open water. It is not uncommon to have plants such as *Lemna spp*. windrowed amongst and against emergents or a berm, resulting in nearly complete inhibition of normal photosynthetic reaeration processes. Proprietary processes have been developed to keep floating aquatic macrophytes from being redistributed by the wind through various anchoring mechanisms. Significant solids handling problems can exist with dredged or harvested aquatic plants. Storage of these materials can result in odors.

The wetland vegetation is also a source of dissolved and particulate material that combines with the influent wastewater to produce a mixture of biodegradable compounds. A wide range of heterotrophic and autotrophic organisms degrade these compounds, similar to the production of BOD via algal growth and degradation in an oxidation pond.

Many of the biochemical transformations that occur in treatment wetlands are mediated by a variety of microbial species residing on solid surfaces such as those provided by plant leaves, stems, and litter. Examples of these processes include the decomposition of organic matter, periphyton fixation, nitrification-denitrification, and sulfate reduction. For example, maximum biofilm production of 1500 $mg/m^2 \cdot d$ has been measured in wastewater treatment wetlands at 60% of maximum sunlight (Tojimbara 1986). In turn, these processes are directly responsible for the water quality improvement potential of treatment wetlands. The submerged surface area of vegetation in a wetland is a function of plant type, plant density, and water depth. Reported submerged plant surface areas for various typical wetland plants are given in Table 3-3.

TABLE 3-3
Submerged surface area of wetland vegetation, normalized for a depth of 0.5 m.

Site	Dominant Vegetation	Submerged Area (m^2/m^2)	Depth (m)	Normalized Submerged Area (m^2/m^2)
Arcata, CA	*Scirpus acutis*	7.6	0.6	6.5
	Typha latifolia	2.6	0.6	2.2
Benton, KY	*Scirpus cyperinus*	1.8	0.25	3.6
	Typha latifolia	1.0	0.25	2.0
Houghton Lake, MI	*Carex* spp.	2.4	Unknown	Unknown
	Typha angustifolia	2.7	0.3	4.5
	Typha latifolia.	2.1	0.3	3.5
Pembroke, KY	*Scirpus validus*	1.2	0.2	3.0
	Typha angustifolia	1.5	0.2	3.7

Source: Kadlec and Knight 1996, Kadlec 1997, Pullin and Hammer 1991, Gearheart et al. 1999 (publication in progress).

Depending on the dominant plant type, plant surface area may be a function of wetland depth. If the primary contribution to surface area in the wetland is the bottom litter layer, then the surface area available for attached growth does not increase significantly with depth once the litter layer is submerged, and effluent quality may be largely independent of water depth in treatment wetlands (Kadlec and Knight 1996). For example, data from a sedge meadow at Houghton Lake indicated that very little additional surface area was observed for water depths greater than 250 mm (Kadlec, 1997). In contrast to this finding, the surface area of live and dead plant material and litter for a *Typha* zone of the wetland at Houghton Lake is still showing a significant increase at 0.3 m (Figure 3-18). The change in leaf and stem (not litter) surface area with depth in a bulrush (*Scirpus acutis*) and cattail (*Typha latifolia*) zone of the Arcata Treatment Marsh are shown in Figure 3-19. For the Arcata marsh, the leaf and stem surface area continues to increase significantly up to the maximum depth measured of 1 meter. From these results, it can be concluded that in wetlands supporting plants that grow in deeper water (e.g., cattails and bulrush), the surface area for attached growth does increase significantly with depth. As a result, those water quality constituent removal mechanisms that are dependent on attached growth surface area are also a function of water depth.

Wetland vegetation also has an effect on the hydraulic characteristics of the wetland, which directly influences water quality constituent removal processes. Wetland vegetation can

- increase water losses through plant transpiration,
- decrease evaporation water losses by shading water surfaces and cooling water temperatures,
- create friction on the flowing water and, thereby, creating headloss and flocculation of colloids,
- provide wind blocks, thus promoting quiescent water conditions and protection for floating plants such as duckweed,
- provide complex water column flow pathways, and
- occupy a portion of the water column, thus decreasing detention time

In summary, it is the vegetation, specifically the emergent and submergent vegetation, that gives a FWS constructed wetland its capability to treat wastewater effectively in a passive manner. Free water surface constructed wetlands are unique in that they grow their own physical substrate for periphytic microorganisms while minimizing incoming radiation addition. The fact that a sedimentation process coupled with an anaerobic digester and fixed film reactor is possible in a shallow aquatic system is due to the ecosystem created by aquatic macrophytes. Without the aquatic macrophytes, the same physical conditions would result in an oxidation pond producing a large amount of total suspended solids (algae) in the effluent.

FIGURE 3-18
Stem, leaf and litter cumulative surface area for *Typha spp.* in Houghton Lake discharge zone wetland (Kadlec, 1997).

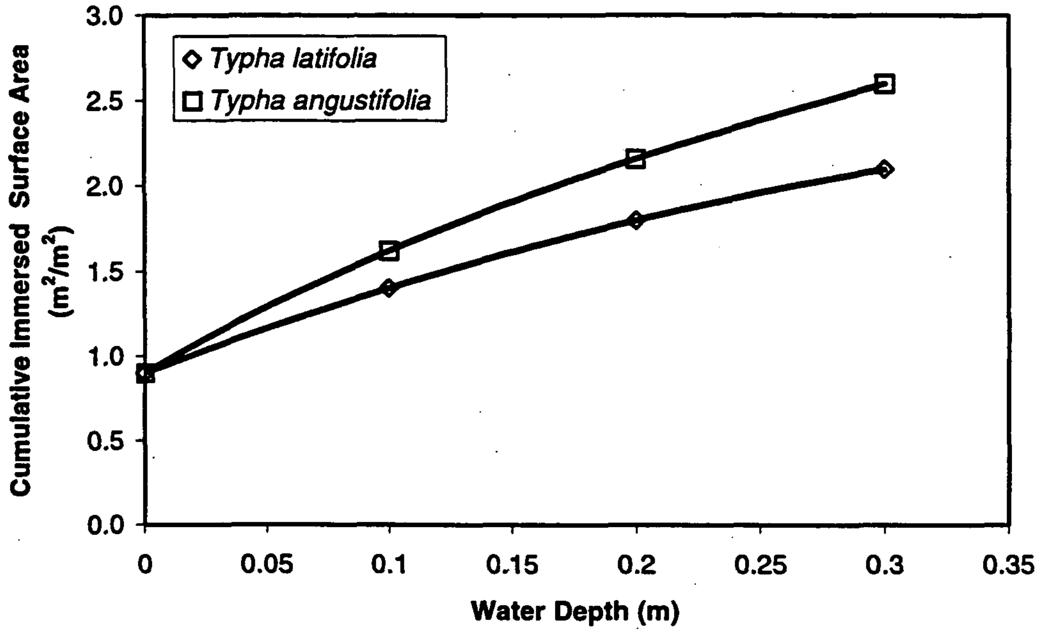
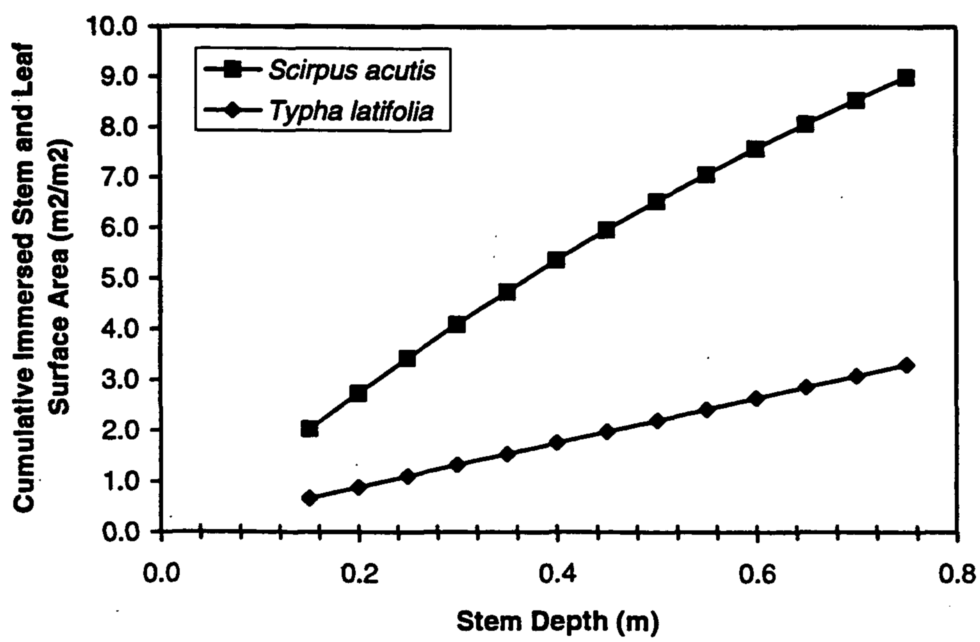


FIGURE 3-19
Stem and leaf surface area for *Scirpus acutis* (hardstem bulrush) and *Typha latifolia* (cattail) in Arcata Treatment Wetland (Gearheart et al., 1999, publication in progress).



SECTION 4

Performance Expectations

Approach to Performance Evaluation

The performance and permit compliance of operating FWS constructed wetland treatment systems reveals the range of effluent quality and the variability of performance possible with these types of systems. Evident in this analysis is the great variety in the range of treatment capacities, and thus the loadings, to which FWS treatment wetlands are subjected. Given the wide variety of settings, design criteria, configuration, and I/O placement, considerable variation in performance should be expected. This section describes and compares the performance of operating FWS constructed wetlands for which sufficient data are available to assess their performance and for which information is available to identify the factors controlling performance.

In addition to the performance assessment, an analysis of permit compliance for those FWS constructed wetland sites that had both permit limits and operational data of comparable frequency available in the NADB is included. Actual system operational flows were compared to design flows as a measure of the loading of each system during the period evaluated. For the sites with adequate data, the length of the data record, the percent compliance, and the average and maximum effluent concentrations during that period are reported. Because of the limitations of the NADB, a subset of the operational data from most of these systems is included in this analysis.

The performance assessment and permit compliance analyses presented in this section are organized by constituent, with subsections for BOD, TSS, nitrogen, phosphorus, fecal coliform, metals, and organics. The chapter concludes with a discussion of background concentrations and stochastic variability.

Data Base Evaluation (NADB and TADB)

FWS treatment wetlands were selected for performance analysis based on the data quality, frequency and availability of criteria listed in Table 2-5. Most of these FWS treatment wetlands performance data are included in the NADB [Knight et al. 1993]. If additional information is available for a particular site, it has been included for this technical assessment. Additionally, data from new systems and recent positions, currently operative large scale pilot/prefeasibility studies, have been included because they incorporate high quality data and meet or exceed the criteria in Section 2, Table 2-5.

The NADB carries with serious limitations for evaluation performance. An attempt was made to select the highest quality data for evaluating FWS wetland performance.

A major limitation is the absence of hydraulic description of the systems influent and effluent flows. Another major constraint is the lack of intra-cellular and individual cell influent and effluent water quality data. These two constraints limit the utility of using the

NADB for the purpose of performance assessment. Free water surface constructed wetlands tend to function as a sequence of coupled processes: discrete settling, flocculant settling, benthal decomposition (ammonification and release of soluble degradable organics, soluble BOD removal, nitrification, phosphorus uptake, denitrification, etc.). The contribution and even presence of each process within a FWS constructed wetland is highly dependent on the design and operation of the treatment wetland. Using the NADB, in its current form, to assess wetland technology is similar to comparing a wide range of wastewater treatment system types operating under different influent flow and constituent characteristics to determine a relationship between flow, wastewater plant area, and effluent quality. It is also important to know the level of treatment and which unit processes preceded the wetland and what the regulatory agency expects in terms of discharge requirements and permit limitations.

Methodology

The FWS constructed wetlands used in this technology assessment were the systems which best met the minimum criteria for inclusion for analysis (see Section 2 and Table 2-5). The Technology Assessment Database (TADB) includes selected systems from the NADB and additional systems for which operational data are available, that have been completed since 1993. The specific data used from each system in the technology assessment are reported in Table 4-1. For some systems, data on all water quality constituents were available, while for other systems only some constituents were available. Permit compliance was evaluated using systems in the NADB, but not necessarily in the TADB.

The performance evaluation of FWS constructed wetlands has been analyzed at three different levels. The first level includes a summary analysis of all the data for the systems listed in Table 4-1, determining the mean influent and effluent concentrations and their range of values. The mean and range of loadings for each water quality constituent are given in Table 4-2. This first level of assessment is useful only in the context of summarizing the range of operating conditions of FWS constructed wetlands and their range of response in terms of effluent concentration. At this level of analysis, only the wide range of application and expected performance for operating FWS treatment wetlands are summarized. No accounting for differences in upstream waste treatment processes, geometric configuration, planting strategy, inlet/outlet works, climate, etc. has been made at this level of analysis. Each of the factors listed above can significantly affect the effluent quality of a FWS constructed wetland.

In the second level of performance data analysis, the performance of those systems with the most extensive monthly influent/effluent data for the constituents of interest are compared. This level of analysis is displayed in terms of cumulative probability over the period of data collection. The third level of analysis is designed to determine how individual systems perform in terms of effluent concentrations over the range of their loadings. In the third level of analysis, monthly loading versus effluent concentrations for a single site are compared, thus demonstrating the expected variability within a single system.

TABLE 4-1
Water quality constituent data availability for the FWS constructed wetland systems included in this assessment, as identified in Table 2-6.

	Water Quality Parameter									
Wetland System	BOD	TSS	NH_4-N	TKN	NO_3-N	TN	OrgN	TP	DP	FC
Arcata Pilot I Cell 8	•	•	•							•
Arcata Pilot II	•	•	•		•					•
Arcata Treatment	•	•								
Arcata Enhancement Allen	•	•								
Arcata Enhancement	•	•						•		
Beaumont	•	•	•							
Benton Cattail	•	•	•	•	•	•	•	•	•	•
Benton Woolgrass	•	•	•	•	•	•	•	•	•	•
Brookhaven Meadow Marsh	•	•	•	•	•	•		•	•	•
Cannon Beach	•	•	•					•	•	•
Central Slough	•	•	•	•	•	•	•	•		•
Clermont Plot H			•		•	•	•	•	•	
Columbia	•									
Fort Deposit	•	•	•	•	•	•	•			
Gustine (89-90) 1A	•	•	•	•	•					
Gustine (89-90) 1B	•	•	•	•	•					
Gustine (89-90) 1C	•	•	•	•	•					
Gustine (89-90) 1D	•	•	•	•	•					
Gustine (89-90) 2A	•	•	•	•	•					
Gustine (89-90) 2B	•	•	•							
Gustine (89-90) 6D	•	•	•	•	•					
Gustine (94-97)	•	•								
Houghton Lake			•		•					
Iron Bridge	•	•	•	•	•	•	•	•	•	•
Lakeland	•	•				•				
Listowel 4	•	•	•	•	•	•	•	•	•	•
Manila	•	•								
Minot	•	•	•							
Mt. Angel	•	•	•							
Orange County	•	•	•	•	•	•	•	•	•	•
Ouray	•									
Pembroke FWS 2	•	•	•	•	•	•	•	•	•	•
Poinciana Boot	•	•	•	•	•	•	•	•	•	•
Reedy Creek WTS1	•	•	•	•	•	•	•	•	•	
Reedy Creek OFWTS	•	•	•	•	•	•		•	•	
Sacramento	•									
Sea Pines Boggy Cut	•	•	•	•	•	•	•	•	•	•
Tres Rios Hayfield	•	•	•	•	•			•		
Vereen Bear Bay	•	•	•	•	•	•	•	•		•
West Jackson County	•	•	•	•	•	•	•	•		

TABLE 4-2
Summary of performance data and loadings for systems analyzed in this assessment (listed in Table 4-1).

	Influent (kg/ha·d)			Influent (mg/L)			Effluent (mg/L)		
Constituent	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Biological Oxygen Demand (BOD)	0.04	31	183	1.7	70	438	1.2	15	69
Total Suspended Solids (TSS)	0.07	22	92	1.0	69	588	1.1	15	40
Ammonia (NH_4-N)	0.02	3.5	16	0.63	8.7	29	0.07	6.8	23
Total Kjeldahl Nitrogen (TKN)	0.04	5.8	20	1.3	18	51	0.82	11	32
Nitrate (NO_3-N)	0.05	0.9	3.5	0.31	3	13	0.01	1.2	3.5
Total Nitrogen (TN)	0.12	3.0	9.9	2.1	12	32	0.85	4.0	9.8
Organic Nitrogen (OrgN)	0.02	1.8	5.7	0.74	5.6	18	0.71	2.1	3.2
Total Phosphorus (TP)	0.01	1.2	4.4	0.27	4.1	11	0.09	2	4.2
Dissolved Phosphorus (DP)	0.01	0.6	1.3	0.23	2.6	5.7	0.04	1.5	3.7
Fecal Coliform (FC) (col/100mL)				1.7	73,000	360,000	47	1,320	9,800

BOD Performance

Database Assessment

The relationship between average BOD loading and average BOD effluent concentration for systems in Table 4-1 is shown in Figure 4-1. There is a general linear trend between increased BOD loading and increased effluent concentration over the loading range of 0.1 to 180 kg/ha·d. Considering the wide range of conditions, wetland design, and data quality, a general trend exists between increasing loading and increased effluent quality. Specific systems have BOD effluent versus BOD loading curves which are better correlated and predict lower effluent quality compared to the general trend observed in Figure 4-1. As shown in Figure 4-1, considerable effluent variation exists for a given BOD loading. For example, at a BOD loading of 25 kg/ha·d, the effluent concentrations vary from 9 to 35 mg/L. Considerable variation in effluent quality at the lower BOD loading rates is evident in Figure 4-1. For example, the effluent BOD varied from 1 to 8 mg/L within the BOD loading rate of 0.1 to 8 kg/ha·d. The effect of the background BOD due to plant decomposition is evident in systems with low loading rates. In addition to plant decomposition, relatively small changes in the inlet/outlet region, levels of animal activities, or weir location and operations, can all significantly affect the effluent BOD concentration under low loading rates.

Temporal BOD Performance

A summary of BOD loading versus effluent BOD concentration for the treatment and enhancement wetlands at Arcata, CA, is given in Figures 4-2 and 4-3, respectively. The seven years of monthly data shows the normal variation observed in two systems in the same location receiving different loads. As seen in Figure 4-2, the treatment marsh effluent BOD concentration is sensitive to influent BOD while the enhancement marsh effluent is not as sensitive to the influent BOD concentration.

FIGURE 4-1
Average BOD loading rate versus effluent BOD concentration for TADB sites.

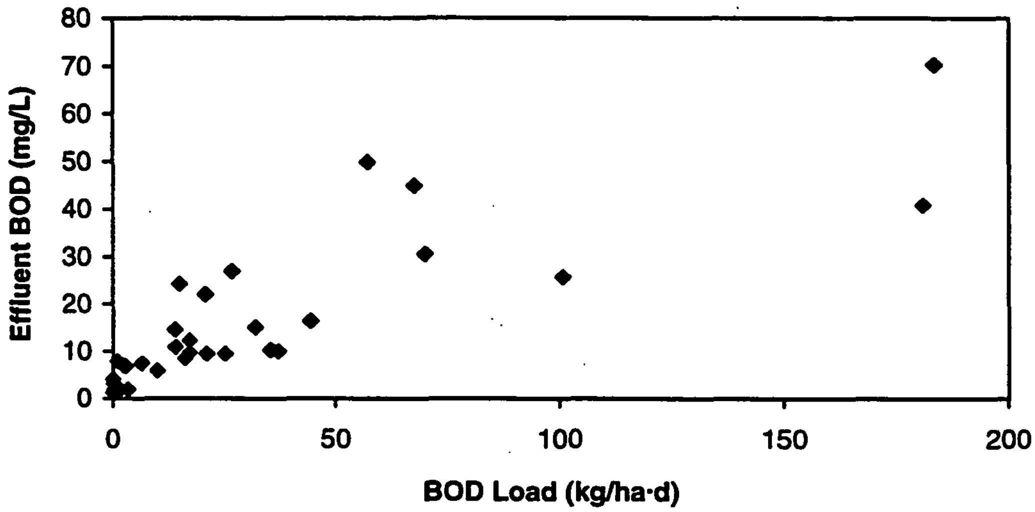
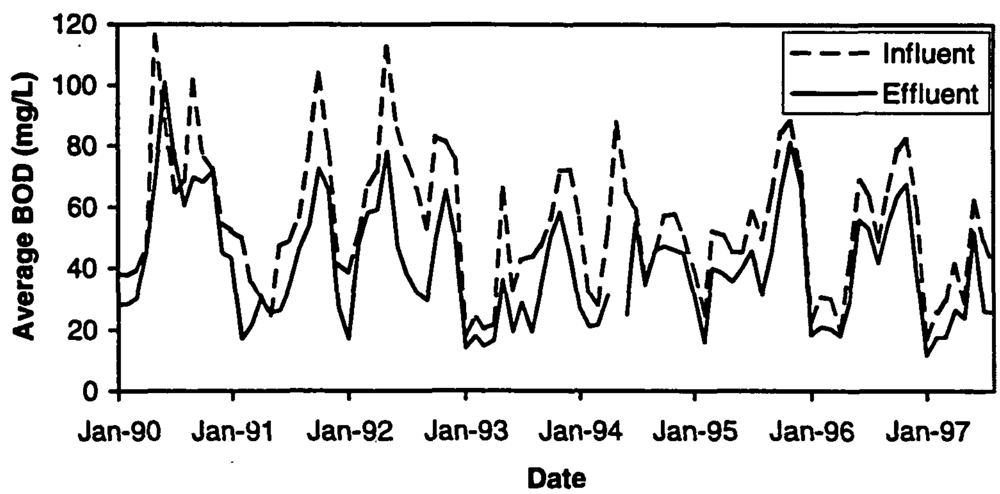


FIGURE 4-2
Monthly influent and effluent BOD values for Arcata's treatment wetland.



Effluent cumulative probability BOD levels from West Jackson County, MS are shown in Figure 4-4. This particular system shows effluent concentrations between 2 and 20 mg/L over influent BOD levels ranging from 8 to 48 mg/L with a mean effluent BOD of 4 mg/L and a mean influent value of 24 mg/L.

FIGURE 4-3
Monthly influent and effluent BOD values for Arcata's enhancement wetland.

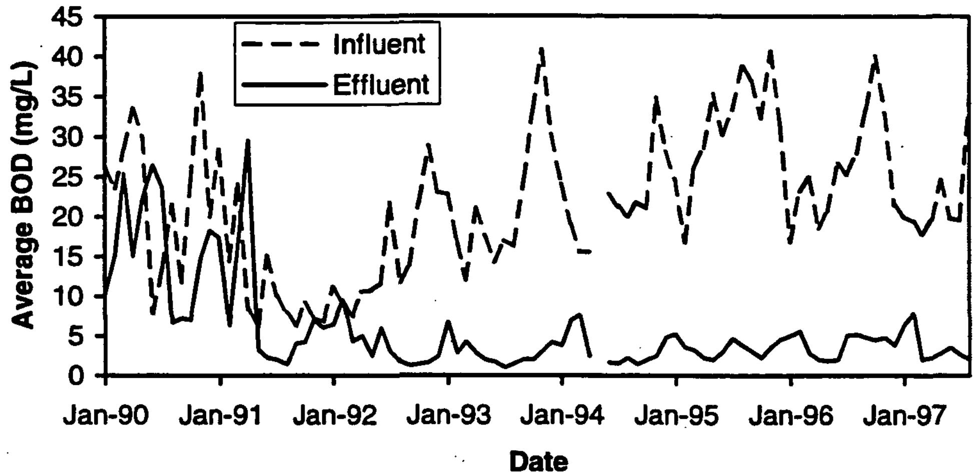
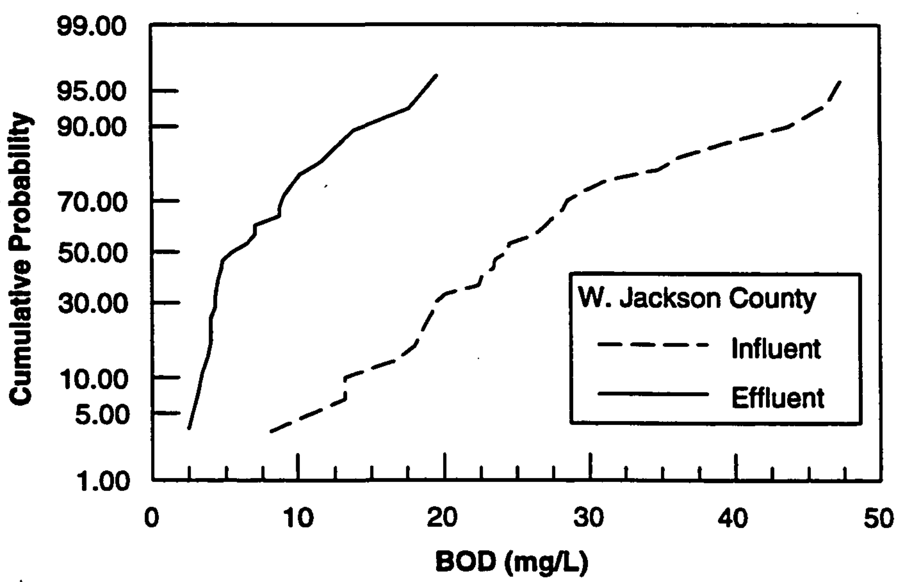
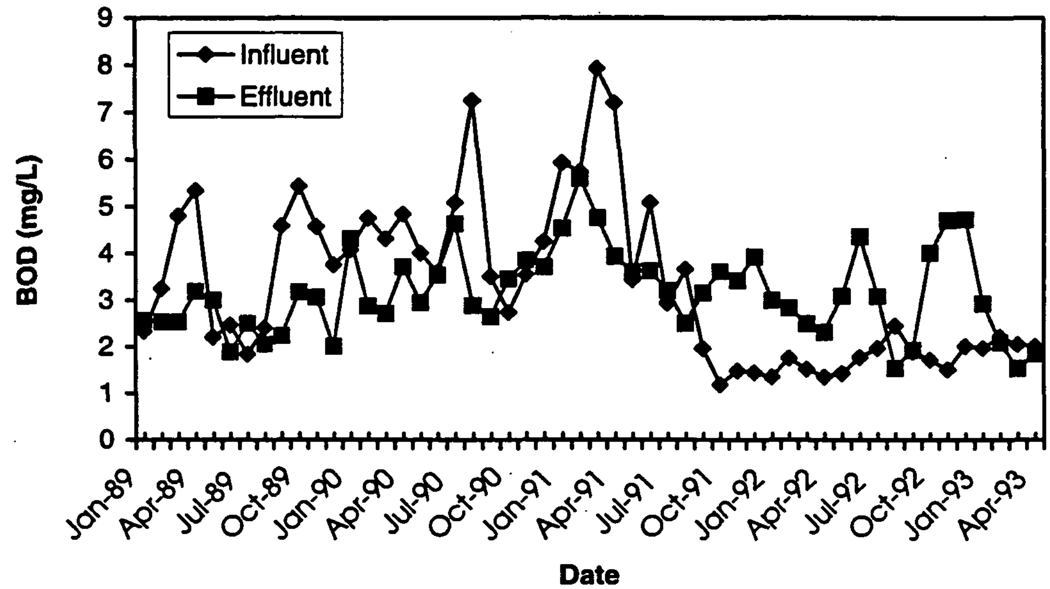


FIGURE 4-4
Influent and effluent monthly BOD cumulative probability values for West Jackson County, MS.



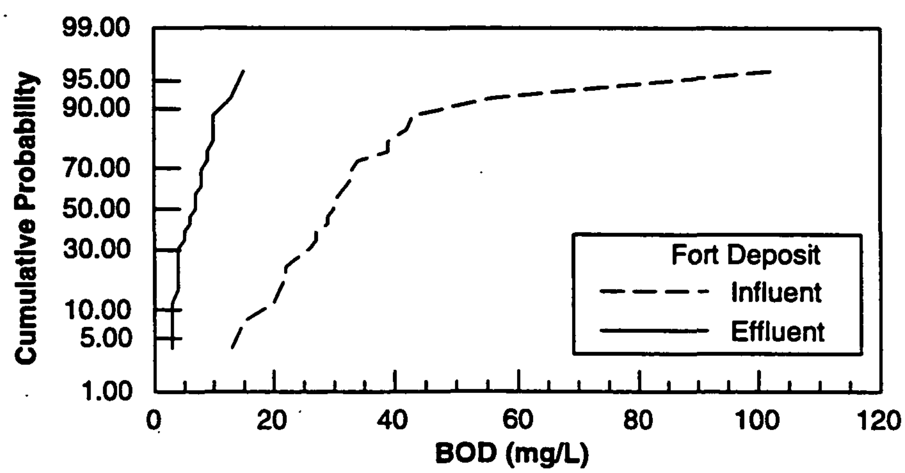
Influent and effluent BOD data for Lakeland, Florida are given in Figure 4-5. In this system, the majority of influent values are less than 5 mg/L and during one 12 month period, the effluent BOD is greater than the influent. In this case, the internal processes producing total suspended solids and dissolved BOD from aquatic plant and epiphyte primary production and decomposition increase the effluent BOD above the influent BOD.

FIGURE 4-5
Influent and effluent monthly BOD for Lakeland, FL.



The Fort Deposit influent and effluent BOD data are presented in Figure 4-6. As shown in the figure, this system exhibits consistently effective BOD removal. The effluent BOD is consistently low, between 2 and 15 mg/L, while the influent varies from 18 to 100 mg/L.

FIGURE 4-6
Influent and effluent monthly BOD cumulative probability for Fort Deposit, AL.



The relationship of BOD loading to effluent BOD concentration for the Arcata Treatment Marsh is shown in Figure 4-7. The BOD loading ranged from 76 to 605 kg/ha·d, with an average of 180 kg/ha·d. The general linear trend between BOD loading and effluent quality is perhaps more evident than the trend shown for all the TADB systems depicted in Figure 4-1. As might be expected, better relationships between loading and effluent concentrations were found on a site-by-site basis than observed when lumping data from all the sites together. The same situation occurred when comparing two systems at the same site

The Arcata Treatment Marshes have removed BOD at a constant rate of 68,000 kg/ha·yr, for the last seven years. These three treatment wetlands with a total area of 1.86 ha operate in parallel and remove approximately 30 percent of their influent BOD. This constant removal rate can also be seen in Figure 4-8, in which the accumulated BOD mass in and out of the treatment wetland is plotted.

For example, the effluent BOD from the Arcata Pilot Project can be predicted using Equation 4-1:

$$C_e = 3.42 + 0.262\, C_i \qquad (4\text{-}1)$$

Where: C_e = effluent BOD (mg/L)

C_i = influent BOD (mg/L)

The equation fit the 3 years of experimental data for cells with hydraulic residence time from 6 to 12 days, with an R^2 of 0.91.

FIGURE 4-7
Monthly BOD loading rate versus BOD effluent concentration for Arcata Treatment Marsh.

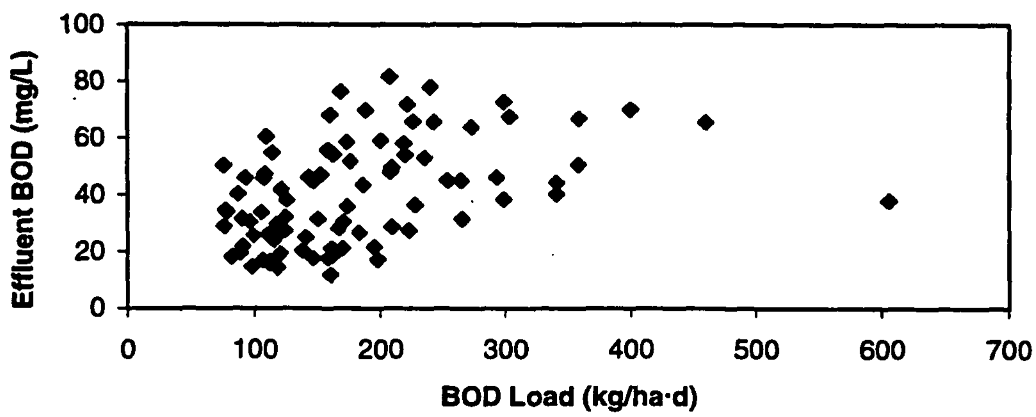
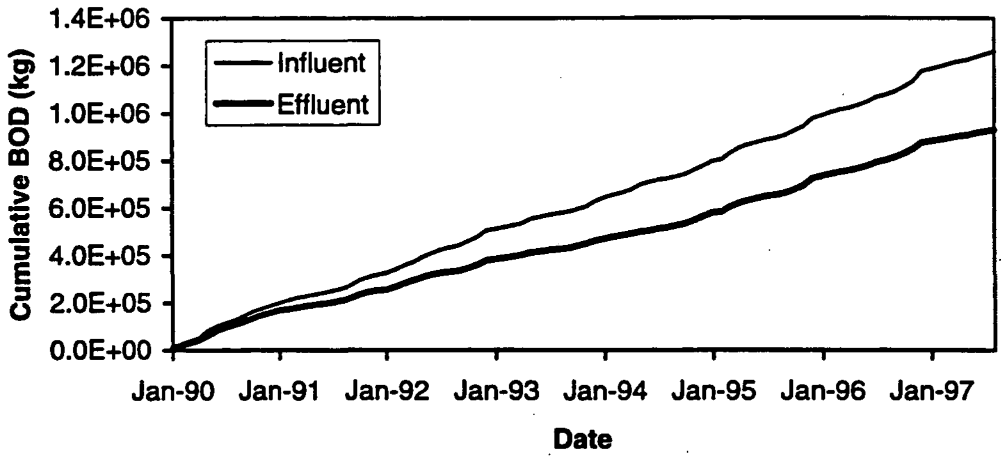


FIGURE 4-8
Cumulative monthly mass influent and effluent BOD for the Arcata Treatment Wetland.



BOD Permit Compliance

Enough information was available from the NADB to evaluate BOD_5 permit compliance for 12 FWS treatment wetland systems. Effluent BOD_5 permit limits varied from 5 to 30 mg/L on a monthly average basis. Summer BOD_5 limits were more restrictive than winter limits for five of these systems. In general, FWS constructed wetlands have been very effective at meeting BOD_5 effluent limits, even with limits as low as 5 mg/L.Only four of the 12 FWS constructed wetlands had less than 100 percent compliance with BOD_5 permit limits during the analyzed period of record. The Central Slough, South Carolina, natural treatment wetland exceeded its effluent permit limit of 30 mg/L just once in 69 months of operational data. Flow for this system was about 40 percent of design flow during that period. The Fort Deposit, Alabama, constructed treatment wetland exceeded the summer BOD_5 limit of 10 mg/L one month out of seven with a concentration of 13 mg/L. Flow at that time was only about 54 percent of design flow. The Norwalk, Iowa, system exceeded its BOD_5 limit of 30 mg/L six times during the 35-month record analyzed. The maximum recorded effluent BOD_5 during this period was 70 mg/L. Flow averaged about 58 percent of design flow during that period. The Pembroke, Kentucky, constructed wetland exceeded its 10 mg/L limit about 67 percent of the time during a 9-month period. The maximum recorded effluent value was 24 mg/L at an average flow of 84 percent of design.

TSS Performance

Database Assessment

The effectiveness of FWS treatment wetlands to remove TSS is recognized as one of their principal advantages. The relationship between TSS loading and effluent TSS levels for the entire data set is shown in Figure 4-9. Over a range of loadings from 0.5 to 180 kg/ha·d, there does not appear to be any relationship between loading and effluent quality with this data set. What is apparent is that under a fairly wide range of solids loadings, relatively low effluent TSS concentrations can be attained. Because physical processes dominate the removal of TSS, it is expected that, to a point, TSS effluent levels are not affected by hydraulic or solids loading rates. The dominant TSS removal processes occur within the first 1 to 2 day HRT period. This effect can only be seen in transect data with 1 to 2 day increments. Most of the wetlands in the wetland database have detention times in excess of 2 days, which allows the removal of TSS to be masked by subsequent internal generation of TSS. The variation in the effluent TSS shown in Figure 4-9 is most likely related to internal TSS sources such as algal growth, sloughed epiphytes, animal sources, resuspension, or detrital particles.

In the case of TSS effluent cumulative probability distribution, there are examples of systems that are consistently effective and systems in which the background levels are sometimes greater than the influent. For example, the Fort Deposit, Alabama influent TSS levels varied from 18 to 183 mg/L, with an average loading of 7.4 kg/ha·d, while the effluent TSS levels varied from 3 to 39 mg/L representing a significant TSS removal rate (Figure 4-10). In contrast, Orange County, Florida, influent TSS ranged from 1 to 4 mg/L, while the effluent ranged from 1 to 17 mg/L, with an average effluent of 4 mg/L, 2.6 mg/L greater than the average influent concentration. Based on the data from sites like Orange County, it can be concluded that wetlands generally will not reduce TSS concentrations below 3 mg/L, and in cases where the influent TSS is less than 10 mg/L, little if any additional TSS removal should be expected.

The removal of TSS is most pronounced in the inlet region of a FWS constructed wetland. Transect data from pilot project studies at Arcata show this pattern of removal (Figure 4-11). Generally 50-60 percent of the TSS from oxidation pond systems are removed in the first 2-3 days of nominal hydraulic detention time. Gravity settling processes account for most of this removal, and the overall removal efficiency is a function of the terminal settling velocity of the influent biosolids. Within the TSS loading range of 50 to 200 kg/ha·d, the removal of the settled total suspended solids does not require any routine solids handling operation. The separated solids undergo anaerobic decomposition, releasing soluble dissolved organic compounds and gaseous by-products, carbon dioxide and methane gas, to the water column.

Long term studies from individual sites have shown low and stable effluent concentrations from a relatively wide range of TSS loading rates. The TSS effluent concentrations rates from the Arcata Enhancement Wetland are consistently low, less than 5 mg/L, 90 percent of the time, with an annual average loading of 16 TSS kg/ha·d (Figure 4-12). The Arcata enhancement marsh has continued to remove TSS at a constant rate of approximately 90% for the last six years. An operational change in January of 1991 increased the BOD removal rate, and TSS removal has continued to date. An increase in hydroperiod (0.25 to 0.5 meters) coupled with no alteration in the weir setting over the year has stabilized the effluent TSS and BOD levels. The effluent TSS concentration does not track the influent levels with the operational strategies used for the last six years.

FIGURE 4-9
Monthy TSS loading versus effluent TSS concentration for TADB wetland systems.

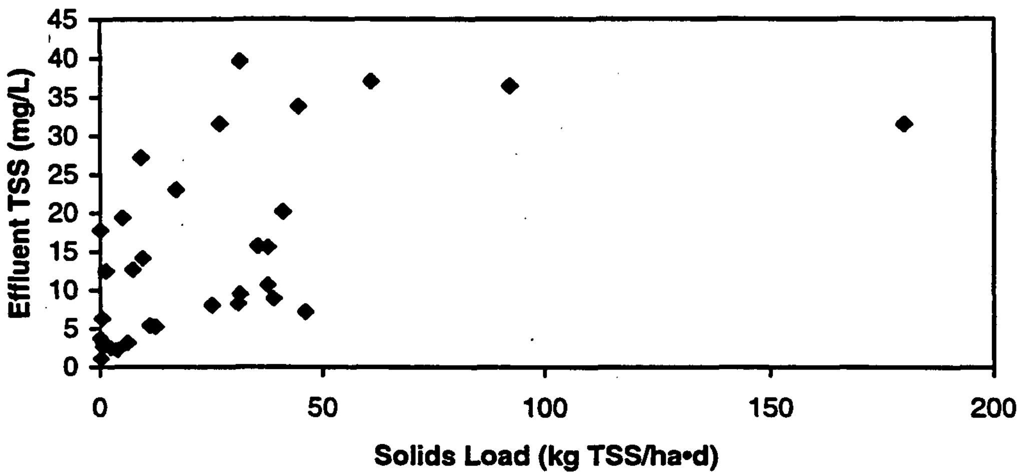


FIGURE 4-10
Cumulative probability distribution of monthly influent and effluent TSS concentration for Fort Deposit wetland.

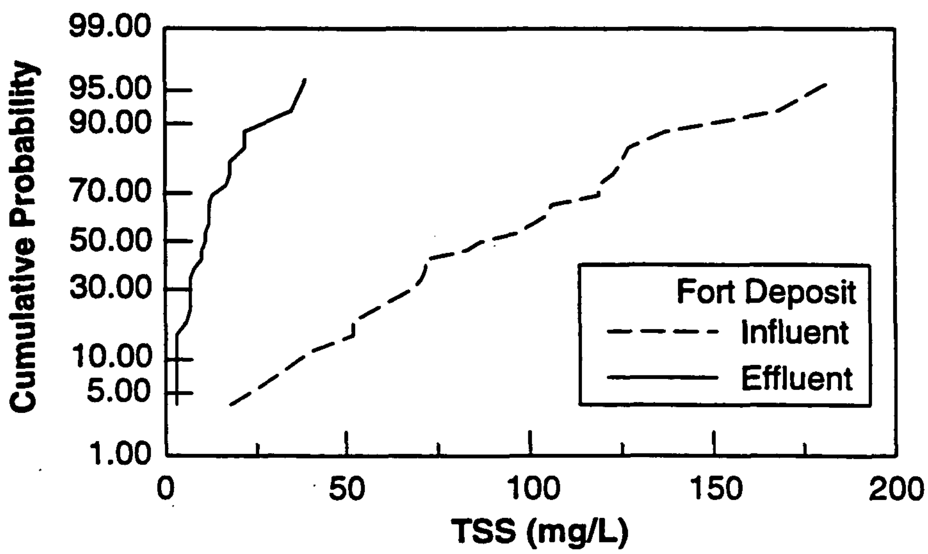


FIGURE 4-11
Weekly transect TSS concentration for Arcata's Cell 8 Pilot Project, with theoretical retention time of 6 days, receiving oxidation pond effluent.

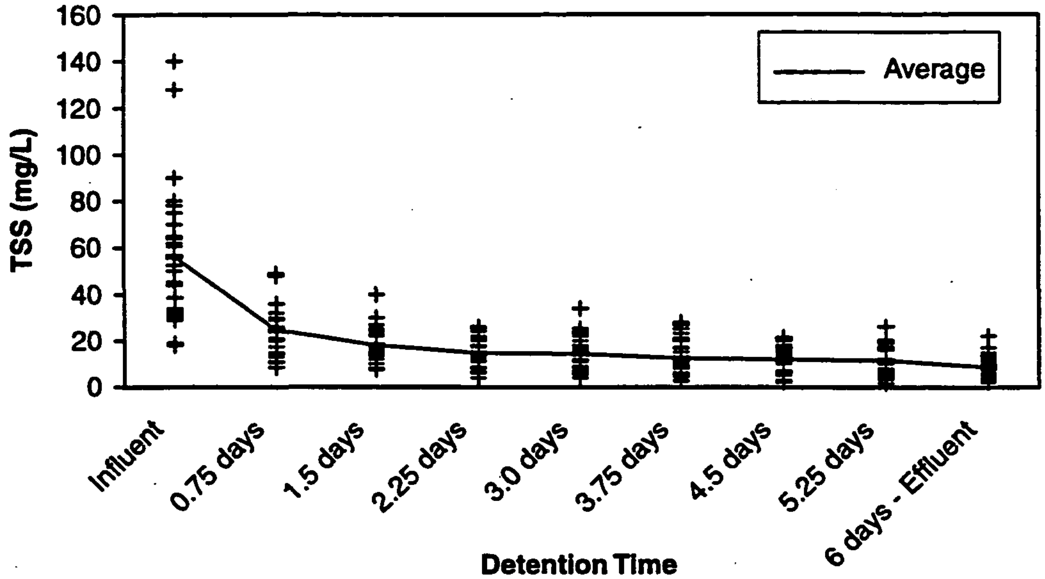
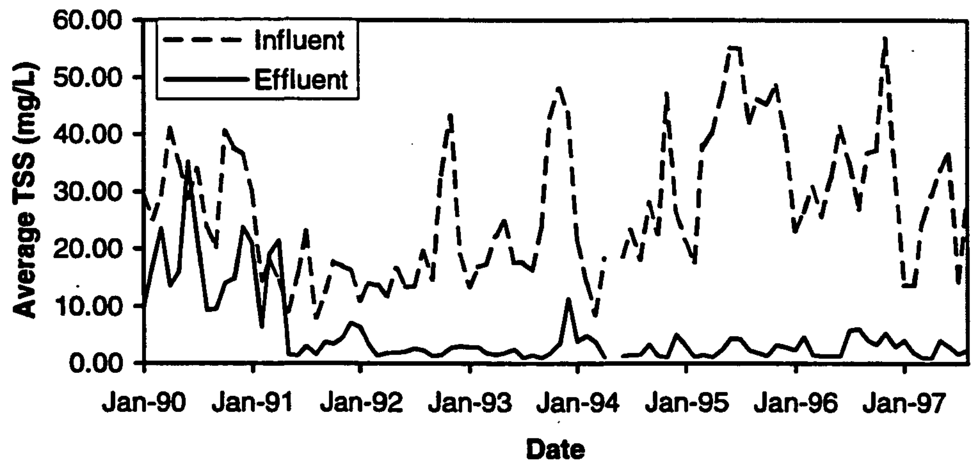


FIGURE 4-12
Weekly Influent and effluent TSS concentration for Arcata Enhancement Wetland.



Temporal TSS Performance

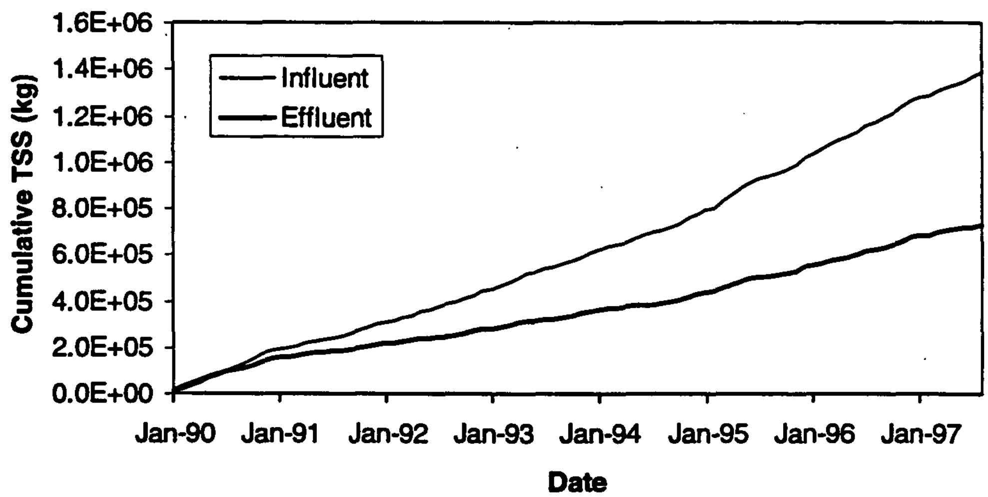
The Arcata Treatment Marshes have the highest average TSS loading in the TADB (180 kg/ha·d, average influent TSS of 60 mg/L), yet the removal has continued at a more or less constant rate of about 50 percent over the last six years (Figure 4-13). The TSS effluent levels from the treatment marsh are less than 27 mg/L, 50 percent of the time.

TSS Permit Compliance

Thirteen FWS constructed wetland systems with permit and effluent data were available in the NADB that could be used to evaluate permit compliance. Effluent TSS permit limits varied from 10 to 30 mg/L on a monthly average basis. One system (Reedy Creek, Florida) also had an annual average TSS limit. Only one of these systems had seasonal limits for TSS (Vermontville, Michigan).

In general, the FWS constructed wetlands were able to meet effluent TSS limits. The cases where limits were exceeded resulted from poor vegetative cover and the subsequent growth of phytoplankton or solids resuspension. Of the thirteen systems in the NADB, eight had 100 percent compliance with TSS effluent limits.

FIGURE 4-13
Cumulative yearly mass influent and effluent TSS for Arcata Treatment Wetland.



Five FWS constructed wetlands had less than 100 percent compliance with TSS permit limits during the period of record in the NADB. The Central Slough, South Carolina, natural wetland exceeded a 30 mg/L effluent limit twice during 24 months of operational data, and had a monthly maximum of 66 mg/L during this period. Benton, Kentucky, Cell 2 exceeded its 30 mg/L permit level twice during 20 months, with a maximum during this period of 53 mg/L. Average flow to this cell was about 65 percent of design flow. Benton Cell 1 exceeded its permit limit of 30 mg/L three times during the same 20-month period. Average flow in this cell was also about 65 percent of design. The Norwalk, Iowa, constructed wetland was in compliance with the 80 mg/L permit limit about 69 percent of the time during the 35 months of record.

Nitrogen Performance

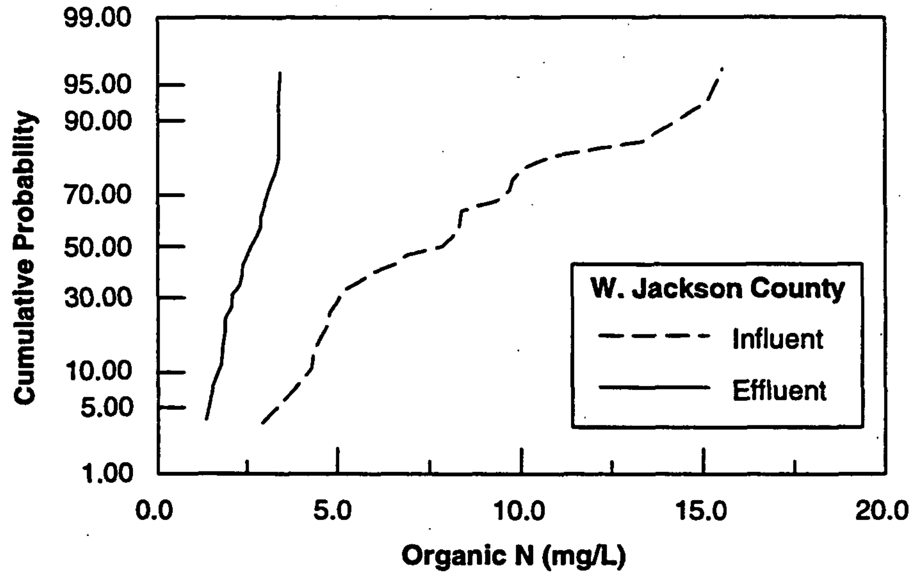
Effluent concentration data for nitrogen species shows considerable variation in response to the nitrogen loading. Total nitrogen (the sum of all nitrogen species) and total Kjeldahl nitrogen (organic plus ammonia nitrogen) effluent concentrations are generally correlated to their respective loadings. However, the other forms of nitrogen, ammonia, nitrate, and organic nitrogen, may exhibit very little correlation between effluent concentrations and influent loadings. This latter set of nitrogen species has both sources and sinks within FWS wetlands and a speciated nitrogen balance for a specific system is necessary to analyze removal performance.

In a number of cases, effluent concentrations of ammonia or nitrate N have been found to be higher than influent concentrations. This concentration increase is rarely the case for organic or total N. The conclusion from these observations is that the sequential nitrogen transformation processes result in an overall uni-directional conversion of elevated total and organic nitrogen forms to oxidized or gaseous nitrogen forms in treatment wetlands. However, these processes can also lead to increasing concentrations of intermediate nitrogen forms due to temporal, spatial, denitrification support (alkalinity/carbon, and redox potential. Distribution of various species of nitrogen within a wetland indicates that the nitrogen dynamics are affected by the influent loading, the degree of plant coverage and maturity of emergent vegetation (Sartorius et al. 1999).

Organic Nitrogen Performance

Nearly all the FWS treatment wetlands that have been studied have reported reductions in total nitrogen and organic nitrogen. The transient nature of organic nitrogen is a consequence of the balance of sources and sinks active at a given site. Organic nitrogen is produced by anaerobic degradation and is converted to ammonia nitrogen by ammonification processes making it difficult to determine the relationship between organic nitrogen loading and effluent concentration. Analysis of performance data requires a complete nitrogen balance for a particular site; it is somewhat meaningless to use data from different sites. A better relationship between influent and effluent organic nitrogen was found for individual sites. For example, a consistent removal of organic nitrogen from influent mean values of 25 mg/L to effluent mean value of 8 mg/L is shown in the data from West Jackson County (Figure 4-14).

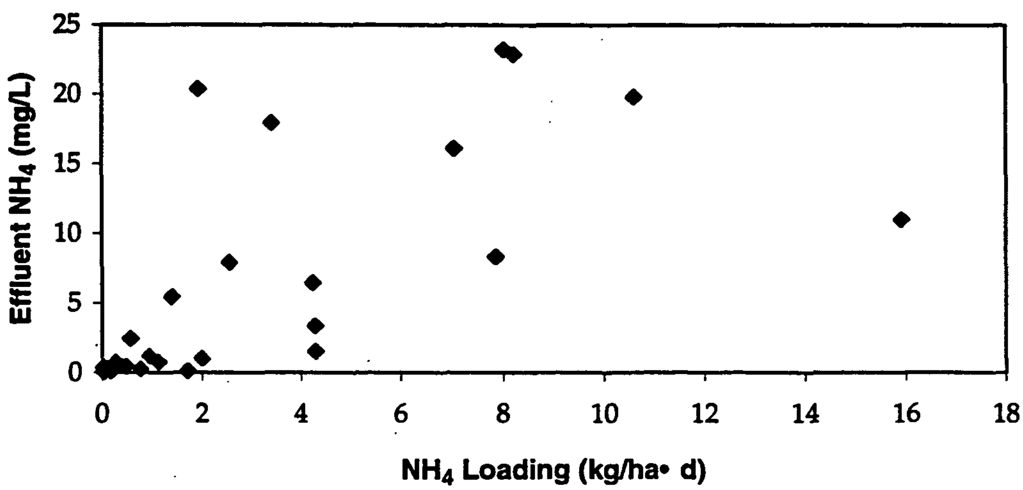
FIGURE 4-14
Cumulative probability distribution of influent and effluent organic nitrogen for West Jackson County, Mississippi.



Ammonia Nitrogen Performance

The ammonia effluent concentrations observed for the range of loading rates in the TADB is shown in Figure 4-15. Ammonia nitrogen effluent concentrations are poorly correlated with ammonia loading rates, due to the internal ammonia contribution due to organic nitrogen (org N) in the TSS. Ammonia nitrogen shows considerable variability for a given loading. At loadings between 2.0 and 3.0 kg/ha·d the effluent ammonia concentrations ranged from 0 to 20 mg/L. The data in the lightly loaded region generally showed low effluent ammonia levels.

FIGURE 4-15
Ammonia nitrogen loading versus effluent ammonia concentrations for TADB systems.



Presentation of ammonia loading versus effluent concentration data for a number of different systems tends to mask the relationship between the various forms of nitrogen, the influent concentrations of ammonia, the water temperature, and the detention time of the wetland. The Beaumont, Texas FWS constructed wetland is an example of a system that showed very consistent ammonia nitrogen removal (Figure 4-16). Over a four year period, the 8 cell system of the Beaumont wetland had an average hydraulic detention time of 17.4 days, an average water temperature of 22.5 °C, and an average ammonia loading of 4.3 kg/ha·d. As shown in Figure 4-17, the average ammonia removal was nearly 90 percent.

Ammonia nitrogen levels in constructed wetlands can increase within the wetland as decomposing particles are solubilized. This increase mirrors the contribution of dissolved organic carbon as settled solids decompose in the inlet zone of the wetland. The contribution of ammonia from decomposition under two different influent ammonia conditions is shown in Figure 4-18. In the winter, Arcata oxidation pond effluent (influent to the marsh) has high ammonia levels, typically 12 to 15 mg/L, and limited ammonia is oxidized within the marsh. During warmer periods, spring and summer, the oxidation pond contributes little to no ammonia to the wetlands, but decomposition adds 5-6 mg/L (Gearheart 1989).

FIGURE 4-16
Cumulative probability distribution of monthly influent and effluent ammonia nitrogen from Beaumont, Texas.

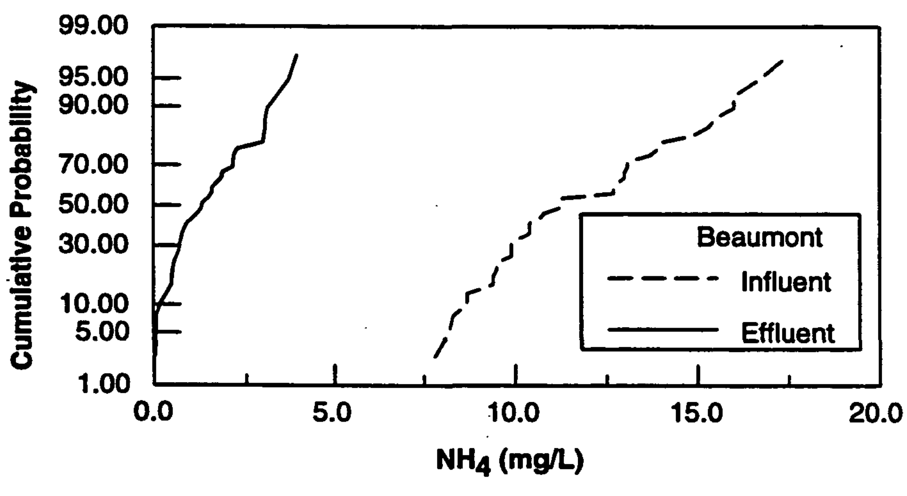


FIGURE 4-17
Ammonia nitrogen removal for Beaumont, Texas through 8 cells with a total HRT of 17 days.

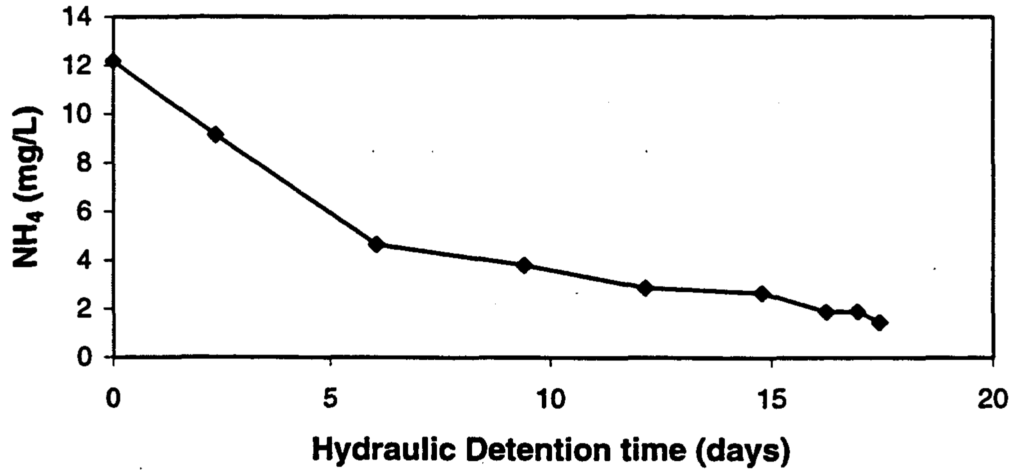
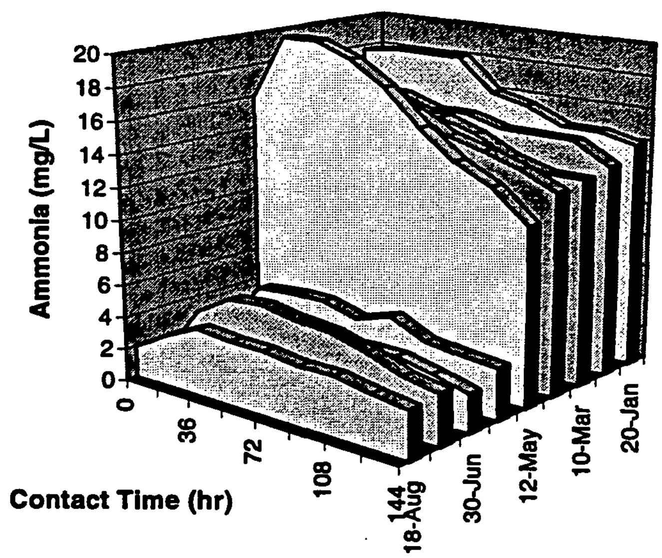


FIGURE 4-18
Ammonia concentration transect through Arcata Pilot Project Wetland.



Total Kjeldahl Nitrogen Performance

Total Kjeldahl nitrogen (TKN) loading versus effluent levels for TADB systems shows general trends of increased loading producing increased effluent concentrations (Figure 4-19). Because TKN is the sum of the organic nitrogen and the ammonia, the correlation between influent and effluent TKN is expected to be higher than for the individual components because analyzing TKN eliminates the effects of internal conversion reactions between the organic and ammonia nitrogen. Generally, those systems with an influent TKN concentration less than 2 mg/L had effluent ammonia concentration significantly less than 1 mg/L, indicating that in treatment wetlands, the background level of TKN is attributed to the organic nitrogen. The cumulative probability distribution of the influent and effluent TKN concentration for the Central Slough wetland is shown in Figure 4-20. The Central Slough system had an average influent concentration higher than the TADB average (17 versus 12 mg/L), and an average removal rate of 75 percent, slightly higher than the TADB average of 67 percent.

FIGURE 4-19
Total Kjeldahl nitrogen loading versus effluent ammonia concentrations for the TADB.

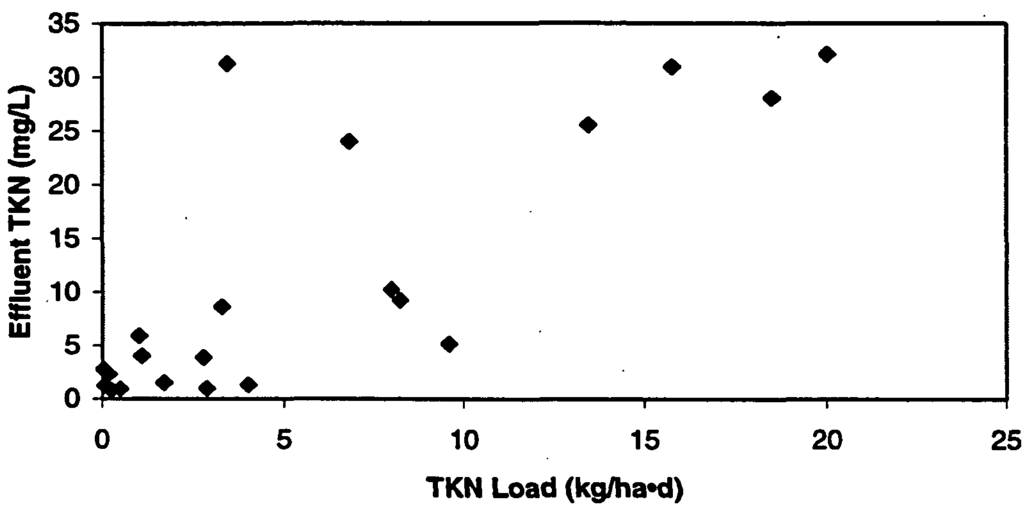
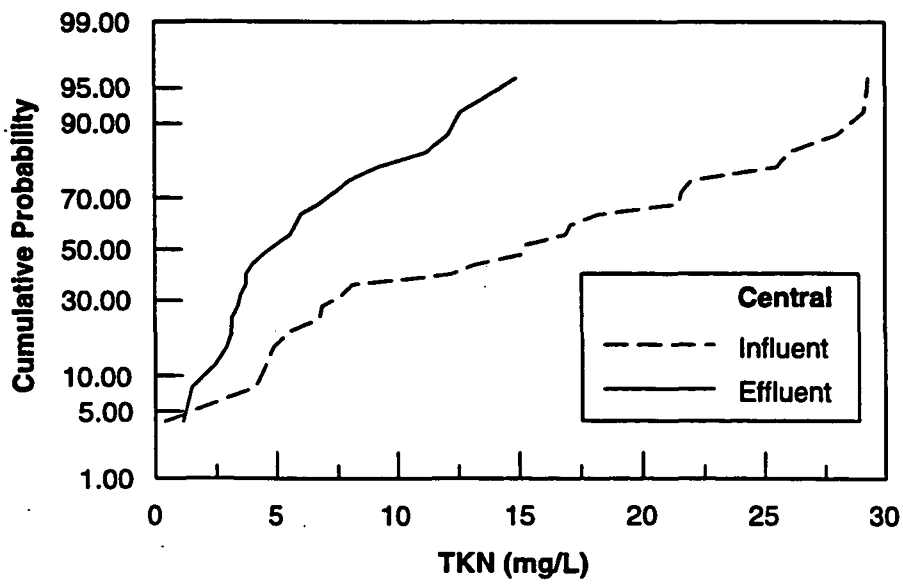


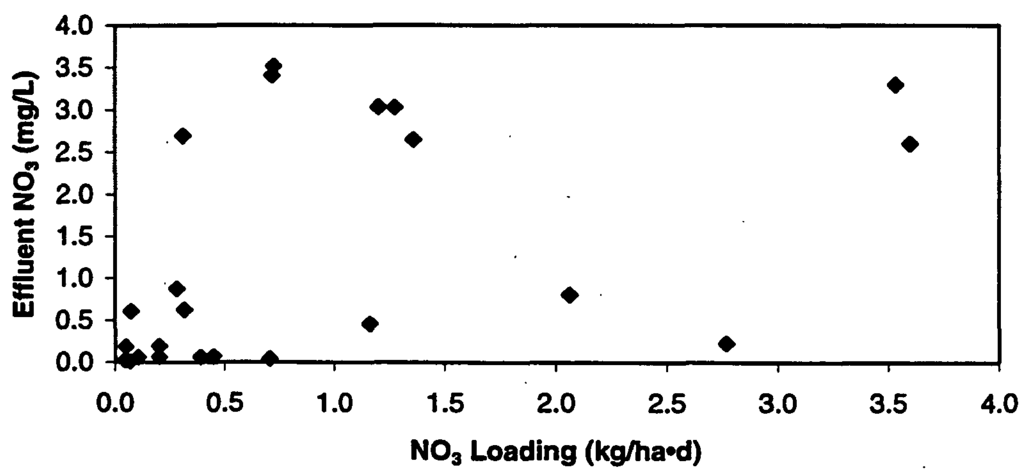
FIGURE 4-20
Cumulative probability distribution of monthly influent and effluent TKN from Central Slough, SC.



Nitrate and TIN Performance

As discussed in Section 3, nitrates are also transient nitrogen species in FWS wetlands. The extent of nitrate removal or production depends on the presence and distribution of oxious (nitrification produces nitrate from ammonia) and anoxieus (denitrification in which nitrate is converted to nitrogen gas) regions within a FWS wetland. As shown in Figure 4-21, essentially no relationship exists between nitrate loading and effluent quality in the NADB systems. Only in the case of a highly nitrified effluent would one expect to see a relationship between nitrate loading and effluent nitrate concentration.

FIGURE 4-21
Nitrate nitrogen loading versus effluent nitrate concentrations for the TADB.



The performance for Orange County, FL, as shown in Figure 4-22 is typical of a lightly loaded system. The Orange County system has nitrate effluent concentrations less than 0.1 mg/L with mean influent nitrate concentrations of 0.80 mg/L. Iron Bridge operates under similar conditions with comparable performance, 95% of the effluent nitrate concentrations are less than 0.1 mg/L with a mean influent concentration of 1.1 mg/L.

The Arcata Enhancement Wetland receives a high loading of total inorganic nitrogen TIN (sum of nitrite, nitrate and ammonia nitrogen) and shows a TIN reduction from a mean of 26 mg/L in the influent to a mean of 4 mg/L in the effluent (Figure 4-23). The performance of this system was very consistent. The org N is approximately 15 percent of the total nitrogen for this system. The majority (95 percent) of the TN is in the form of ammonia and nitrate nitrogen.

FIGURE 4-22
Cumulative probability distribution of monthly influent and effluent nitrate concentrations for Orange County, FL.

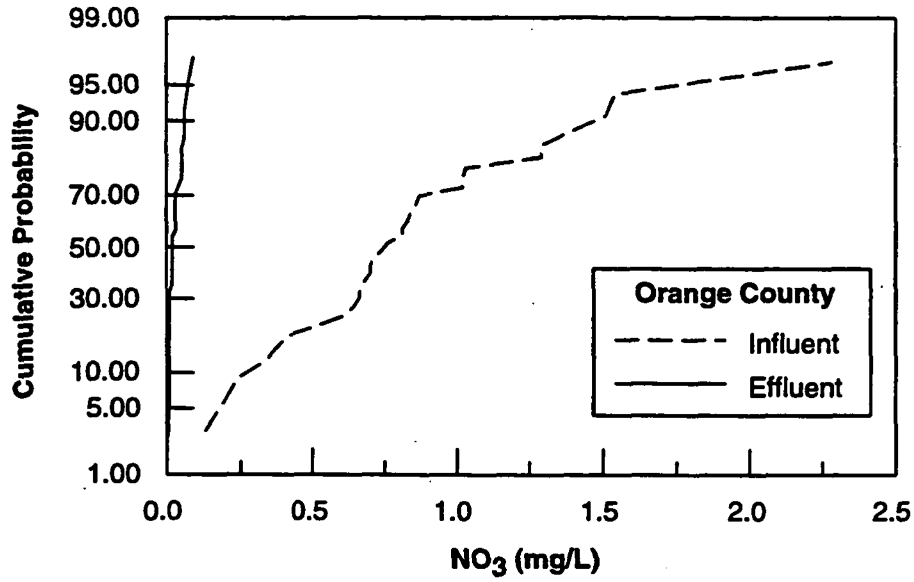
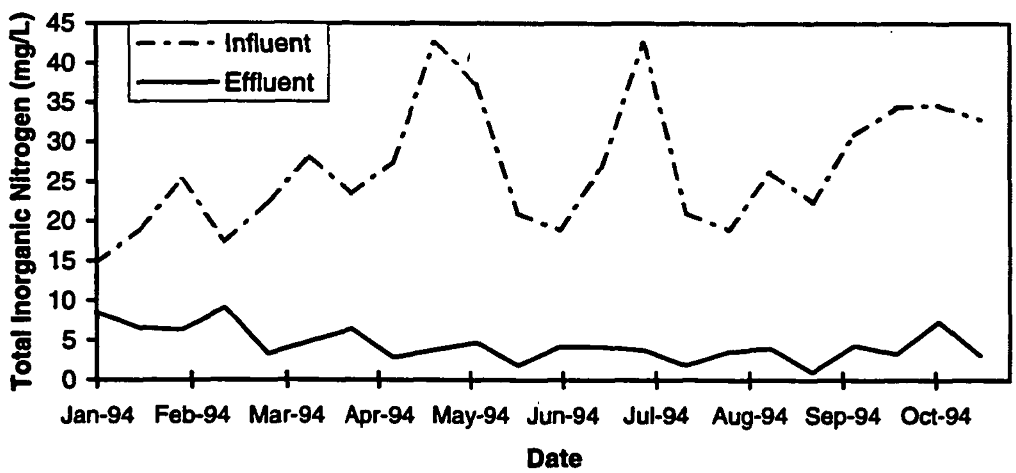


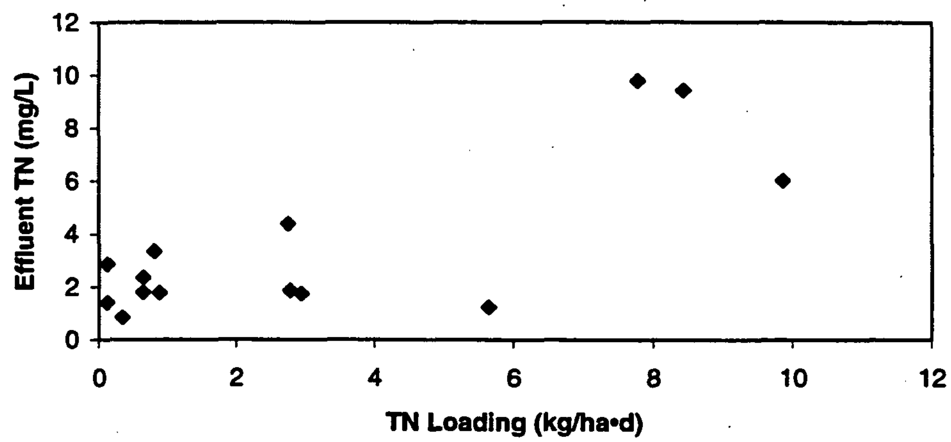
FIGURE 4-23
Monthly influent and effluent of total inorganic nitrogen (TIN) for the Arcata Enhancement Wetland.



Total Nitrogen Performance

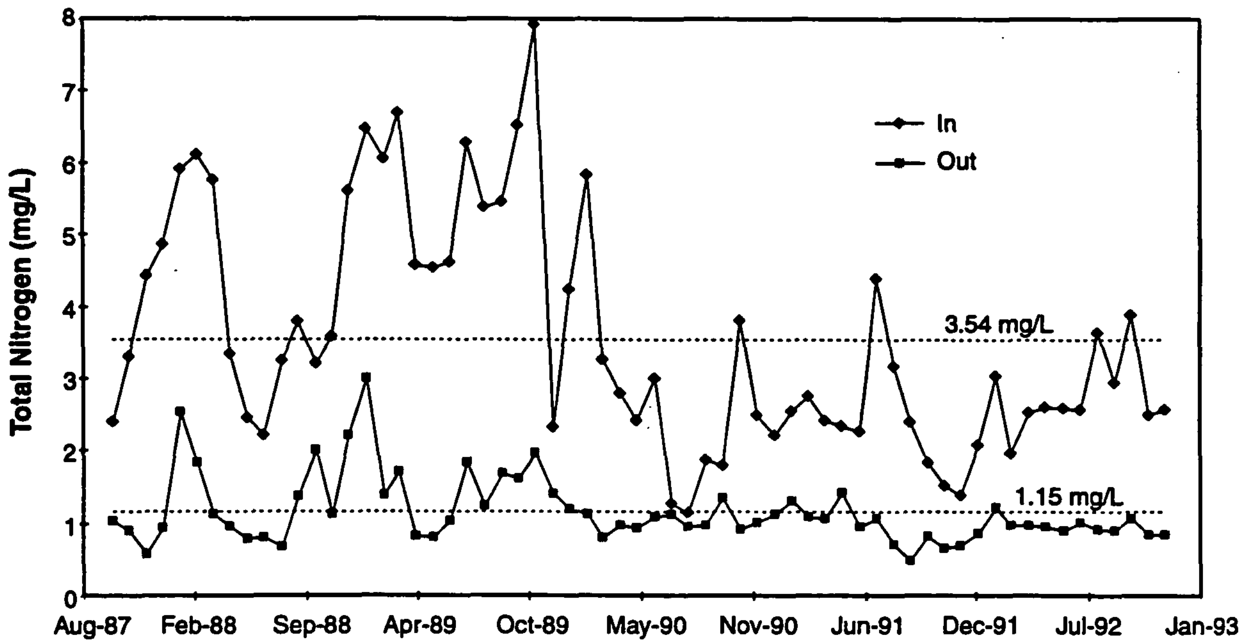
Total nitrogen, the sum of the organic and inorganic nitrogen, removal from FWS constructed wetlands shows a correlation between increased loading and increased effluent concentrations (Figure 4-24). However, within the range of 0.1-6 3 kg/ha·d considerable variation exists in the effluent concentrations.

FIGURE 4-24
Total nitrogen loading versus effluent total nitrogen concentrations for TADB wetland systems.



The typical range of inlet and outlet TN concentrations for the first 12 cells of the FWS constructed wetland at Iron Bridge, Florida, is illustrated in Figure 4-25. Individual maximum monthly outlet concentrations are more than two times higher than the long-term average.

FIGURE 4-25
Range of monthly inlet and outlet TN concentrations for cells 1 through 12 at the Iron Bridge FWS wetland near Orlando, Florida.



Nitrogen Permit Compliance

Ammonia Nitrogen

Ten FWS constructed wetland systems with NH_4-N permit and effluent data were available for evaluation from the NADB. The NH_4-N effluent permit limits varied from 1 to 20 mg/L on a monthly average basis. Six out of ten of these systems had seasonal limits for NH_4-N.

Effluent NH_4-N limit compliance continues to be a challenge for FWS constructed wetlands. Of the ten systems in the NADB, only four had 100 percent compliance with NH_4-N effluent limits.

Six FWS constructed wetlands had less than 100 percent compliance with NH_4-N permit limits during the period of record in the NADB. Benton Cells 1 and 2 had 100 percent compliance with winter NH_4-N effluent limits of 10 mg/L, but they exceeded summer limits of 4 mg/L 83 percent of the time during their 6 months of record. Maximum outlet NH_4-N concentrations were about 12.5 mg/L at an average flow of approximately 69 percent of design flow. The Fort Deposit, Alabama, constructed wetland exceeded its NH_4-N effluent limit of 2 mg/L only once out of 25 months with a maximum monthly value of 4.84 mg/L. The Norwalk, Iowa, wetland exceeded its summer limit of 8 mg/L only one time out of 20 months of record in the NADB. The maximum monthly value was 16.3 mg/L for Norwalk. The West Jackson County, Mississippi, system missed its NH_4-N permit limit of 2 mg/L 6 months out of 33 months of record with a maximum value of 3.92 mg/L. The average flow during this period was about 96 percent of the design flow.

Total Nitrogen

Only four FWS constructed wetlands had TN permit limits and associated data in the NADB. The permit limits for TN varied from 2.0 to 2.5 mg/L for these wetlands. The Reedy Creek, Florida, natural wetland systems had annual average limits in addition to monthly limits. A few treatment wetlands receiving highly pretreated (full nitrification) wastewater have been able to attain low TN effluent limits.

Two out of four systems in the NADB had 100 percent compliance with their TN effluent limits. The Iron Bridge, Florida, constructed treatment wetland met its TN effluent limit of 2.3 mg/L during all of the 63 months of record in the NADB at an average flow about 61 percent of design. The maximum TN outlet concentration recorded during this period was only 1.7 mg/L. The Orange County, Florida, hybrid treatment wetland (both constructed and natural cells in series) met a TN permit limit of 2.2 mg/L 86 percent of the 37 months of record. The maximum recorded TN value during this period was 2.6 mg/L at an average flow of about 48 percent of design. The Reedy Creek System 1 exceeded TN effluent permit limits of 2 to 2.5 mg/L about 15 percent of the time during the period reported in the NADB. The maximum recorded annual average TN outflow value for this system was 8.2 mg/L and was the result of a 6-month upset in the activated sludge conventional treatment system preceding the natural wetland.

Total Phosphorus Performance

Database Assessment

Total phosphorus removal in wetlands has been of great interest to system operators and researchers, thus the amount of data and analysis is much greater than for many other constituents. There are hundreds of wetland-years of performance data for phosphorus, spanning two decades. The majority of these studies focused on non-domestic wastewater phosphorus sources. While comparisons can be made, it is important to separate the inorganic particulate phosphorus performance from the organic particulate phosphorus performance.

The relationship between the total P loading and effluent concentration for the TADB data set is shown in Figure 4-27. Over a range of loading from 0.5 to 4.5 kg/ha·d, total phosphorus effluent concentration increases with loading. At the lower loading rates (<0.5 kg/ha.day) however, the effluent phosphorus concentration ranged from 0.1 to 1.5 mg/L. Mean site specific data from Central Slough for influent and effluent total phosphorus were 4.5 and 2.2 mg/L, respectively (Figure 4-28). Iron Bridge was the only data set in the TADB that included dissolved phosphorus. At this site, the mean influent and effluent dissolved phosphorus values were 0.35 and 0.1 mg/L, respectively.

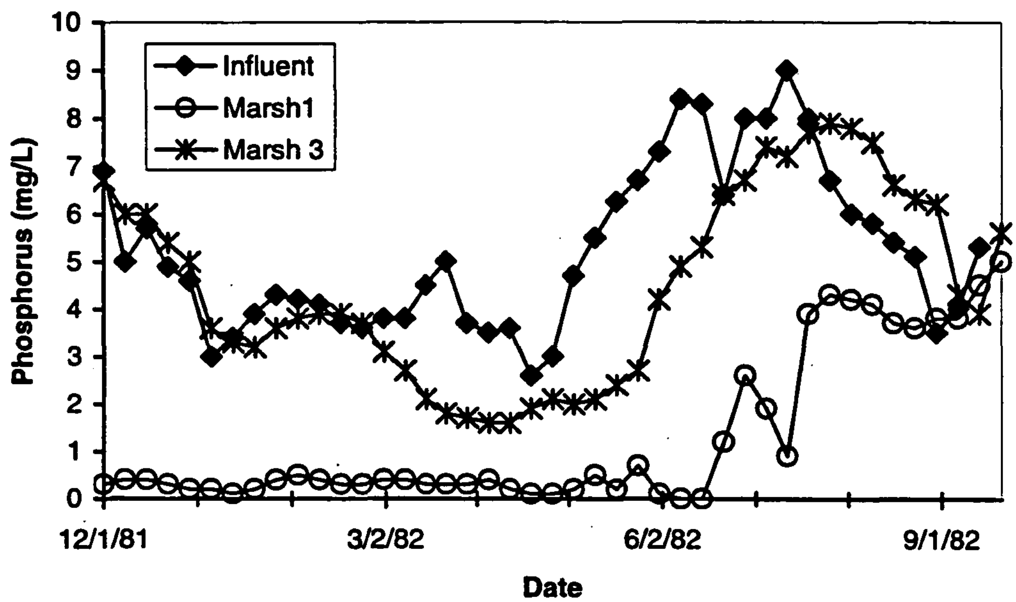
Temporal Phosphorus Performance

Phosphorus removal in FWS constructed wetlands follows a seasonal pattern in most temperate climate conditions. The form of the phosphorus, the type and density of the aquatic plants, the phosphorus loading rate, and the climate determine the amount of phosphorus removed in FWS constructed wetlands. The aquatic plants serve as seasonal reservoirs for phosphorus as they take up SRP (soluble reactive phosphorus) during the growing season. There is a finite amount of SRP that can be incorporated in the aquatic plants and plankton in the water column. In those temperate climates where senescing of the aquatic plants occur in the fall, the majority of biologically incorporated phosphorus is released back to the water column upon decomposition of the particulate organic phosphorus (POP) and detrital plant material.

Figure 4-26 shows an example of the pulsing of SRP for the conditions in Arcata, California. In this example SRP was loading at a rate of 0.15 kg/ha/day for a year (Marsh 3). A separate control cell, Marsh 1, was fed tap water (no phosphorus load) at the same HRT) at the beginning of the growing season (late January and early February). At a loading rate of 0.15 kg/ha·d, 1 to 2 mg/L of SRP was taken up by the aquatic plants and associated microbes through mid-summer. The stored phosphorus in the plant material is being released as the plants stop growing and begin to senesce, in late July. For example, by early August the effluent from Marsh 3 is 1-2 mg/L higher than the influent to the marsh cell. A cell which received effluent for one year, with the same standing crop as Marsh 3, then received tap water for one year. This cell, Marsh 1, showed a significant contribution of SRP in the late summer as phosphorus is released from the plant material and the detrital layer.

Cell 1 also shows that about 0.5 mg/L of SRP is always in solution even with no phosphorus inputs. The SRP is moving between various biological compartments with relatively short half-lives as microbial communities dominate. The standing crop in this particular wetland was approximately 15,000 kg/ha·yr above-ground material.

FIGURE 4-26
Phosphorus pulsing, as illustrated in a pilot cell in Arcata, California. Marsh 1 received tap water (no phosphorus load), while Marsh 3 received oxidation pond effluent (Gearheart 1993).



Total Phosphorus Permit Compliance

Only five FWS wetlands had TP permit limits and associated data in the NADB. Permit limits for TP varied from 0.2 to 1.0 mg/L. The Reedy Creek, Florida, natural wetland systems had annual average TP limits in addition to monthly limits. Based on the limited data, it appears that FWS constructed wetlands can comply with very stringent TP effluent limits.

FIGURE 4-27
Total phosphorus loading versus effluent phosphorus concentrations for the TADB FWS systems.

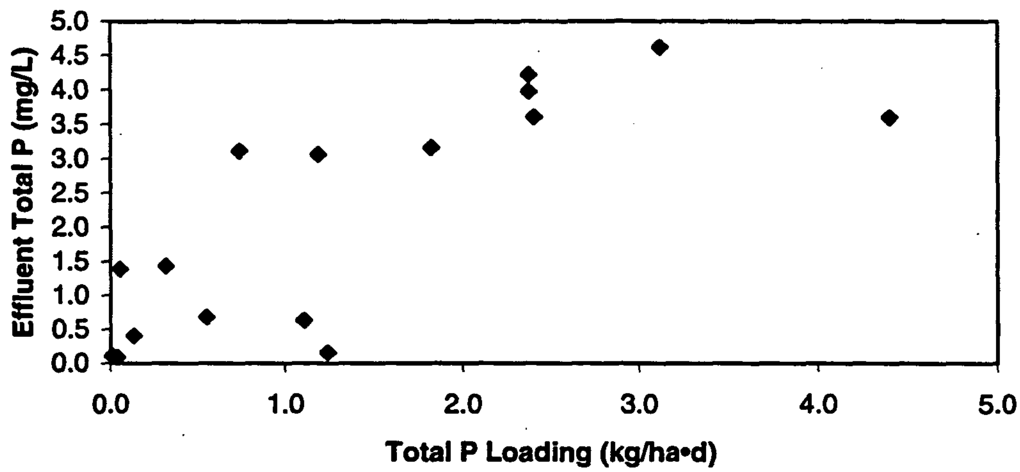
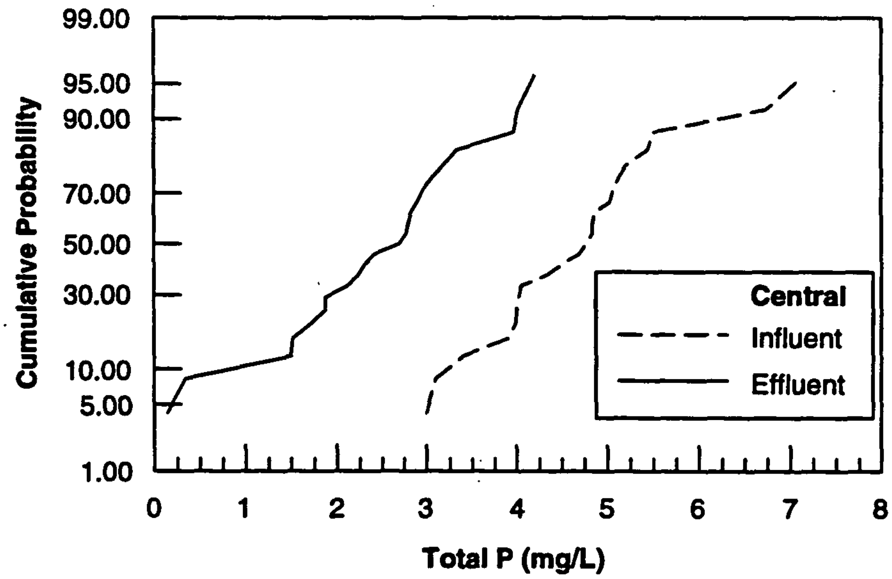


FIGURE 4-28
Cumulative probability distribution of monthly influent and effluent total phosphorus concentrations for Central Slough, SC.



Four of the five systems in the NADB had 100 percent compliance with their TP effluent limits. The Iron Bridge, Florida, system met the most stringent limit, 0.2 mg/L, every month out of 63 recorded in the NADB with an average effluent TP concentration of 0.09 mg/L and a maximum of 0.16 mg/L during that period. The Orange County, Florida, hybrid wetland exceeded its monthly limit of 0.2 mg/L five months out of 37 months of record. The maximum TP value recorded during this period was 0.39 mg/L.

Fecal Coliform Performance

Database Assessment

As shown in Figure 4-29, there does not appear to be any general relationship between the influent and effluent concentrations of fecal coliform from the TADB systems. In general, the correlation between influent and effluent conditions was better for specific sites (Gersperg et al. 1989). For example, a consistent 2 to 3 log removal with a 6 day hydraulic residence time was measured in Cell 8 in the Arcata Pilot Project. The mean influent (from an oxidation pond) fecal coliform was 5,000 cfu/100 mL and the mean effluent concentration was 35 cfu/100 mL. The cumulative probability distribution for influent and effluent fecal coliform is shown in Figure 4-30. Fecal coliform removal was also found to be correlated with TSS removal in this system.

FIGURE 4-29
Influent FC versus effluent FC for the TADB systems.

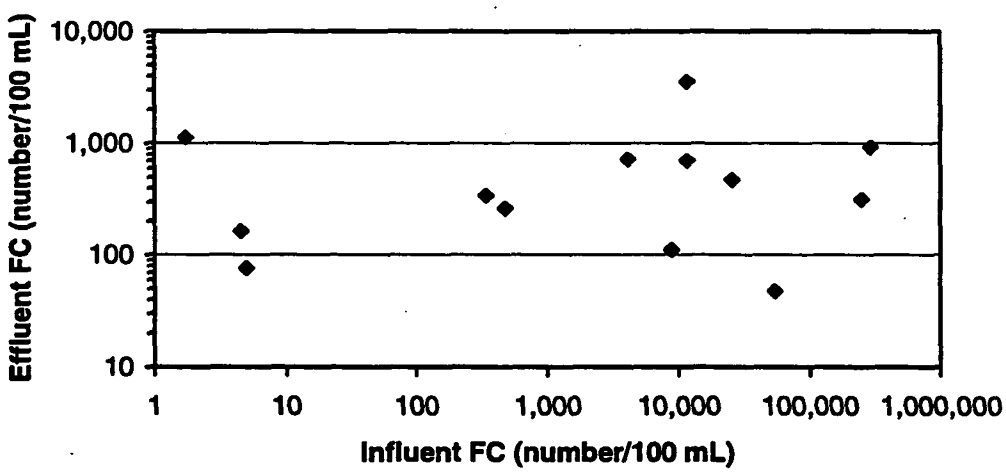
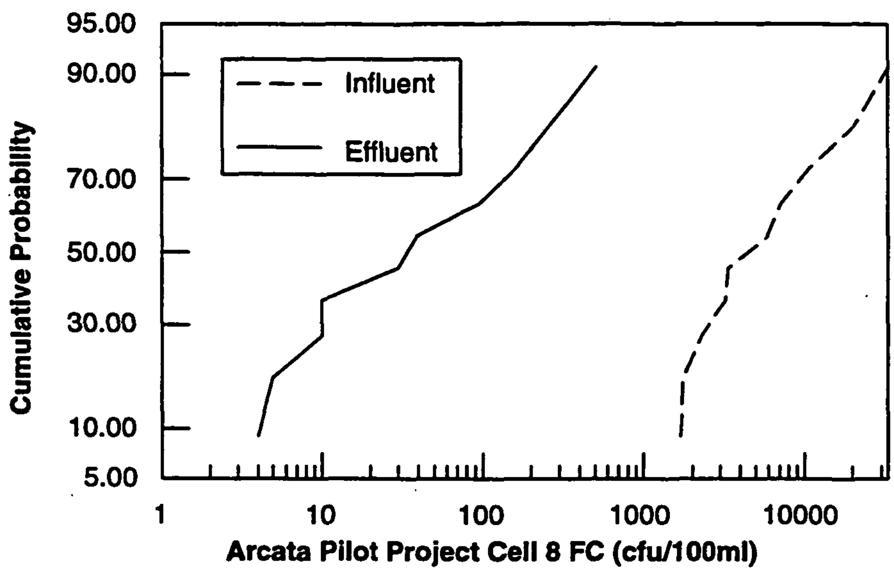


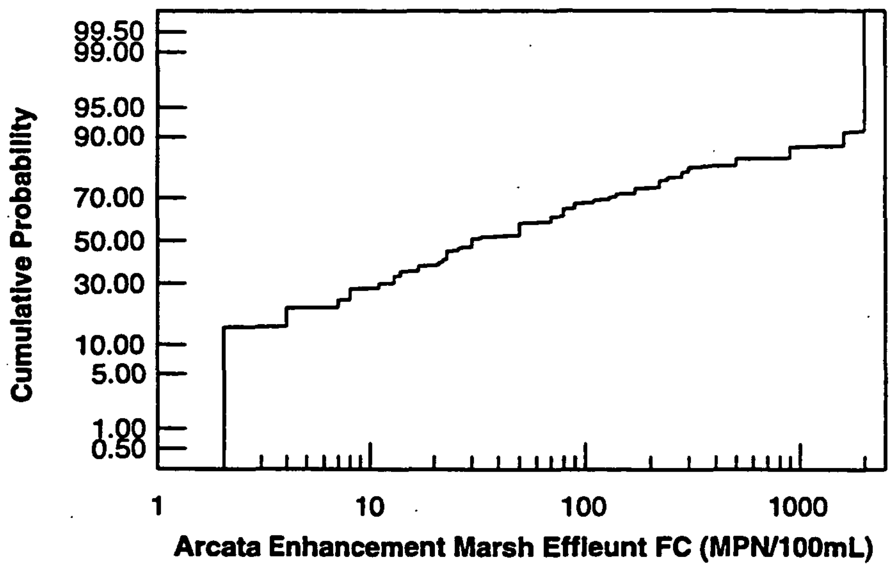
FIGURE 4-30
Cumulative probability distribution of influent and effluent fecal coliform from Arcata Pilot Project Cell 8, CA (Gearheart et al. 1986).



Estimates of the internal production of background of fecal coliforms in treatment wetlands is provided by those systems that receive disinfected influent. For example, the Arcata Enhancement Wetland receives chlorinated effluent, and during the period 1990-1997, the effluent FC was less than 500 MPN /100 mL about 80 percent of the time (Figure 4-31). A similar study on the same system during 1995-1996 showed that the effluent FC had a mean of 40 cfu/100 mL, was less than 300 cfu/100 mL over 90 percent of the time, and that no sample exceeded 500 cfu/100 mL. While some of the differences between these two sampling results can be attributed to comparing MPN versus membrane filter results, they also indicate the variations that can occur over time at a single site.

In studies performed with MS-2 bacteriophage, virus removal appears to follow the removal of fecal coliforms (Ives 1988).

FIGURE 4-31
Cumulative probability distribution fecal coliform from Arcata Enhancement Wetland, CA (Gearheart 1998, unpublished data).



Temporal Fecal Coliform Performance

The considerable temporal variability in the effluent organism counts produced by treatment wetlands and conventional treatment technologies suggests the use of geometric averaging to determine monthly mean values from daily or weekly measurements. Even with geometric means, individual monthly values are frequently 10 times larger or smaller then the long-term mean for many treatment wetlands. As indicated by the preceding discussion, exiting organisms did not necessarily originate with the incoming wastewater.

Fecal Coliform Permit Compliance

Only four FWS constructed wetlands had fecal coliform permit limits and associated data in the NADB. In each case, monthly effluent permit limits were 200 colony forming units (cfu)/100 mL; only one system met this limit 100 percent of the time (Apalachicola, Florida, with only 2 months of data). Percent compliance for the other four systems ranged from 22 to 83 percent. A maximum value of 27,000 cfu/100 mL was reported for one month from the Benton, Kentucky, constructed wetland, and maximum values of 2,600 to 5,800 cfu/100 mL were reported for Central, South Carolina, and Pembroke, Kentucky, respectively. Based on this review of limited data, it appears that most FWS constructed wetlands will have problems consistently meeting fecal coliform limits of 200 cfu/100 mL.

Metals

While some metals are required for plant and animal growth in trace quantities (barium, beryllium, boron, chromium, cobalt, copper, iodine, iron, magnesium, manganese, molybdenum, nickel, selenium, sulfur, and zinc), these same metals may be toxic at higher concentrations (Gersberg et al. 1984, Crites et al. 1997). Other metals have no known biological role, and may be toxic at even very low concentrations (e.g., arsenic, cadmium, lead, mercury, and silver).

Information from FWS treatment wetlands indicates that a fraction of the incoming metal load will be trapped and removed effectively through sequestration in plants and soils (Crites et al. 1997). A summary of published treatment wetland inlet/outlet metal concentrations from a variety of sites is presented in Table 4-3. For many metals, the limited data indicate that concentration reduction efficiency (EFF) and mass reduction efficiency (RED) correlate with inflow concentration and mass loading rate (Kadlec and Knight 1996). Wetland background metal concentrations and internal profiles are not well established.

TABLE 4-3
Metal removal data from free water surface treatment wetlands.

		Concentration (µg/L)		Mass Removal	
Metal	Wetland Type	In	Out	(kg/ha·yr)	Reference
Antimony	Constructed	0.45	0.20	0.6	Nolte & Associates 1998
Arsenic	Constructed	2.41	2.47	-0.1	Nolte & Associates 1998
Beryllium	Constructed	0.58	0.05	1.25	Nolte & Associates 1998
Cadmium	Constructed	43	0.6	2.4	Herskowitz 1986
	Constructed	0.10	0.05	0.1	Nolte & Associates 1998
Chromium	Constructed	160	20	7.9	Herskowitz 1986
	Constructed	3.4	1.5	4.5	Crumpton et al. 1993
	Constructed	1.57	1.13	1.0	Nolte & Associates 1998
Copper	Constructed	1,510	60	82	Herskowitz 1986
	Constructed	8	3	11	Crumpton et al. 1993
	Constructed	7.87	3.48	10.4	Nolte & Associates 1998
	Natural	20.4	6.1	0.21	Cooper 1990
Iron	Constructed	6,430	2,140	243	Herskowitz 1986
	Constructed	205,000	6,300	29,900	Ewel and Odum 1984
	Natural	241	766	-4.3	Cooper 1990
Lead	Constructed	1.7	0.4	3.1	Crumpton et al. 1993
	Constructed	2.2	1.63	0.085	Ewel and Odum 1984
	Constructed	1.28	0.25	2.4	Nolte & Associates 1998

Metal	Wetland Type	Concentration (µg/L) In	Out	Mass Removal (kg/ha·yr)	Reference
	Natural	2.0	5.5	-0.03	Cooper 1990
Manganese	Constructed	210	120	5.1	Herskowitz 1986
	Constructed	7,400	3,900	526	Ewel and Odum 1984
Mercury	Natural	<0.2	0.21	0.0001	Cooper 1990
	Constructed	0.0112	0.0042	0.017	Nolte & Associates 1998
Nickel	Constructed	35	10	1.4	Herskowitz 1986
	Constructed	7.5	3.8	0.8	Crumpton et al. 1993
	Constructed	6.26	7.10	-2.0	Nolte & Associates 1998
	Natural	17.0	9.1	0.14	Cooper 1990
Selenium	Constructed	0.68	0.71	-0.07	Nolte & Associates 1998
Silver	Natural	0.36	0.53	-0.0005	Cooper 1990
	Constructed	0.40	0.11	0.7	Nolte & Associates 1998
Zinc	Constructed	2,200	230	112	Herskowitz 1986
	Constructed	36	11	60	Crumpton et al. 1993
	Constructed	36.85	6.71	71.3	Nolte & Associates 1998
	Natural	20.6	5.6	0.22	Cooper 1990

Other Performance Considerations

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 non-zero levels of BOD, TSS, TN, and TP. Enriched wetland ecosystems are likely to produce higher background concentrations than oligotrophic wetlands because of the increased biogeochemical cycling that result from the addition of nutrients and organic carbon.

Background concentrations are not constant, but have a cycle of release that is a function of the biogeochemical cycle rates and external (other than wastewater inputs) factors. An example of this cycling can be seen in Figure 4-32 from the Arcata Enhancement Wetland. Six years of weekly BOD measurements show that for this system the background concentration varies between 1.3 and 4.0 mg/L. The higher values of 3.5 to 4.0 mg/L occur in the fall and the lower values occur in the summer. This variation is attributed to the accelerated decomposition of the vegetative material and to increased bird activity in the fall. The lower values in the summer are correlated with low decomposition rates (low recent litter production) and decreased bird activity.

Treatment wetland background concentration ranges can be estimated from systems that are loaded at a low enough rate to result in asymptotic concentration profile along a gradient of increasing distance from the inflow (several examples exist in the NADB). Long-term average annual outflow constituent concentrations for this selected group of FWS treatment wetlands are summarized in Table 4-4. Wetland systems typically have background concentrations within the ranges listed in Table 4-5.

TABLE 4-4
Long-term average annual outflow concentrations for lightly loaded FWS wetlands in the NADB.

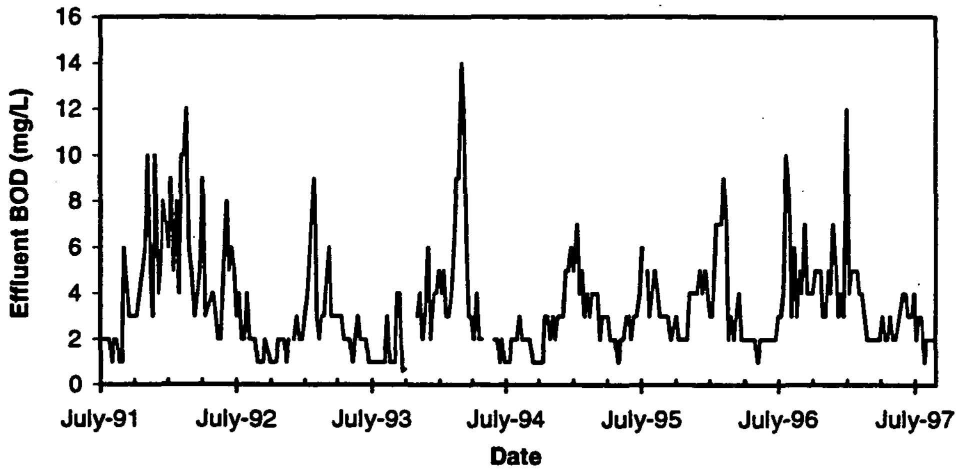
	Concentrations, mg/L				
System	BOD_5	TSS	NH_4-N	TN	TP
Eastern Service Area, FL	1.2	3.0	0.07	1.45	0.09
Iron Bridge, FL	2.0	2.8	0.18	0.95	0.08
Bear Bay, SC	1.9	2.7	0.27	2.35	0.40
DesPlaines, IL	--	5.2	0.03	1.34	0.02
Hidden Lake, FL	3.0	13.0	0.05	0.66	0.16

Source: NADB 1993

TABLE 4-5
Expected range of background concentrations for constituents of interest.

Constituent	Unit	Concentration Range
5-day biochemical oxygen demand (BOD_5)	mg/L	1 to 10
TSS	mg/L	1 to 6
Organic and total nitrogen	mg/L	1 to 3
Fecal coliforms (FC)	MPN/100 mL	50 to 500
Ammonium N	mg/L	less than 0.1
Nitrate N	mg/L	less than 0.1
Total Phosphorus	mg/L	less than 0.1

FIGURE 4-32
Variation in effluent BOD at the Arcata Enhancement Marsh.



Natural Variability

Free water surface treatment wetlands demonstrate the same type of 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 is always significant spatial and temporal variability in wetland water pollutant concentrations. The stochastic character of rainfall and the periodicity and seasonal fluctuation in ET contribute to much of this variability in the concentrations in wetland effluents.

SECTION 5

System Planning and Design Considerations

Planning Considerations

Like other wastewater treatment processes, FWS constructed wetlands perform within definable limits. These limits must be identified and summarized to allow designers to size FWS constructed wetlands that consistently achieve pollutant reductions from a known influent to a desired effluent concentration. Regression equations, areal loading rate methods, and simple first order models are the most common tools used to summarize constructed wetland performance. With a general knowledge of performance expectations, the designer can also use these tools to specify characteristics such as wetland area, water depth, cell configuration and plant selection to achieve desired treatment efficiency.

Consideration must also be given to specific constraints associated with the living, autotrophic ecosystems comprising FWS constructed wetlands. The natural processes that occur in FWS wetlands result in background concentrations for some constituents that may be higher than the influent concentrations of the same constituent. Knowledge of these background concentrations is important to avoid overly optimistic expectations for constructed wetlands performance. Additionally, a certain amount of statistical variability is inherent in wetland effluent concentrations, some of which is due to environmental factors (such as seasonal temperature and plant community changes) outside the control of the wetland designer and operator. Unless discharge permits are written to include this natural variability, the inevitability of the "scatter" in wetland effluent quality must be factored into design to avoid permit violations.

Some of the modeling tools and general considerations that are important to wetland planning, design, and sizing are described in this section. In addition, compliance of existing FWS constructed wetland with their permit limits for common target pollutants and related constituents (BOD, TSS, NH_4-N, TN, TP, fecal coliform and DO) are summarized.

Role of Wetlands in the Watershed

The first step in assessing the feasibility of FWS constructed wetland is to identify the goals and objectives of the wetland within the watershed. Natural wetlands are an integral part of their watershed; functioning as water storage areas, nutrient sinks, and wildlife habitat. Free water surface constructed wetlands used for wastewater treatment can also provide considerable benefits beyond water quality improvement and these additional objectives should be integrated into the feasibility and planning process. Ideally, a master plan establishing restoration goals for the watershed and its receiving waters will exist and the benefits of a FWS constructed wetland can be incorporated into this plan.

The process used to evaluate the feasibility of FWS constructed wetlands for water quality improvements and to function as landscape units on a watershed requires a sequence of assessments. The process is similar to the evaluation of conventional wastewater unit treatment processes because FWS constructed wetlands function similarly to conventional wastewater treatment processes in terms of their ability to convert, remove, and store specific constituents. However, the process steps are dissimilar in that FWS constructed wetlands fulfill other functions and values as landscape units within a watershed. The procedure described below (Steps 1 through 12) incorporates evaluation of the possible additional functions of FWS constructed wetlands. The type of information required at each step and its relationship to the decision process is depicted graphically in Figure 5-1.

Step 1 - Identify the goals and objectives of the project. In this initial step, the role the wetland will play in maintaining, restoring, or enhancing the beneficial uses in the receiving system is established.

Step 2 - Characterize the wastewater entering the FWS constructed wetland. Each type of wastewater or non-point water source has its own unique physical, chemical, and biological characteristics. A thorough characterization of the constituents and their concentrations combined with identification of pathogen indicators or pathogens should be conducted. This step should also include a thorough literature review and may require laboratory and mesocosm testing.

Step 3 - Determine the discharge requirements and limitations. The discharge constraints coupled with the constituent properties determined in Step 2 will dictate the required effectiveness of treatment.

Step 4 - Determine the ability for wetland processes to reduce, retain, and transform constituents. Mesocosm and bench scale treatability studies might be required prior to proceeding to the next step. Wetland treatability studies usually require more time than most biological treatment systems because of the time it takes to develop the aquatic macrophyte standing crop.

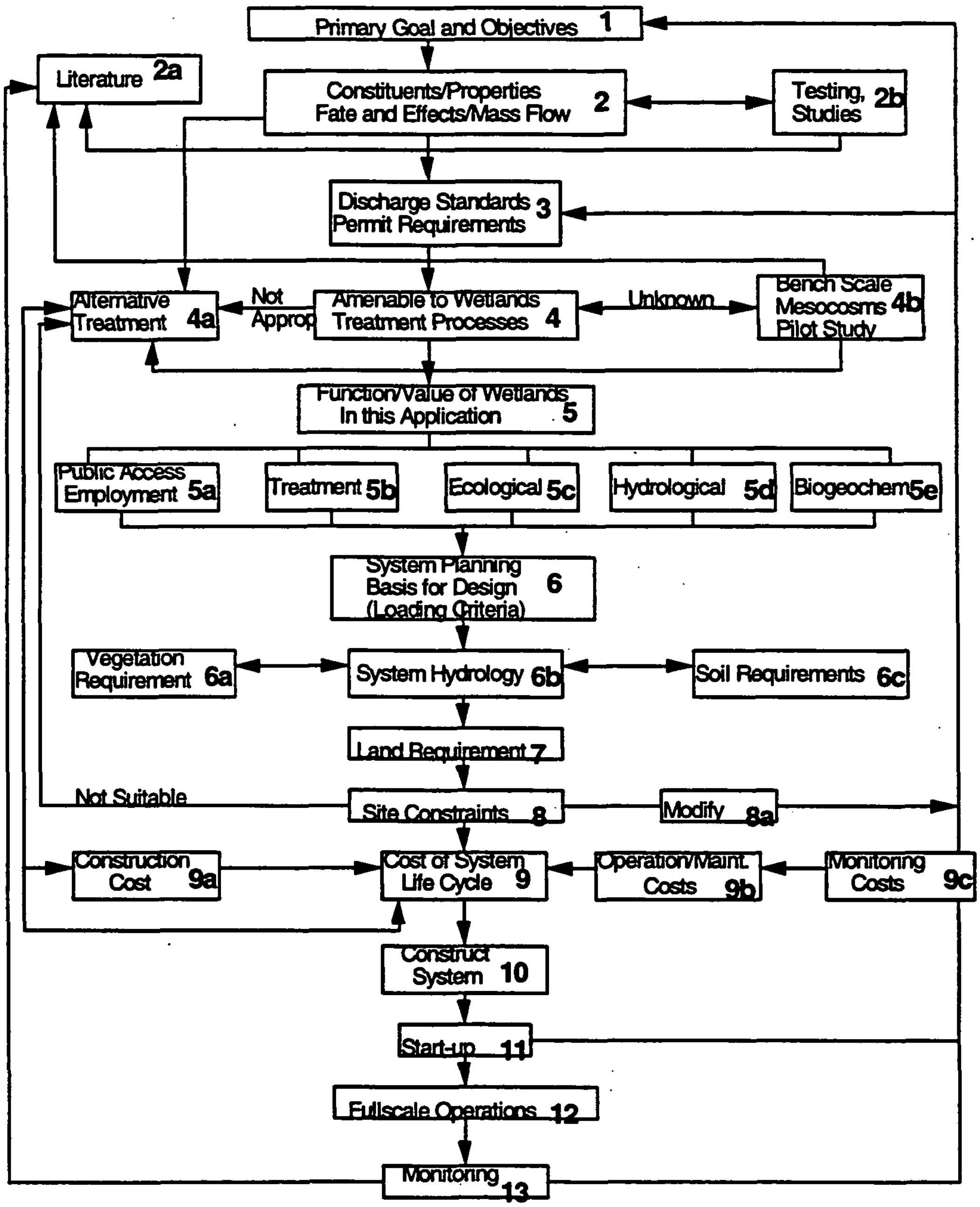
Step 5 - Identify the roles the wetland can fulfill in the watershed given the constituent concentrations and treatment goals imposed upon it. Certain wetland roles may not be appropriate due to factors such as loading variations, types of constituents, and site location. The function and value of wetlands such as ecological (habitat/production), hydrological, biogeochemical, and educational can be important in determining the economic costs or benefits of the system.

Step 6 - Evaluate the site characteristics and constraints. The planning and design of a system is site specific. Once the type of system and the treatment goals have been established, the soil, vegetation, and hydrologic conditions necessary to achieve these goals are identified. The inherent characteristics of the site should be evaluated and compared to these requirements to determine the need for modifications and additions.

Step 7 - Determine the FWS wetland area required to achieve the treatment objectives. For planning purposes, the methods described in this section can be used to estimate the area required to achieve the treatment objectives identified in Step 3.

Step 8 - Evaluate alternate sites. The land capacity in terms of quantity and quality must be compared between alternate sites and technologies based upon constraints and capabilities.

FIGURE 5-1
Diagram of a methodology for determining the appropriateness of the use of a constructed wetland and the factors necessary for the design of a multi-use constructed free surface wetland.



Step 9 - Estimate the total cost of the system. The life cycle cost is a function of capital cost, and operational/maintenance cost distributed over a predetermined time base. The computed life cycle cost can be compared with alternative treatment systems or can be used to determine cost effectiveness and benefit/cost analyses. The value of the additional benefits, such as habitat, recreation, flood control, and water resource, should be included in the development of a total cost for the system.

Step 10 – Develop construction and wetland system development plans. Wetland systems have several major differences from the construction of a conventional wastewater treatment plant. The primary difference is that aquatic macrophytes take time to develop into the requisite standing crop to support the treatment processes. The soils which support these plants are also critical to the start-up of the system. Preparing bid documents for the planting and maintenance of aquatic macrophytes should include the skills of a landscape architect and/or botanist with related experience. FWS constructed wetlands must also include flexible hydraulic controls for operational tasks such as isolating and draining cells. Inlet and outlet location and configuration is critical to maximize treatment efficiency.

Step 11 - Plan the system start-up. The start-up of a wetland system might require changes in the hydrodynamics and density of vegetation. The start-up period for FWS constructed wetlands takes from 18 to 36 months because it takes time for the plants to reach operational density. The discharge permits for a wetland must reflect the lag time necessary to develop the standing vegetation to support the treatment processes.

Step 12 – Full scale operation requires placement and density of aquatic plants, inlet and outlet control structures, design hydroperiod, and design HRTs. The full scale operation should have established background levels of soluble BOD, COD, ammonia nitrogen, etc. Full scale operation could include procedures to store and/or drawdown the wetland system in anticipation of discharge constraints and/or peek monthly flow conditions. Procedures for control of vectors and nuisance mammals, vegetation management, etc., should be developed and ready to implement.

Step 13 – Daily monitoring of influent flow and effluent flow and monitoring at minimum monthly average (weekly samples) BOD, TSS, coliform and others (ammonia, nitrates, etc.). The vegetation coverage should be monitored annually along with the detrital accumulation (TSS and plant detritus, and hydroponic floating litter layer). An inspection of the hydraulic integrity of berms, inlet and outlet works, and bottom (if required) should be performed annually. Under certain conditions monitoring for mosquito larvae and adults might be required during the mosquito breeding season. Other nuisance organisms such as nutria, beavers, and muskrats need to be monitored monthly to optimize their effect on carrying capacity of populations in the system. These organisms might have an effect on effluent quality and wetland performance, in which case they might require management.

Additional Benefits/Habitat Considerations

Designers interested in providing habitat value in FWS treatment wetlands have had to turn to the ample literature on wildlife management to find clues to optimizing wildlife use. There is a significant amount of published and unpublished literature on habitat richness and wildlife populations in FWS treatment wetlands, but these data have not yet been assembled and correlated to wetland design criteria to elucidate relationships. A treatment wetland habitat database is currently being prepared with funding from EPA's Environmental Technology Initiative to begin to fill this information void (Knight, in preparation, 1999). A document published by EPA (USEPA 1988b) provides a general description of the habitat features of 17 treatment wetlands in the United States. USEPA has published a book on Created and Natural Wetlands for Controlling Nonpoint Source Pollution which has chapters on habitat considerations (USEPA, 1993). The habitat quality of two FWS constructed wetlands was evaluated by the EPA's Environmental Research Laboratory in Corvallis, Oregon (McAllister, 1993).

Effluent Quality Considerations

Free water surface constructed wetlands produce a wide range of effluent qualities, depending on the influent characteristics, constituent operational loading rates, climate, and areal extent of the system. When designed and operated properly, FWS constructed wetlands perform within a predictable range of effluent values and meet their permit limitations. The limitation to using FWS constructed wetlands as a wastewater treatment system is the background concentration of constituents produced by the loading and internal wetland processes.

The natural background concentrations of BOD, COD, turbidity, total phosphorus, total nitrogen, and total and fecal coliform will control the effluent quality achievable using FWS constructed wetlands. The natural variation in the effluent from FWS wetlands is unique to each site and dependent upon the inlet/outlet configuration, hydroperiod, and seasonal factors controlling detrital decomposition, wildlife activity, and constituent influent loading. The natural cycle of nutrients and the potential re-release of constituents incorporated in the wetland biomass must be considered in the effluent permit requirements for FWS constructed wetlands. In most cases, nutrient cycling and release follows seasonal patterns. The seasonal cycle of decomposition release or reduced microbiological conversion is often synchronous with the critical water quality requirement for the receiving waters. For example, seasonal ammonia standards are often specified to protect receiving waters during periods of warm temperatures and low flow conditions. These conditions often occur during periods of high biological ammonia uptake in the wetland resulting in the highest rates of ammonia removal. A similar situation often applies for phosphorus. Soluble phosphorus releases occur during the non-growing season (low plankton standing crop), whereas some fraction of the soluble phosphorus is incorporated into the plant material during the growing season.

In the case of coliform effluent standards, seasonal increases in coliform bacteria (total and fecal) may result from high bird populations in the wetland. If disinfection is required, the potential increase in wildlife populations in and near FWS constructed wetlands needs to be taken into consideration and may require seasonal permit exceptions. The extent and placement of open water, prime habitat for migrating waterfowl, is an important factor in minimizing increased coliform counts in the effluent.

Wetland Treatment System Objectives

The required effluent quality from a FWS constructed wetland is specified, in most cases, by the state water quality control regulatory agency. The effluent limitations are based upon 1) receiving water beneficial uses and, to some extent, by the receiving waters hydraulic and biogeochemical assimilative capacity and 2) by reuse and reclamation guidelines specified for various reuse options. While FWS constructed wetlands have been shown to be effective wastewater treatment processes, they do have treatment limitations due to factors such as seasonal nutrient cycling, plant decomposition, and bird activity. These limitations must be considered in both the design and the permitting of these systems.

Another critical treatment objective consideration is the discharge point of the effluent. Most FWS constructed wetlands discharge to surface waters, but a leaky FWS constructed wetland can be designed to serve as both a treatment and disposal system. Infiltration wetlands are designed to combine the horizontal processes in the FWS constructed wetland with the vertical processes through the sediment and soil to meet water quality objectives for either groundwater infiltration or surface water discharge. Examples of infiltration FWS constructed wetlands performance can be found in the Hillsboro, OR, data and the Orange County Water District, FL, wetland demonstration project.

Permitting

A major constraint on the use of many natural marshes is the fact that they are often considered part of the receiving water by regulatory agencies (Reed et al. 1995). As a result, wastewater discharged to a natural wetland has to meet discharge standards prior to application. In Arcata, this obstacle was avoided by taking advantage of the "enhancement" clause of California State law regarding water quality, in which wastewater application can be allowed if enhancement of the existing wetlands can be shown. The distinction between natural and constructed FWS wetlands is not always clear, and the barriers to using natural FWS wetlands for treatment may also be applied to constructed FWS wetlands.

Historically, the use of natural wetlands in wastewater management in the Southeast occurred because of convenience or the lack of other reasonable alternatives. Only in the past decade have wastewater management systems incorporated design elements to optimize the wastewater renovation capabilities of wetlands. The use of natural wetlands for wastewater management may not be appropriate in many cases. Most situations will require site-specific analyses to determine site feasibility and acceptability based on existing natural wetland type, size, condition and sensitivity. In general terms, the use of natural wetlands should be avoided when:

- The wetlands being considered are pristine wetlands and representative of unique wetland types;
- Projected impact to the wetlands would result in changes that would threaten the viability of the system; and
- Conflicts with other uses could not be mitigated adequately such as adjacent land use activity, availability and cost of land.

Most natural wetlands are waters of the U.S. These wetlands are either adjacent to other waters of the U.S., or whose use, degradation, or destruction could affect interstate or foreign commerce, and as such are afforded protection under the programs of the Clean Water Act. Additionally, other wetland protection programs must be considered when evaluating the use of natural wetlands. Under the Clean Water Act, the four programs that can directly or indirectly affect wetland wastewater management decisions are:

- Construction Grants (Section 201)
- Water Quality Standards (Section 303)
- National Pollutant Discharge Elimination System (NPDES) Permits (Section 402)

- Discharge of Dredge/Fill Permits (Section 404).

For each program area, there are existing specific program regulations, guidance and procedures. However, the use of wetlands for wastewater management has not been addressed specifically by any program, and clear guidelines do not exist. Minimum criteria relating to waters of the U.S. that can be applied to wetlands discharge require that:

- Water quality standards be maintained;
- A minimum of secondary treatment is required for discharges from municipal treatment facilities to natural wetlands considered waters of the U.S.;
- An NPDES permit is required for each discharger; and
- A 404 Permit would be required for the discharge of dredge and fill material into wetlands.

The regulations for the U.S. Environmental Protection Agency's (EPA) three major wastewater management programs (Water Quality Standards, NPDES Permit, and Construction Grants) are designed for facilities discharging to lakes, streams, rivers, estuaries or other free-flowing surface waters. Wetlands are different from these aquatic systems due to their nature as a transition between fully terrestrial and fully aquatic systems. As such, wetlands are often hydrologically slow-moving systems, as opposed to the free-flowing nature of most streams and rivers. Additionally, the functions and use of wetlands cover a broader range of ecological, water quality, and hydrological values. Because the regulatory guidelines and programs developed under the Clean Water Act's wastewater management programs did not acknowledge or address specific wetland considerations, they usually are not applicable to wetland wastewater management systems.

Although wetlands that are waters of the U.S. cannot be classified for "waste transport," they can be used in wastewater management as long as established uses are protected. Many wetland functions and values (e.g., storm buffering, water storage), however, are not covered by existing use classifications. Additional qualitative or quantitative criteria addressing wetland characteristics (e.g., hydroperiod, water depth, seasonal influences) may be necessary and appropriate to protect wetland uses.

Section 402 of the Clean Water Act authorizes EPA and delegated states to administer the NPDES Permit Program. This program requires a permit for the discharge of pollutants from any point source into waters of the U.S. Therefore, the discharge to wetlands that are waters of the U.S. or from treatment wetlands into waters of the U.S. requires the issuance of an NPDES permit.

Important elements of the permitting process include the application process, establishing effluent limits, establishing permit conditions and requirements, permit issuance, and compliance monitoring. Alternatives which accompany the application for the NPDES permit for wetland wastewater systems include the use of a tiered approach for information requests and monitoring requirements based primarily on wetland types and hydraulic loadings. The use of performance criteria as a permit requirement to monitor wetland and downstream water quality is also suggested.

An important step in establishing effluent limits is determining whether the stream segment (or in this case the wetland) to which a discharge is proposed is classified effluent limited or water quality limited as defined by EPA (1985). A stream segment that is effluent limited requires best available technology or secondary treatment. A stream segment that is water quality limited requires greater than secondary treatment. The task of establishing effluent limits in water quality limited situations is not straightforward. The use of water quality models may not adequately predict wetland responses to wastewater discharges and the use of an on-site wetland assessment will likely be necessary. The qualitative results of an on-site assessment then need to be related to quantitative or qualitative effluent limits.

Public Access

The ancillary benefit of wetland and riparian habitat associated with free surface constructed wetlands has given some communities the opportunity to allow total or limited public access to the wetland treament facility. These ancillary (or value-added) benefits have allowed some communities to extend the public and environmental services of the wetland to other uses. Ancillary benefits include but are not limited to passive recreation, environmental education, green belts, mitigation wetlands, etc. Various states have their own guidelines and regulations concerning public access to wastewater treatment facilities. The addition of a passive recreation and/or an environmental education facility has in many cases greatly enhanced the local and regional visibility of the project. This visibility and usage has in most cases resulted in community support related to the wetland treatment concept as well as for the community environmental service efforts, i.e., watershed planning, stormwater management, riparian/wetland corridors, etc.

Requirements placed on public access vary considerably from site to site even within the same state. In California for example, Arcata allows 24 hour, 365 day access to the Arcata Marsh and Wildlife Sanctuary, while Hayward does not allow any public access except for environmental education visits, by appointment only. Much of these differences are due to the demographic and geographic settings of the two sites. Hayward is a highly urbanized area with no direct community management. Arcata, on the other hand, is a mostly rural area in where intensive volunteer involvement and management efforts exist.

Public access which does not disturb wildlife is generally considered to be a favorable component of a project. Careful planning and design of a system can minimize human disturbances while maximizing the habitat value.

Hydrological Considerations

FWS constructed wetlands have been utilized successfully in a wide range of hydrologic, climatic and geographic settings, establishing the general utility of FWS constructed wetland systems over the same array of locations and conditions. However, although these systems are robust enough to operate under a variety of conditions, consideration must be given to the effects of local conditions on the performance. When possible, these local condition effects need to be mitigated by design constraints.

Precipitation and Evapotranspiration

As described in Section 3, precipitation and evapotranspiration affect the performance of FWS constructed wetlands by altering the concentration of constituents in the wetland and by changing the volume of water transported through the wetland. In areas of high rainfall or during periods of high rainfall, the precipitation accumulation in the wetland can dilute the effluent concentration and reduce the hydraulic residence time (HRT). High evapotranspiration rates act in the opposite manner, concentrating the effluent water quality constituents and increasing the HRT.

In the arid regions of the United States, the monthly net loss of water can be as much as 25-400 mm. At typical hydraulic loading rates of 50 to 80 mm/d, the loss of water can concentrate the dissolved constituents 10 to 25 percent. At the same time, the nominal hydraulic residence time would increase proportionally. The opposite effect is observed in the wetter regions of the United States.

In regions with long dry periods, dramatic increases in coliform bacteria, total suspended solids, ammonia, and turbidity can occur at the start of the wet season. These increases in water quality constituents are due to bird fecal material and other particulates being washed off the plants and into the water column at the beginning of the rainy season.

Groundwater

Free water surface constructed wetlands are normally designed to be isolated from underlying aquifers. For site design, the elevation of the seasonal high groundwater table and direction of predominant flow should be determined to ascertain potential problems with interception or berm failure. In the case of unlined FWS constructed wetlands designed to discharge through infiltration, groundwater monitoring will be necessary to measure constituent concentrations and hydraulic effects of the discharge.

Ice and Snow

In areas of significant snow cover or thick ice formation, free board is made available in FWS constructed wetland design and operation to allow the ice cover to serve as insulation over the water column. Ice formation requires an increase of 300 to 500 mm in the operating depth to maintain the design water column depth. Operationally, it is also important to prevent the presence of an air gap between the water surface and the bottom of the ice layer. An air gap may allow a second layer of ice to form on the new water surface, complicating the system hydraulics. In some cases, better effluent quality is obtained in the colder months due to the lack of external factor effects (wind, wildlife, etc.) and seasonal low contributions from internal sources such as plant litter and solids decomposition.

Engineering Considerations

Pre-Treatment Requirements

FWS constructed wetlands have pre-treatment requirements similar to other biological wastewater treatment processes. Floatable solids and large settleable solids should be removed from the influent wastewater. Excessive levels of oil and grease should be avoided. Specific constituents or constituent loadings that may upset biological processes should receive pre-treatment. The influent delivery system should be designed to distribute evenly the incoming solids loads across the wetland cross-section to maximize the treatment volume available to remove settleable and suspended solids.

Also important to a FWS constructed wetland is the incoming metal concentrations. While a FWS constructed wetland can remove and immobilize many heavy metals, the same limits that apply to receiving waters should apply to FWS constructed wetlands influent to prevent metals accumulation. A source reduction program and an industrial waste pretreatment ordinance are required if significant metals concentrations are present in a wastewater.

Soils, Slope and Subsurface Geology

The principal soils considerations in siting and implementing a FWS constructed wetland are the infiltration capacity of the soil and its suitability for berm construction. In most cases, FWS constructed wetlands are required to meet stringent infiltration restrictions. Specifications of infiltration losses from wastewater ponds and wetlands range from 1×10^{-9} to 7×10^{-6} mm/s depending on the state regulations for construction and groundwater protection. Systems designed to incorporate infiltration as part of the treatment and discharge process of the plant are an exception. In these cases, the underlying soil must have infiltration rates compatible with the design rates of discharge. In both cases, the native soils may need amendment or restructuring.

An additional soil consideration for FWS constructed wetlands is the suitability of the soil to wetlands plants. Aquatic macrophytes generally reproduce asexually by tuber runners. Soils with high humic and sand components are easier for the tubers and runners to migrate through and plant colonization and growth is more rapid.

FWS constructed wetlands can be built on sites with a wide range of topographic relief. Construction costs are lower for flat sites as highly sloped sites require more grading and berm construction. With proper design, high slope sites can possibly reduce pumping costs by taking advantage of the existing hydraulic gradients.

Percolation and Use of Liners

If the native soil does not have sufficiently low infiltration rates, amendment with clay or soil binders can be used. Another option for minimizing infiltration is installation of a geosynthetic membrane beneath the system (Kays 1986). Both of these requirements can add significantly to the construction cost of a FWS constructed wetland. Clay liners are generally more effective and a more sustainable component of the wetland structure than the geosynthetic membranes.

Inlet/Outlet Types and Placement

The hydraulic response of a FWS is dependent on several factors: vegetation type, amount and location, geometry of the system (especially as it might relate to dominant wind directions and velocities), and the type and location of the inlet and outlet works.

The distribution system should insure a uniform distribution of the influent normal to the direction of flow. This can be accomplished in several ways. One technique is a manifold which extends across the inlet zone with adjustable ports located every meter or so. Another technique is to have several large inlet weirs (control that allow to shut off the flow) which discharges into a mixing volume which extends across the entire entrance of the wetland. This area tends to be deeper to minimize emergent plants and to insure an even distribution of the influent through the aquatic plants in the wetland.

The outlet works can also be of several types. The outlet works serve both as water level controls and as collection points for the effluent. No work has been done comparing the various types of weir structures and locations as they relate to effluent quality. Geometry of the wetland cell has a lot to do with the number and type of inlet weir structures. In general, weir structures are placed every 8 to 25 m along the effluent receiving zone of a FWS constructed wetland. Similar to the influent collection/distribution zone, some systems have effluent collection volumes which then flow to a weir collection/control structure. This type of system tends to produce variable TSS and coliform as both algal population and wildlife are attracted to this deeper clear water volume. Best successes have been observed where the aquatic plant communities are more or less contiguous with the effluent zone/control structure. Extremely high weir overflow rates in this type of system suggest that increasing total weir length might assist in improving effluent quality.

Wildlife/HabitatConsideration

A FWS constructed wetland utilized for treating municipal wastewater can also function as wildlife habitat, and in some cases constructed wetlands are being designed with wildlife habitat creation as a secondary or primary goal. This approach is similar to the role in which oxidation ponds are used by waterfowl and wildlife. Constructed FWS wetlands can provide incidental support of wildlife, or it can be enhanced by considering certain factors which encourage and support a wide range of wildlife communities. In the case of FWS constructed wetlands, the amount of openwater area and the types of submergent and floating macrophytes are positive habitat factors. The proportion and location of open water areas can also affect wetland effluent water quality. Based on pilot project work performed in Arcata, California (1986), which was subsequently used to design enhancement wetlands, it was shown that having 25 to 70 percent of the water surface dominated by submergent and floating macrophytes allows optimal water quality and habitat enhancement objectives to be met.

Another important design consideration for wildlife habitat is the inclusion of islands with low sloped sides. Waterfowl and shorebirds can use the islands for feeding, nesting and rest areas. Slopes of 1:4 to 1:10 around the island will encourage shallow zoned aquatic plants, while allowing easy access for aquatic fowl. Islands have been used effectively in many wetlands to support resident and migrating bird populations.

Environmental Impact

Planning level considerations for the possible use of FWS constructed wetlands are important in communicating advantages and disadvantages of these types of wastewater treatment systems to clients, community members, and regulatory officials.

Land Use

The first major consideration for the use of FWS constructed wetlands is the land requirement and issues associated with general plans and zoning restrictions. Depending on the size of the community and the land uses adjacent to the community, these could represent constraints or time consuming requirements. Several possible strategies could be employed to expedite these issues. One successful strategy is to highlight the major advantages of FWS constructed wetlands; the multiple land use activities that can be assigned to their footprint. Overlays of land use activities, such as: parks, passive recreation, wetland habitat, environmental education, green belts, possible wetland mitigation, open space, and viewshed corridors increase the public value of FWS constructed treatment system. This beneficial impact can assist in mitigating the cost of the land for wastewater treatment.

Insect Vectors

Potential problems with insect vectors, particularly mosquitoes, are another major concern. Wetlands are prime habitats for mosquitoes and black flies, and are habitat for most of their major predators. Proximity of the wetland to houses and areas of intense use can become a siting constraint. For the most part, mosquitoes do not fly more than a 400 m from their breeding area. However, under certain circumstances, wind direction and speed can disperse mosquitoes and black flies distances farther than 400 m. Regardless of location, mosquitoes will be present at some time of the year in any FWS constructed wetland. Serious consideration should always be given to implementing integrated pest management to control mosquito populations. Integrated pest management requires measures such as introducing natural adult mosquito predators (dragonflies and damsel flies, bats, swallows, frogs), larva predators (mosquito fish, guppies, three spine stickleback, aquatic insect larva), growth inhibitors (methoprene), and parasites (Bti). Chemical adultcides (pesticides) are not generally required to manage mosquitoes populations.

Odors

A FWS constructed wetland will have a seasonal odor associated with the normal decomposition of plant material and incoming settled solids. These odors will be more or less concentrated around the wetland as a function of micrometeorological factors such as wind speed, humidity, and lapse rate close to the surface. The odors associated with a FWS constructed wetland are not the same type or magnitude as the odors associated with a wastewater treatment plant. Hydrogen sulfide is the predominant odor mixed with gaseous by-products of actinomycetes. The large area over which the odor is released tends to keep the concentration low, easily diffused, and dispersed. Odors can also develop if the influent wastewater is not properly introduced into the wetland.

Wildlife and Ecological Attractive Nuisances

While one of the major potential objectives of a FWS constructed wetland is to provide habitat value, some concerns are often voiced about the potential for attracting endangered species. At the present time there is mixed information related to this issue. There is no state or federal law that exempts constructed wetlands from Endangered Species Act issues. There are examples where wastewater discharges support the habitat for endangered or listed species (e.g., pupfish in China Lake, California). For the most part it is considered a net gain if a FWS constructed wetland becomes habitat for an endangered species. Oxidation ponds function similarly in many arid regions.

A FWS constructed wetland that has been designed to provide habitat will attract wildlife. One major potential impact is the problem of attracting too large a population of migrating birds. If the wetland support large bird populations and water quality conditions conducive to pathogen survival exist, then potential disease problems develop (vibrio, clostridium). The disease potential is particularly a problem for several wetlands in the San Francisco Bay Area (Hayward Marsh). For example, Hayward Marsh is the only source of freshwater on the Bay perimeter and attracts large bird populations. Hayward Marsh has limited vegetation cover which results in a large extent of open areas for resting, watering and feeding. The potential for introduction and spread of disease in migratory bird populations can be minimized by diversifying the types of aquatic and riparian habitats and by having the flexibility to set the hydroperiod and flow rate into and out of the wetland.

Another major problem associated with constructed wetlands is the intentional release of domestic aquatic fowl and other domestic animals such rabbits, cats, and dogs. In the case of domestic ducks, their interbreeding with wild aquatic fowl presents a major wildlife problem. Feral cats may also be a significant problem as they feed on birds at the wetland. The issue of domestic species management requires advance plans be developed and implemented before problems escalate. Domestic animal control will frequently require capturing and destroying these animals.

Wetland Sizing

As FWS constructed wetlands became recognized as a viable wastewater treatment process, a need arose for FWS design models. These models aid engineers in the process of FWS wetland design and performance assessment (e.g. wetland area requirements and effluent quality predictions).

Approaches to Sizing

The current trend in wetland design modeling is the development of simple mass balance or input/output models. These simplified models do not explicitly account for the many complex reactions that occur in a wetland, either in the water column or at interfaces such as the water/sediment interface. Instead, all reactions are lumped into one overall reaction rate parameters that can be estimated from FWS wetland input/output data. At this stage of wetland model development, more complex and theoretical wetland models in which the kinetics of known wetland processes are described explicitly are not possible, due to limitations in the existing wetlands data.

To date, a number of wetland design methods have been proposed for predicting constituent removals in FWS wetlands. The methods include four fundamentally equivalent design relationships and equations presented by Reed et al., (1995), Kadlec and Knight (1996), Crites and Tchobanoglous (1998). The design relationships and methods have been used to predict the reactions (degradation or generation) of BOD, TSS, TN, NH_4, NO_3, TP and coliform. The four design relationships are summarized in Table 5-1 along with two new relationships proposed by Gearheart et. al. (1998). Regression equations have been used to summarize system performance for a wide variety of constituents and physical parameters. General loading relationships have been used to predict removals for TSS, BOD, nitrogen, phosphorus and coliform. An estimate of the wetland surface area can also be made by rearranging the relationships to solve for wetland area given constituent removal goals.

To utilize one of the FWS design relationships or methods, it will be necessary to estimate or assume various parameters. Generally, the influent concentration, the expected or desired effluent concentration, and the flow rates are known from project goals and/or previous work. However, the remaining parameters will need to be estimated from pilot project studies or assumed from literature values.

Assessment of Predictive Equations

In most of the existing FWS wetland design relationships, it is assumed that the hydraulics of FWS wetlands can be approximated by a plug flow reactor (PFR) model and the reactions of constituents are described by first order reaction kinetics. The use of the PFR to approximate the wetland hydraulics appears to be generally accepted by the wetland modeling community. However, there is ongoing debate over the appropriate form of the first order reaction rate constant.

The general relationship, assuming steady-state plug flow hydraulics and first order constituent removal, is:

$$\frac{dC}{dt} = -k_{app}C \qquad (5\text{-}1)$$

where: C = pollutant concentration (m/L^3),

t = mean hydraulic detention time (t), and

k_{app} = apparent first-order rate constant (t^{-1}).

TABLE 5-1
Equations used to compute the performance of FWS constructed wetlands

Formula	Type	Definition of Terms
Reed et al. (1995)	Volumetric	A = fraction of BOD not removed as settleable soids near headworks of the system, a variable depending on water quality (decimal fraction)
$\frac{C_e}{C_0} = \exp(-k_V t)$		A_W = total surface area of the wetland (m^2)
		α = Delaying constant, temperature-dependant
		C_D = background BOD concentration contributed by decaying plants (g/m^3)
Kadlec and Knight (1996)	Areal	C_e = effluent BOD concentration (g/m^3)
$\frac{(C_e - C^*)}{(C_0 - C^*)} = \exp\left(-\frac{k_A t}{q}\right)$		C_0 = influent BOD concentration (g/m^3)
		C_1 = BOD concentration due to solubization of TSS and residual total BOD (1 to 65 days)
		C^* = background BOD concentration (g/m^3) curve-fitting parameter
Retardation Model (Crites and Tchobonoglous, 1998, Gearheart, 1999 [in preparation])	Volumetric BOD only	ε = porosity of system (decimal fraction)
$C_e = C_0 e^{\left[\frac{-k_V t}{(1+\alpha t)}\right]} + C_D$		k_{AT} = temperature corrected first-order areal reaction rate constant (m/yr)
		k_{VT} = temperature-dependent first-order rate volumetric reaction rate constant (d^{-1})
		K_{V1} = volumetric based solids/particulate BOD removal rate
Sequential Model (Gearheart, 1999 [in preparation])	Volumetric Two-rates BOD only	K_{V2} = volumetric based dissolved BOD removal rate – temperature-dependent
$C_e = C_0 e^{-K_{V1} t} + C_1 e^{-K_{V2} t} + C_D$		L = length of the system parallel to flow path (m)
		q = nominal hydraulic loading rate (m/yr)
		Q = average flow in the system (m^3)
		t = theoretical hydraulic detention time (d)
		t_T = adjusted nominal hydraulic residence time (d)
		V = volume of wetland (m^3)
		W = width of the system (m)
		y = average water depth in the system (m)

This differential equation has the exact solution:

$$C_t = C_0 \exp^{-k_{app} t} \quad (5\text{-}2)$$

where: C_0 = initial pollutant concentration at t = 0 (m/L^3).

The apparent first order reaction rate constant (k_{app}) may be a function of temperature and values are generally reported at 20° C. The k_{app} value can be adjusted to the desired temperature using a modified form of the van't Hoff-Arrhenius relationship:

$$k_T = k_{20} \theta^{(T-20)} \quad (5\text{-}3)$$

where: k_T = apparent first order reaction rate constant at T degrees C (t^{-1}),

k_{20} = apparent first order reaction rate constant at 20° C (t^{-1}),

θ = empirical temperature coefficient, and

T = temperature at which k_T is adjusted.

The FWS wetland predictive equations presented in Table 5-1 are derived from the general PFR model (Equations 5-1 to 5-3). However, each of the models uses different concepts and approaches in defining the general PFR parameters (i.e. k and t).

The Reed et al. (1995) and Crites and Tchobanoglous (1998) relationships incorporate the adjusted nominal hydraulic detention time (t) through the wetland, and an apparent first order volumetric reaction rate constant. To utilize these equations, the depth, porosity and average flow through the wetland is required. The background pollutant concentration (C*) is not directly incorporated into these equations, but can be included as a boundary condition (implied lower limit on effluent concentration) of the model.

The relationship proposed by Kadlec and Knight (1996) is based on the nominal hydraulic loading rate (q) to the wetland, and a temperature dependent first order *areal* reaction rate constant. For some constituents, such as BOD, Kaldlec and Knight report that the areal reaction rate constant is not temperature dependent. In this model the depth, porosity and water losses and gains through the wetland are not required, but lumped into the first order areal reaction rate constant. Also, the background pollutant concentration, C*, is directly incorporated into the model equation.

Areal Loading Rate Method

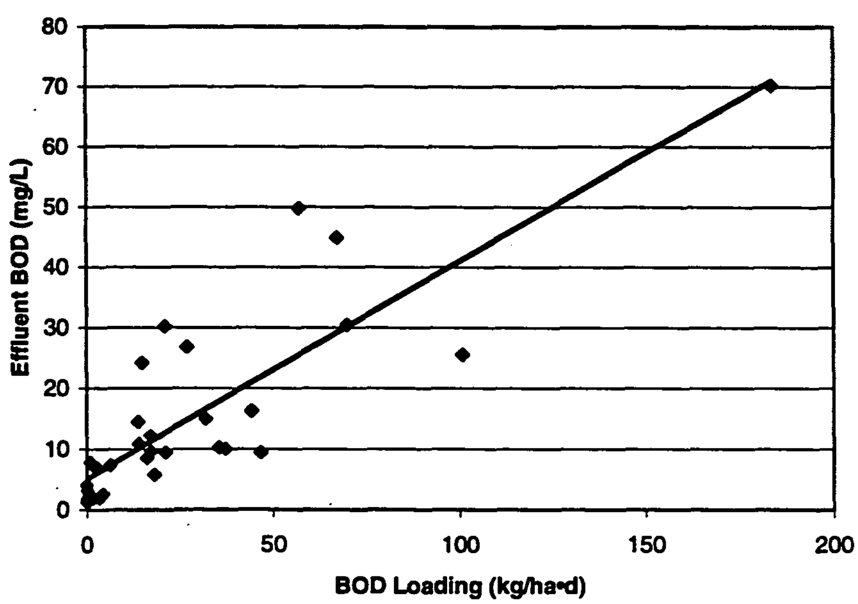
In the areal loading rate method, a maximum loading rate per unit area for a given constituent is specified. The use of loading rates is common in the design of oxidation ponds. Areal loading rates can be used to give planning level surface area estimates for FWS constructed wetlands from projected pollutant mass loads. Areal loading rates are also used to check a FWS wetland designed using one of the above mentioned design models to ensure that the wetland is not overloaded. A range of typical influent concentrations, target effluent concentrations, and constituent areal loading rates for FWS wetlands are listed in Table 5-2. The suggested values given in Table 5-2 are based on the data from the FWS wetland systems listed in Table 2-5. The areal loading rates can also be used to give a preliminary estimate of the FWS wetland surface area required for a given constituent loading, and can also be used to check wetland areas determined from equations in Table 5-1.

A typical areal loading design curve based on the long term average performance of systems listed in Table 2-5 is shown in Figure 5-2. Knowing the areal loading rate, BOD effluent concentration can be estimated from or compared to the long term average performance data of full scale operating systems.

TABLE 5-2
Range of areal loading rates for FWS constructed wetlands

Constituent	Typical Influent Concentration (mg/L)	Target Effluent Concentration (mg/L)	Loading Rates (kg/ha·d)
Hydraulic loading rate (mm/day)	10-100		
BOD	5 - 60	5 - 20	10 - 50
TSS	5 - 60	5 - 20	10 - 60
TN	2 - 20	1 - 10	2 - 10
NH_4	2 - 20	1 - 10	2 - 10
NO_3	2 - 10	0.5 - 3	1 - 5
TP	1 - 10	0.5 - 3	1 - 5

FIGURE 5-2
Annual average BOD concentration vs. annual average areal BOD loading rate for NADB systems



Design Approach to Sizing

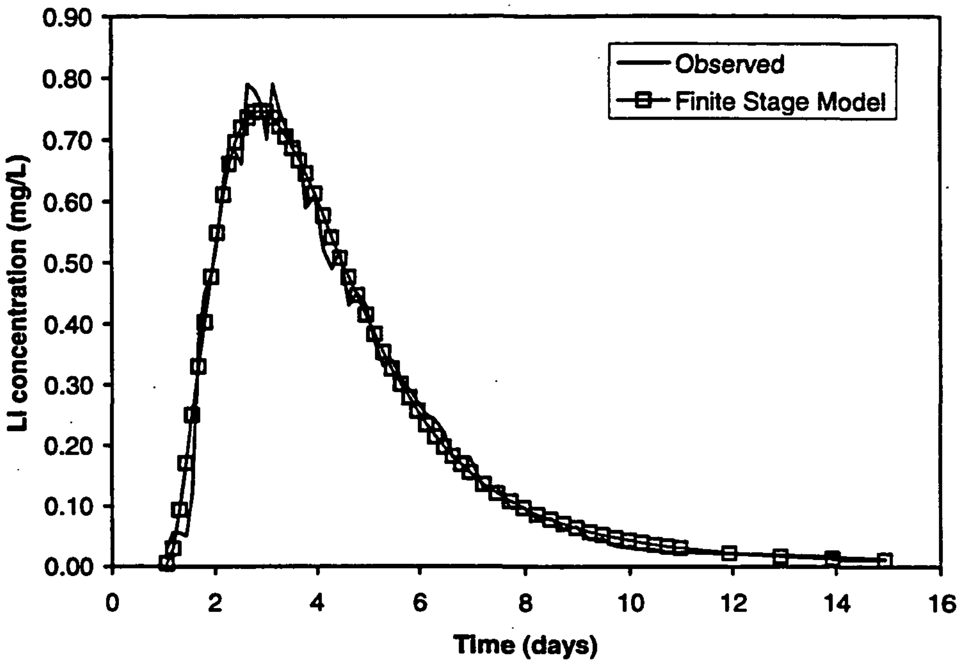
The approach to design of free surface constructed wetlands should consider a wide range of local factors as well as general operational experience gathered on these systems. Design equations used to size FWS constructed wetlands summarized in Table 5-1 require the estimation of one or two parameters. Based upon observed data summarized in Chapters 3 and 4, best fit parameter values vary greatly from site to site. The use of statistically derived national parameters suffer from the disadvantages discussed in Chapter 4. The equation parameters incorporate many factors and should be applied carefully when the setting and condition are different than those used to generate the parameters. As discussed in Chapter 4, most of the systems in the database were underloaded and therefore are over-designed in terms of areal requirement. None of the design formulas used to determine wetland areal requirements include the effect of inlet/outlet type and location and vegetation type and distribution, which are potential determinants in wetland treatment effectiveness.

The first order decay constant in all of the design equations is an apparent "k" value since it incorporates many factors including hydrological factors, temperature, solubilization factors, and removal/transformation processes. Over-designed wetlands mask the effect these factors have on the performance of most of the wetlands in the database. As more experience is gained from multiple celled and/or intermediate sample point systems, a more useful database for the removal constant values will be developed. At present, the approach to design should include using one of the equations given in Table 5-1 with the resulting area checked against the empirical areal loading rates given in Table 5-2. This design approach is detailed in the EPA Wetland Design Manual (EPA, 1999).

Though plug flow is assumed for the purposes of FWS constructed wetland design, the actual wetland flow hydraulics will not follow an ideal model. The deviation from plug flow of an existing FWS constructed wetland can be determined through the use of tracer tests. One of the important results of a tracer test is the determination of the tracer detention time, defined as the centroid of the response curve (Figure 5-3). The tracer detention time is equal to the active water volume divided by the volumetric flow rate, and thus represents a direct measure of actual detention time. Comparison of the theoretical to the actual detention time is an important tool for evaluating the performance of existing FWS constructed wetlands.

Because actual detention times are always less than the theoretical (plug flow) detention time, apparent removal rate constant estimates based on the plug flow assumption will be lower than the actual removal rate. Using an apparent removal rate constant from one system for a different wetland system with a different degree of actual to theoretical detention time can lead to serious over or under-designed systems. For example, using the tracer data shown in Figure 5-3, Treatment Marsh 1 (TM1) at Arcata has an observed hydraulic detention time of 84 hours. The theoretical detention time for this marsh is about 200 hours, nearly 250 percent longer. If an apparent removal rate constant computed based on the Arcata TM1 theoretical detention time is used for sizing a new system where the ratio of theoretical to actual hydraulic detention time is higher (say 3.5 :1), the new system will not meet performance expectations due to the relatively shorter actual detention time. The plug flow assumption is conservative in design if the degree of non-ideality (represented by the ratio of the theoretical plug flow to actual hydraulic detention time) in the designed system is less than that in the wetlands from which model parameters were determined (Hovorka, 1961). The degree of non-ideality should be similar in wetlands with similar geometry, vegetation patterns and hydraulic loadings. The treatment wetland literature typically provides only apparent plug flow k values.

FIGURE 5-3
Tracer response curve for Sacramento Cell 7 (Nolte and Associates 1997).



SECTION 6

Lessons Learned and Recommendations

A successful FWS treatment wetlands project requires that a number of other considerations be addressed which are just as important as the wetland process and design issues (e.g. water conveyance and wetland area) discussed earlier. Issues and considerations that are important in the implementation process for a FWS treatment wetland are described in this section. Items discussed include potential nuisance conditions, providing adequate open water/emergent vegetation areas, major components of wetland civil design and construction, issues surrounding wildlife enhancement wetlands, multiple benefits and public access, and general operation and maintenance considerations.

Information Management

New information from free water surface treatment wetlands is accumulating at a rapid pace. Between existing projects with ongoing monitoring programs and new projects that incorporate updated design features, the amount of useful information that could be applied to resolving technology issues is greater than can be accumulated and analyzed by individual wetland designers. Coordinated state or federal activities have not proven to be an effective method for keeping up with this accelerating information supply. The most useful information has been generated by well documented moderate to high loaded systems with cell by cell flow and constituent level data.

Databases provide a convenient method of accumulating and analyzing large amounts of treatment wetland design and operational data. Expansion, maintenance, and analysis of a FWS constructed wetland database is presented as a priority for future technology assessments. Research-level pilot studies provide the best method for testing the effectiveness of new treatment wetland design criteria. However, many pilot studies have failed to address new issues, and most have had such short operational periods that drawing general conclusions about the performance of a mature wetland from their data is difficult. New treatment wetland research efforts should consider focusing efforts on some of the key technology issues that have been identified in this report.

Planning

Multiple Benefits and Public Access

The general public rather than individual landowners primarily receive benefits produced by wetland areas. The wetland ecology, multiple benefits, and pubic access (birdwatching, walking, jogging, and picnicking) aspects of FWS constructed wetlands are one of the strongest endorsements for the use of this treatment process. The advantages of a multiple benefit investment in landuse can be a positive aspect of any FWS constructed wetlands project. These landuse types could include (1) parkland, (2) wildlife habitat, (3) environmental education, (4) open space, (5) greenways, (6) water reclamation storage, and

(7) landuse set aside for future public use and treatment. These overlays of multiple uses increase the societal value of the land investment made for treating wastewater. Public access is essential for communication and maintaining the multiple benefits of a FWS constructed wetlands project.

As a wastewater treatment system, FWS constructed wetlands have introduced a unique management opportunity. If the wetland system has multiple benefits, such as education, recreation and research, a public access policy needs to be developed specifying public use guidelines. Public access to a wastewater facility is normally restricted due to the potential risk associated with wastewater. Many states have specific regulatory constraints concerning public access to wastewater treatment facilities. Clearly, a paradigm shift must occur before full acceptance and consideration of FWS constructed wetlands can take place.

Some communities have successfully convinced regulatory agencies to allow full and/or limited public access to the wetland component of the wastewater treatment facility. Public access is provided for or encouraged at a number of treatment wetland sites, including Arcata, Hayward, and Martinez, CA; Cannon Beach, Oregon; Incline Village, Nevada; Phoenix, AZ; and Iron Bridge and Everglades National Park, Florida. Limited published data concerning public use of these sites are available, including a thesis (Benjamin 1993) in which it was reported that there are about 90,000 visitors per year over the 2,000-acre Hayward Marsh, and 140,000 visitors per year at the Arcata Marsh and Wildlife Sanctuary.

Environmental Education and Interpretation Centers

Wetland treatment systems present an excellent focus and facility for implementing community wide environmental education dealing with water conservation, pollution prevention, wastewater treatment, water reclamation, wetland ecology, watershed management, and energy conservation. The wetland site should be designed to incorporate public access (limited or full), esthetically pleasing viewsheds, riparian and upland fringe areas, and physical structures for interpretative purposes. All of these components can complement the wastewater treatment objectives of a city, and increase public awareness, protection and participation in their natural surroundings. One of the strongest cases for incorporation of these benefits can be seen in subsequent support for water quality and watershed protection requirements.

Some communities have constructed Interpretive Centers, which are the focus of much of the organized environmental education occurring at FWS constructed wetlands. Examples of interpretive centers can be found at Hayward Marsh, CA (East Bay Park District), and the Arcata Marsh and Wildlife Sanctuary, CA (Friends of the Arcata Marsh). Many other wetland systems have incorporated information signs into the trail system surrounding the wetlands for environmental education. Local education institutions typically use FWS constructed wetlands as a field trip site for biology, wildlife and engineering classes. In some communities, the wastewater utility forms partnerships with school districts to allow use of the wetland and center for environmental education. This component of a FWS constructed wetland allows for unique and creative sharing of resources and spaces to meet larger community needs.

Open Water/Emergent Vegetation Ratio

Providing adequate open water areas (open water/emergent vegetation ratio) is an important, but often overlooked, component in the design and implementation of FWS constructed wetlands. Historically, many FWS constructed wetlands were designed and built as fully vegetated basins with no open water areas. Many of these systems proved problematic with very low water column dissolved oxygen levels, that resulted in high odor production and vector problems, primarily mosquitoes.

Many natural wetlands contain a mix of open water and emergent vegetation areas. These open water areas provide many functions such as reoxygenation of the water column from atmospheric reaeration and algal photosynthesis, and habitat and feeding areas for waterfowl, as well as allowing for the predation of mosquito larvae by fish and other animals. Open water areas in FWS constructed wetlands will not only provide the same functions as for natural wetlands, but will also provide increased BOD reduction and nitrification of wastewater because of the increase in oxygen levels. It is recommended that a FWS constructed wetland not be vegetated fully, but should include some open water areas. Open water areas in a FWS constructed wetland will result in a more complex, dynamic, and self-sustaining wetland ecosystem, that mimics a natural wetland.

The ratio of open water to emergent vegetation depends on the function and goals of the FWS constructed wetland project. For constructed wetlands whose primary function is wastewater treatment, the location and amount of open water is a function of the nitrification requirement for that system. Open water (submergent and floating aquatic plants) supports nitrification processes while minimimizing the internal carbon load. If land area is at a minimum, and/or costs are to be kept low, then a minimal amount of open water area should be provided. However, if land availablility is not an issue, then a maximum amount of open water area can be provided. Recommended open water to emergent vegetation requirements range from 0 to 30 percent for treatment wetlands and 40 percent and greater for enhancement wetlands. While higher open water is desirable treatment wetlands can operate successfully at the suggested lower limits if land availability and construction cost are a major constraint. Generally,enhncement wetlands will be designed with large open water areas for waterfowl and other wildlife, and open water to emergent vegetation is usually not a concern.

Two methods can be used for creating open water areas: (1) excavate zones that are deep enough to prevent vegetation growth, and (2) periodically raise water levels to a depth that limits vegetation growth. Thus, wetland design and operation can also be used to control the types of plant communities that can exist in FWS treatment wetlands. The type of macrophytes (i.e. emergent, submergent, and floating) can be somewhat controlled by the design operating water depth. Water column depths of 1 to 1.5 m planted with submergents such as *Potamogeton spp.*, will not be encroached upon by emergent macrophytes like *Scirpus spp.* and *Typha spp.* If the water column depth is between 0.2 to 0.6 m and planted with emergent vegetation, such as like *Scirpus spp.* and *Typha spp.*, they will prevail over submergents and fill in the surface area through rhizome and tuber propagation. Alteration of water depth is a determining factor in establishing various aquatic macrophyte communities to meet both water quality and habitat objectives. A list of common wetland vegetation species and typical growing depths is included in Section 3.

Large open water zones that are not shaded by emergent or floating macrophytes can allow significant blooms of phytoplanktonic or filamentous algae to establish in FWS wetlands. However, if the open water areas are designed for less than 3 to 4 days open water travel time, then algal growth should not occur, as the growth cycle of algae is approximately 7 days. If open water zones are adjacent to the wetland outlet, the wetland may not be able to consistently meet stringent standards for BOD, TSS, or nutrients. For this reason, it is recommended that a large vegetated zone exist at the outlet of a FWS constructed wetland.

Site Topography and Soils

Pre-existing topographic, geological, and soil chemistry conditions can greatly affect wetland cost and performance. Excessive site topography creates large earthwork volumes for a given wetland area, significantly increasing wetland construction costs. Surface and subsurface geologic conditions can also increase costs by requiring removal of rock or by resulting in the need for liner materials to reduce groundwater exchanges. For the most part, level land with clay soils affords the best physical setting for a FWS constructed wetland. However, potential wetland sites with other conditions can be used, but may require more substantial engineering, earthwork, construction requirements, and the use of geotextile membranes.

Another consideration in the construction of a FWS constructed wetland is the soil required to support the emergent aquatic plants. The substrate for these plants should be agronomic in nature (e.g. top soil), well loosened, and at least 150 mm deep. If this type of soil exists at the site it should be scraped off prior to excavation and saved. After the wetland basin, berms and other earthen structures are constructed, and the liner is installed (if required), then the agronomic type soil can be placed back into the excavated region. This pre-conditioned substrate will greatly increase the rate of plant growth, and extent of plant community coverage.

Another concern regarding soils is elevated concentrations of organic carbon, organic nitrogen, or phosphorus, which may result in increasing concentrations (negative removal efficiencies) between the wetland inlet and outlet following system startup. This potential problem can be anticipated during design and managed effectively by initial batch flooding to allow desorption and refixation (SFWMD unpublished).

Hydrology

Wetland performance can be affected by hydrological factors. Some of these factors can be taken into account in the design of the wetland. For example, effluent values can be concentrated due to high ET rates as a result of overdesigning a wetland (areal requirement) in an area of high ET rates. Maximum ET rates for wetlands are in the range of 2-3 cm/day (Gearheart et al. 1993). For hydraulic loadings of 7-10 cm/day, the effluent values could be concentrated by 20 to 40 percent. High precipitation rates can both dilute and reduce the hydraulic retention times in wetland systems. For example, daily precipitation rates of 10 cm/day could dilute effluent concentrations by half at a hydraulic loading rate of 10 cm/day. These effects of the hydrological cycle on wetland effluent quality are for the most related to extreme values of ET and precipitation.

Infiltration losses can increase the performance of a FWS wetland by increasing the HRT in the system. Infiltration can also afford some level of treatment as liquid moves through the anoxic organic layer on the bottom of the wetland.

Wetland Hydraulics

Inlet/Outlet Structures

Placement and type of inlet and outlet control structures are a critical feature in FWS constructed wetlands. Within the general loading guidelines, control structures are the most important feature after shape, in terms of wetland treatment effectiveness and reliability. To minimize short-circuiting in a FWS constructed wetland, two guidelines concerning inlet/outlet structures are critical: (1) effective distribution of inflow across the entire width of the wetland inlet, and (2) the uniform collection of effluent across the total wetland outlet width. These guidelines will also minimize localized velocities around inlet/outlet structures, thus reducing potential resuspension of settled solids. It is important that any outlet structure be designed so that the wetland can be drained completely, if required. Listed below are some of the common types of wetland inlet/outlet systems in use today, and general guidelines regarding their design.

Two types of inlet/outlet structures are commonly used in FWS constructed wetlands. For small or narrow wetlands perforated PVC pipe can be used for both inlet and outlet structures. The length of pipe should be approximately equal to the wetland width, with uniform perforations (orifices) drilled along the pipe. The size of the pipes, and size and spacing of the orifices will depend on the wastewater flowrate and the hydraulics of the inlet/outlet structures. It is important that the orifices be large enough to prevent clogging with solids, but small enough to provide uniform distribution along the length of the pipe. Generally, the perforated pipes are connected to a manifold system by a flexible tee joint, which allows the pipes to be adjusted up or down. In some cases, a wetland with this type of inlet/outlet structure will cover the perforated pipes with gravel to provide more uniform distribution or collection of flows. This type of inlet/outlet structure requires some level of operation and maintenance to ensure equal flow through the pipe, to clean clogged orifices, and to maintain a level pipe alignment normal to the direction of flow.

For larger wetland systems, multiple weirs or drop boxes are generally used for inlet and outlet structures. Weirs or drop boxes are generally constructed of concrete. These structures should be located no greater than every 15 m apart across the wetland inlet width, with a preferred spacing of 5 to 10 m apart. The same spacing requirements apply for the outlet weirs or drop boxes. Depending on the source of the wastewater influent, the inlet weirs or drop boxes can be connected by a common manifold pipe, or directly to the wastewater influent source (a common arrangement for wetlands adjacent to oxidation ponds). Whatever the configuration, it is important that the hydraulics of the manifold and weirs be analyzed hydraulically to insure that uniform distribution occurs. Simple weir or drop box type inlet structures are relatively easy to operate and maintain, but generally provide less potential for solids settling in the inlet zone than a perforated pipe inlet with its axially distributed load.

Depending on the type of wastewater influent, the inlet structure outflow point can be located below or above the wetland water surface. Oxidation pond effluent, for example, which is high in algal suspended solids should be introduced near the surface to allow for maximum settling, autoflocculation, and predation to occur. Primary or secondary treated effluents should be introduced below the surface if flocculated solids are expected, or if oil and grease, and/or primary solids are expected. Perforated pipe inlet/outlet structures can be difficult to operate and maintain when they are submerged.

Outlet structures represent an operational control feature that can affect wetland effluent water quality. It is important that outlet structures have a wide range of operating depths. By adjusting the outlet structure, both the water depth and hydraulic detention time can be increased or decreased. The quality of wetland effluent found in the upper layers of the water column is generally of higher quality then water from lower depths, especially in terms of dissolved oxygen, TSS, BOD, and hydrogen ion (pH). However, the differences in water quality between water depths can be highly variable, and in some instances water from lower depths can be of higher quality then upper layers. An outlet structure design which allows for maximum flexibility of collection depths is recommended. With this type of design, the outlet structure can be raised or lowered to draw wetland effluent from the water depth with the best water quality.

Flow Measuring Devices

After analyzing the NADB it became apparent that many existing wetland systems do not have flow measuring devices. Even if accurate estimates of inflows and/or outflows to the treatment plant are known, internal flow distribution to individual wetland cells was not known or measured. Without accurate flow measurements to individual wetland cells, it is impossible to determine actual flowrates and hydraulic detention times to each cell, thus making flow adjustments difficult. It is recommended that some type of flow measuring device be installed in all FWS constructed wetland projects. Separate flow measuring devices should be provided on each inlet for multiple wetland cell configurations. Typical examples of flow measuring devices include simple 90° V-notch or rectangular weirs, and more sophisticated Parshall flumes. Depending on the size and layout of the wetland, flow measuring devices can and should be incorporated directly into inlet/outlet structures.

Internal Drainage

In the event a FWS constructed wetland needs to be drained, the wetland bottom should have a minimum slope of 1 percent to assist in drainage. Drainage may be required for maintenance reasons such as liner repair, vegetation management, and berm repair. Deeper channels may be required to allow for drainage and/or continued use when serial cells are taken out of service. Channels can also be used to connect deep water pools, which may have been designed into the project to afford open water for waterfowl. Culverts connecting internally constructed drainage channels can be used under submerged berms to allow for drainage through a wetland with varying water level elevations.

Internal Flow Pattern

Due to the low gradients found in FWS wetlands, water generally moves at very low velocities, approaching conditions of laminar flow (non turbulent flow). This type of flow regime produces quiescent conditions, an ideal situation for many of the physical, chemical and biological processes that occur in FWS wetlands.

Water does not flow through a FWS wetland in one continual flow direction or path. Instead, water flows through a complex maze of submerged vegetation, litter, peat and other obstructions (e.g. islands); forcing the flowing water to increase and decrease velocities and continually change direction. Water in open areas located away from submerged vegetation and/or accumulated bottom material is less subject to friction and generally moves at faster velocities than water located in densely vegetated areas. Open water zones are subject to wind-driven surface flows, which can move at higher velocities than water below the surface, and cause mixing to occur at different depths. Some areas of a FWS constructed wetland, such as corners and behind islands, may become isolated from the main flow path, creating pockets of dead space for which no or minimal water exchange occurs. The bottom topography may also form deeper pockets or pools, creating more dead space zones. The result is an internal flow pattern that is intermediate between the ideal extremes of plug flow and complete mixing.

All of these processes combined can cause water to flow through a FWS wetland in a shorter time period than defined by the theoretical hydraulic detention time (flowrate divided by wetland volume). In some extreme cases, such as a poorly designed wetland, water can flow at high velocities through a small portion of the total wetland volume, significantly lowering the hydraulic detention time: a phenomena known as short-circuiting.

Engineering

FWS treatment wetland construction has several planning issues based upon soil type, slope of the land, and cell configuration and shape. Other issues are associated with the civil engineering aspect of the design, such as impermeable barriers and liner materials, berm construction and specifications, inlet/outlet structures, flow measuring devices, internal drainage, sediment settling zone, and wetland planting. Many of these issues should be considered during the site selection process, as they may become difficult or costly to correct later in the actual design and construction of the FWS constructed wetland. For the most part, the construction/civil engineering requirements are similar to other earthen water quality management systems such as sedimentation ponds, oxidation ponds, and sludge lagoons. The more important construction/civil engineering design issues that need to considered in a FWS constructed wetlands project are as follows.

Berm Construction and Specifications

The height and width of berms or levees around FWS treatment wetlands is important for a number of reasons. First, the berms must be able to contain all design flows over a range of roughness conditions, including significant headloss through densely vegetated wetland cells with high aspect ratios. Secondly, the berms must be high enough to account for normal or excessive rates of solids deposition and peat building over the planned life of the wetland. The third consideration is the need to hold and release peak wastewater inflows, especially from collection systems with high infiltration and inflow rates or to planning storage for systems that do not discharge during periods of the year (typically winter). A fourth consideration is the need to protect berms from damage by animals and root penetration.

Berms containing FWS wetland cells are generally built with 3:1 side slopes, unless the soil characteristics allow for a steeper slope configuration, and a minimum of 0.6 m of freeboard above the average operating water depth. For wetlands that will receive high peak inflows, additional freeboard may be required to ensure that berm overtopping does not occur. All external berms should have a minimum top width of 3 m, which provides an adequate road wide enough for most standard service vehicles to operate on. In some cases, internal berms can have smaller top widths, as routine operation and maintenance can be carried out by small motorized vehicles, such as ATVs. Road surfaces should be of the all weather type, preferably gravel to minimize direct runoff into the wetland.

Berm integrity is critical to the long term operational effectiveness of FWS constructed wetlands. Common berm failures mechanisms include burrowing by mammals such as beaver and muskrat, and holes from root penetration by trees and other vegetation growing on or near the berms. Several design features can eliminate and/or minimize these problems. The insertion of a thin impermeable wall, or internal layer of gravel, can be installed during construction, which will minimize mammal burrowing and/or root penetration. Also, planting the berm using vegetation with a shallow root system can also be effective. Unlike oxidation ponds, berm erosion in FWS constructed wetlands from wave action is generally not a concern due to the dampening effect of the wetland vegetation.

In the design and site selection process, an important consideration is the amount of additional area required for berms. In general, the higher the length to width ratio for a FWS constructed wetland, the more area will be required for the berms and for the entire wetland system. This increase in required total wetland area to accommodate berms is more pronounced for smaller wetlands (less than approximately 10 ha) than for larger wetlands.

Wetland Configuration and Shape

There is substantial evidence, in both the design of oxidation ponds and FWS constructed wetlands, that a number of cells in series can consistently produce a higher quality effluent. This is based upon the hydrodynamic characteristics of "tanks in series", where constituent mass is gathered at the outlet end of one cell, and redistributed to the inlet end of the next cell. This process also minimizes the short circuiting effect of any one unit, and maximizes the contact area in the subsequent cell. It is generally recommended for treatment and water quality purposes that a FWS constructed wetland should consist of a minimum of 2 to 3 cells in series. The effects of headloss and inlet/outlet structures need to be considered for wetland cells in series.

The shape of a FWS constructed wetland can be highly variable depending on site topography, land configuration, and surrounding landuse activities. FWS constructed wetlands have been configured in a number of shapes, including rectangles, polygons, ovals, kidney shapes, and crescent shapes. There is no general data that supports one FWS constructed wetland shape as being superior in terms of constituent removal and effluent quality, over another shape. However, any wetland shape needs to be designed and configured following the general guidelines of this report, and other wetland design manuals. Design issues such as hydraulic detention time, short circuiting, headloss, inlet/outlet structures, internal configurations, etc., do significantly affect wetland effluent quality, and some wetland shapes can compound these problems over other shapes. For example, a long rectangular shaped wetland with a poorly designed inlet/outlet structure will probably perform better than a square, oval, or kidney shaped wetland with the same inlet/outlet structure, by reducing the potential for short circuiting.

Sediment Storage Zone at Inlet

A majority of the incoming settleable total suspended solids are removed by discrete settling in the inlet region of a FWS constructed wetland. Because a significant portion of the solids can be removed in the inlet area of the wetland, every effort should be made to optimize the treatment potential of this region. It is recommended that some type of open water area (settling zone) be provided in the inlet region of a FWS constructed wetland.

The settling zone should consist of an open water area that exists across the entire width of the wetland inlet. A recommended guideline is to design a settling zone that provides approximately 1 to 2 days hydraulic detention time at the average wastewater flowrate. Most suspended solids are removed in the first 1 to 2 days of detention time in a FWS constructed wetland (refer to Section 4). The settling zone should be deep enough to provide adequate accumulation and storage of settled solids, and to prevent the growth of emergent vegetation, such as bulrush and cattails. The accumulated solids will slowly decay and reduce in volume over time. However, at some time in the future the accumulated solids may need to be removed from the settling zone. It is likely (and encouraged) that floating aquatic vegetation will exist in the settling zone. Inlet structure location and design will directly influence inlet velocities in the settling zone. Velocities in the outlet zone is a function of the cell geometery, vegetation pattern, and inlet/outlet type and location.

Wetland Planting

One of the most important considerations in the construction of a FWS constructed wetland is the lead time necessary to develop a fully vegetated wetland. This factor enters into effluent compliance schedules and start-up periods. The planting strategy can determine the length of time it will take to reach functional densities of wetland vegetation. In general, the greater the initial planting density, the sooner the vegetation stands are developed. However, greater planting densities can also lead to greater planting costs. The source and type of planting material is also a major concern. Wetland planting success is highly dependent on the skills of the planting contractor, the type and quality of planting material, the soil matrix, and the time of planting. At best, it can be expected that a wetland will be producing target effluent values 2 or 3 years after completion of the planting.

Two periods exist when wetland planting is most successful: fall and spring. In the fall, tubers or clumps of aquatic emergent vegetation can be planted. Fall planting allows the plants to acclimate to the new soil substrate slowly, as wastewater is introduced at shallow depths. The hydroperiod (i.e. water depth and duration of flooding) of the wetland should stay below the tops of any newly planted emergent vegetation clumps or tubers. The other planting period is spring when seeds, sprigs, tubers, and/or clumps can be introduced. Water level control is much more critical to spring planting of sprigs, seeds, and tubers.

The most successful planting method for emergent vegetation, in either fall or spring, is by placing soil clumps of 4 to 10 plants into the wetland on 0.6 to 1 m checker board centers. These clumps include the native soils, along with multiple tubers, which insures the highest success rate of wetland planting. This type of planting is limited to smaller systems and in areas where plant material is available for harvest. Backhoes and dump trucks can be used to extract and harvest the plants from acceptable and approved harvesting areas. The stems can be cut off in late summer and fall plantings to facilitate transporting and planting of the clumps of emergent vegetation. The cost of planting clumps is dependent on the distance to the source of material. It is possible to have a fully functioning wetland in 1 to 2 years after planting with emergent clumps.

Other planting techniques include the use of purchased tuber stock and seeds from commercial sources. The tuber stock are typically planted in a similar fashion to transplanting seedlings, and depending on the size of the stock can be planted in spring of fall. For small tuber stock, spring planting is best. The use of seed is the most risky way to vegetate wetlands. Seed treatment (acid, base, oxidizing agents), seed placement (hand casting, hydroseeding), and water level manipulation are all critical factors in the success of seed germination. Planting with seed is less expensive then planting clumps or tubers, but the success rate of vegetation development is much less.

When planting seeds, sprigs, or tubers it is necessary to bring to water levels up slowly with the plant growth, starting at an initial depth of 20 to 30 mm, and slowly increasing depth to 200 to 300 mm as the plants grow. Slow water depth increases also ensure that wetland vegetation does not float before the roots take hold into the soil. If the size of the wetland does not allow a 0 to 1 percent bottom slope, then grading the wetland bottom into small sections separated by shallow internal berms (200 to 300 mm in height) will be required. This particular requirement is not needed when planting techniques incorporate clumps of soil, roots and stems. Planting of the wetland should be done as soon as possible in the construction sequence of a wastewater treatment plant. Often during wetland start-up, the water quality is degraded due to algae growth, sediment resuspension, and wildlife activity in the more open shallow water units. Permit requirements should be written to take this start-up period into consideration.

Regional sources are usually able to supply relatively small amounts of plant material. Planting tubers or clumps on 0.5 m centers, for example, requires approximately 40,000 plants per hectare. Planting on 1 m centers require 10,000 plants per hectare. Given a planting budget constraint, it is better to place more plants in the last half of the cell, then in the first half. It is important to insure success of planting of the last effluent half of the wetland. Planting 5 to 10 m wide vegetated strips across the wetland width and perpendicular to the flow will minimize short circuiting, and allow for a future source of plant material for later planting.

The emergent plants of choice for wetland treatment purpose are *Scirpus species* (bulrushes) and *Typha species* (cattails). Of these two, *Scirpus spp.* appears to have higher treatment potential. Hardstem bulrush, for example, affords much greater specific surface area in the water column than cattails. This specific surface area is a critical growth location for attached microflora and microorganisms. Cattails are generally larger in diameter than the bulrush, and have a much larger stem to tuber transition in the water column. Hardstem bulrush does not contribute as much detrital material during the dormant period as cattails, thereby reducing potential BOD leaching back into the water column. *Scirpus spp.* wetlands have about 1/3 the background BOD as *Typha spp.* wetlands. The seasonal change in plant community coverage in a FWS constructed wetland is shown for the City of Arcata's Enhancement Marshes in Table 6-1. The loss of open water to duckweek and sago pondweed coverage from spring to fall is evident from the data given in Table 6-1.

TABLE 6-1
Percent of dominant plant species areal coverage of the Enhancement Wetlands of the Arcata Marsh and Wildlife Sanctuary.

	Enhancement marsh units, date					
	Allen Marsh		Gearheart Marsh		Hauser Marsh	
	April	Sept.	April	Sept.	April	Sept.
Type of Cover	1986	1987	1985	1985	1986	1987
Open water	70.0	36.2	83.8	5.0	32.5	23.0
Common cattail		6.3	5.5	6.0	10.5	4.3
Marsh pennywort	5.6		10.0	11.8	27.0	
Sago pondweed		NV[b]		77.2	NV[b]	NV[b]
Alkali bulrush		11.9				0.8
Lesser duckweed		40.0[a]			30.0[a]	69.6
Hardstem bulrush						2.3
Common spikerush				0.7		
Upland grass spp.	30.0					

[a] Duckweed coverage was too low because the wind had pushed it into windrows.
[b] NV = not visible because of duckweed coverage

Wetland plant growth and survival is also dependent on environmental factors other than hydroperiod. Two of these factors include soil texture and soil chemistry. Many wetland plants grow rapidly in soils of sandy to loamy texture. Soils with excessive rock or clay material may retard plant growth and actually result in mortality. Excessively acidic or basic conditions may limit the availability of the nutrient required for plant growth. In some cases, soil concentrations of macro or micronutrients may not be available in the native soil for initial plant growth, and organic fertilizers may have to be used.

As discussed earlier, there are several water quality reasons for balancing the amount of open water area (submergent and floating), and the amount of vegetated water area (emergent). Dissolved oxygen levels are maintained at higher levels in open water areas, which supports aquatic organisms such as aquatic insect larva, amphibians and fish. All of these organisms feed on mosquito larva in the water columns.

Impermeable Barrier and Liner Materials

A major concern with FWS constructed wetlands is the potential loss of water from infiltration. While there are some wetland applications where infiltration is desirable, the majority of the applications require some type of barrier to prevent groundwater contamination. Under ideal conditions, the wetland site will consist of natural soils with low permeability that restrict infiltration. However, many wetlands have been constructed or proposed on sites were soils have high permeability. In these cases, some type of liner or barrier will be required to restrict infiltration. Some general guidelines and specifications for minimizing infiltration and berm storage losses are as follows.

Existing natural site soils with permeability less then approximately 10^{-6} cm/s are generally adequate as an infiltration barrier. For site soils with higher permeability, some type of liner material is required. Some examples of wetland liner materials include bentonite soil layers, chemical treatment of existing soils, asphalt, and synthetic membrane liners. In some instances, existing in-situ soils can be compacted to acceptable permeability. Whatever liner material is chosen, an important consideration is to provide adequate soil cover and depth that protects the liner from incidental damage and root penetration from the wetland vegetation. Burrowing mammals such as muskrats, nutria's rats, etc., can damage liners by chewing and consuming liner material.

Operation and Maintenance

The operation and maintenance of FWS constructed wetlands is much less demanding than for mechanical wastewater treatment technologies such as the activated sludge and trickling filter processes. Routine operation and maintenance requirements for wetland systems are similar to those for oxidation pond systems, and include hydraulic and water depth control, inlet/outlet structure cleaning, grass mowing of berms, inspections of berm integrity, wetland vegetation management, vector control, and accumulated solids/peat management if required.

Operation and maintenance considerations for FWS constructed wetlands are as important as design issues in meeting regulatory requirements pertaining to effluent water quality. The treatment effectiveness of most of the existing FWS constructed wetlands can vary considerably depending on water depth, weir overflow rate, plant density/plant location, and wildlife activity. Following are some of the more important operation and maintenance considerations for FWS constructed wetlands.

Management of FWS Constructed Wetlands

Limited attention has been paid to the overall operation and maintenance strategies of a FWS constructed wetland to meet water quality objectives. To be accepted readily by regulatory agencies and owners, more effort should be directed to developing holistic and sound management plans that cover a wide range of issues associated with FWS constructed wetlands (Hammer 1992). Many management issues pertaining to FWS constructed wetlands are not mutually exclusive. Typically, one management decision or action influences other management goals.

Listed below is some management considerations that need to be considered when developing a FWS constructed wetlands management plan:

- regulatory requirements
- hydroperiod and hydraulic retention time- water depth and flowrate
- hydraulic control - weir overflow rate/Inlet-outlet distribution
- vegetation control (planting, harvesting and monitoring)
- wildlife management
- vector control (mosquitoes)
- structural integrity
- nuisance conditions (odors)
- inlet/outlet structures
- public access
- environmental education

A set of operation and maintenance procedures needs to be developed for each of the goals of the management plan developed above. This management manual should be organized in a manner to assist the operator and owner in effectively operating the wetland system under a wide range of environmental conditions. At a minimum, the following categories should be included for each goal of the management plan.

1. Objective and goal for the component
2. Startup condition/monitoring
3. Normal operating condition/monitoring/lead time
4. Abnormal operating condition/monitoring/lead time
    - Problems
    - Indicator
    - Cause of abnormal condition
    - Course of action to solve problem
5. Maintenance requirements
6. Sampling/monitoring program

Potential Nuisance Conditions

Constructed and natural FWS wetlands are typically enriched semi-natural wetland ecosystems. Because of their very nature, they have the potential to create conditions that may be a nuisance to human neighbors or to the wildlife species they harbor. Nuisances that could conceivably occur include mosquito breeding habitat, creation of odors, attraction of dangerous reptiles (snakes and alligators), potential for accidental drowning and attractive nuisance for wildlife (Hammer 1992; Wass 1997). There is limited quantitative FWS treatment wetland data available for these potential nuisances, however some information is available on mosquito and odor control. There is inadequate data on any of these issues to help assess their possible effects on implementation of FWS treatment wetlands.

Wetlands and other stagnant water bodies can provide breeding habitat for mosquitoes. Some of these mosquito species can transmit diseases to humans or to valuable livestock. In addition, mosquitoes may be a nuisance because of their 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 not higher than 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).

Generally, odors in FWS treatment wetlands are associated with high organic loadings, especially in the inlet region of the wetland. It has been observed that most treatment wetlands have odors similar to the normal range of odors observed in natural wetlands. No published qualitative information has been found during preparation of this assessment on odors associated with treatment wetlands.

Dangerous reptiles including poisonous snakes and alligators are attracted to FWS treatment wetlands in some regions of the U.S. These same species are generally a natural component of natural wetlands in those same areas, and most citizens are aware of the need to avoid these animals when they are encountered. No published information has been found on population densities of these organisms in treatment wetlands or relating the occurrence of these species to wetland design. Further, no data has been found indicating that treatment wetlands are more or less likely to create risks to wildlife species than adjacent natural wetland ecosystems. This issue is being examined further through another EPA-funded project in progress.

Vegetation Management Implications

Routine harvesting of vegetation is not necessary for FWS constructed wetlands (Reed et al., 1995). In many cases, the only routine vegetation management consists of annual or biannual harvesting of emergent vegetation from designed open water areas, and inlet/outlet structures. Over some period, whose exact length is unknown, some removal of accumulated plant material and detritus may be required in FWS constructed wetlands. Studies at Arcata have indicated that detrital/litter has reduced the wetland volume by about 50 % in 12 years with no apparent change in performance. This type of harvesting may only be required if the vegetation significantly affects removal efficiencies and or restricts water flow.

If routine harvesting is required, it is recommended that the vegetation be removed in 5 to 10 m strips perpendicular to the direction of flow. The strip of harvested vegetation should be replanted and allowed to grow, before the next adjacent strip of vegetation is harvested. This process should be repeated over a number of years. The primary goal of this type of vegetation harvesting is that the wetland is never completely devoid of vegetation at any one time. The harvested vegetation can be transplanted, composted or burned; harvested wetland vegetation has also been used for the production of methanol. It is also important to consider potential effluent water quality impacts during vegetation harvesting. Typically, the wetland cell being harvested is taken off line during this period of time.

One problem that can be very difficult to manage for, is the potential for animals, in particular nutria and muskrat, to use the emergent wetland vegetation as a food source. Some FWS wetland systems have had these creatures consume all the emergent vegetation. If this occurs, the only action possible is to trap and relocate the animals, and revegetate the damaged wetland cells.

Mosquito Control

Mosquitoes are common in any wetland or open water environment. However, in some cases, especially urban environments, a FWS constructed wetland can produce mosquito populations that are viewed as a nuisance by the public. Mosquito populations appear to be controlled effectively in FWS treatment wetlands by small fish, such as the mosquito fish (*Gambusis affinis*) (Dill 1989, Steiner and Freeman 1989). However, fish may not be able to control mosquito populations in portions of FWS treatment wetlands that are colonized by dense populations of floating vegetation mats (Walton et al. 1990). This condition can be avoided by designing the FWS constructed wetland with open water areas. Other animals, such as frogs, birds, and especially bats, are also effective in controlling mosquito populations. When a FWS constructed wetland is designed to mimic a natural wetland, mosquito populations can be controlled effectively by the natural wetland ecosystem.

Sprinklers have also been successfully utilized to control adult mosquito populations in constructed wetlands (Epibare et al. 1993). The spray from overhead sprinklers disrupts the water surface and affects the ovipositioning. This technique was very effective in reducing mosquito larva production in a FWS wetland. However, this technique requires additional capital investment in the spray equipment, and operation and maintenance of the pump and sprinkler system.

A bacterial insecticide, *Bacillus thuringiensis israeliensis* (Bti), has been used effectively to control mosquito populations. Bti was applied to the Sacramento Regional demonstration wetland cells when mosquito larva reached 0.1 larva/dip. Bti was applied to an entire half cell at a rate of approximately 2 kg (liquid) per hectare. Repeated Bti application and vegetation harvesting around the edge appeared to be effective in avoiding high larval densities. Application of Bti on a six week interval during the mosquito breeding season appears to be best for meeting a less than 0.1 larva/dip threshold.

Process Control

FWS constructed wetlands have minimal need for active process control. The only two operational control for FWS wetlands are hydraulic loading and outlet weir level control (if designed to allow varying hydro periods). Hydraulic loadings can only be varied if alternative hydraulic pathways exist.

Under certain conditions increasing the outlet weir level for a given period of time will result in no discharge. This would allow for short term periods of no discharge to a receiving system. This increase in water level will increase the HRT while maintaining the areal loading at a constant value. Water level increase is limited by the maximum hydroperiod for emergent plants in the FWS wetland. Generally this maximum depth is 1.0

to 1.5 meters. Normal hydroperiods for emergent plants is usually 0.4 to 0.75 meters. Vegetation and detritus removal is necessary for long term performance of a FWS constructed wetlands. It appears that 15-20 years is a typical reoccurance internal for some of the vegetation/detritus removal. To-date no detritus or vegetation has had to be removed from Arcata's treatment marsh after 15 years of service. Based on studies by Gearheart, 1986 selected partial removal of vegetation/detritus maintains effluent quality, while reinstated flow through volume.

Monitoring Requirements

The most critical monitoring issue during the wetland startup period is vegetation growth and coverage. A wetland that does not develop sufficient emergent/submergent vegetation becomes a shallow oxidation pond, producing algae, BOD, and solids. The planting strategy, combined with hydroperiod control as the plants grow, determines the effectiveness of vegetation growth during the startup period. Other monitoring factors include control of aquatic birds, mammals, and invasive vegetation during the startup period.

Once the wetland vegetation has established, the wetland can be brought on line and wastewater introduced. After the startup period is over, routine monitoring requirements will be necessary

The most important monitoring task in the operation of a FWS constructed wetland is monitoring hydraulic and organic loadings, and discharge from the wetland system (including the monitoring through individual wetland cells). Such monitoring requires measuring influent and effluent flowrates, and water depths in each wetland cell. This information has not been collected routinely from many existing FWS constructed wetland systems. In fact, many of these systems were not designed to gather this type of data. This information can be used to develop seasonal strategies, based upon hydraulic and organic loadings, hydraulic detention times, and areal loadings. Such information can also be used to assess inlet/outlet distribution and performance.

Influent and effluent water quality constituents should also be measured on a weekly or at a minimum on a monthly basis. Parameters such as BOD, TSS, pH, nutrients, temperature, specific conductance, and dissolved oxygen should be monitored. These parameters can be used to assess wetland performance, and determine constituent loadings. The minimum monitoring requirements for a FWS constructed wetland are summarized in Table 6-2.

TABLE 6-2
Minimum monitoring requirements for a FWS constructed wetland.

Monitoring requirement	Location of monitoring	Frequency of monitoring: Large system	Frequency of monitoring: Small system
Hydraulic monitoring			
Water depth	Each cell	Weekly	Weekly
Inlet flowrate	Inlet of each cell	Daily	Weekly
Outlet flowrate	Outlet of last cell	Daily	Weekly
Water Quality monitoring			
Dissolved oxygen	Inlet each cell, outlet last cell	Weekly	Monthly
Temperature	Inlet each cell, outlet last cell	Weekly	Monthly
Conductivity	Inlet each cell, outlet last cell	Weekly	Monthly
pH	Inlet each cell, outlet last cell	Weekly	Monthly
BOD	Inlet each cell, outlet last cell	Weekly	Monthly
TSS	Inlet each cell, outlet last cell	Weekly	Monthly
Nutrients (e.g. TN, NH_4, NO_3, TP)	Inlet each cell, outlet last cell	Weekly	Monthly
Wetland biota monitoring			
Vegetation coverage/distribution	Each cell	Bi-annually	Annually
Wildlife (nuisance animals)	Each cell	Bi-annually	Annually
Vectors (mosquitoes, etc)	Each cell	Weekly during season	Weekly during season
Fish	Each cell	Monthly	Monthly
Birds[1]	Each cell	Monthly	Monthly
Aquatic insect larva[1]	Each cell	Monthly	Monthly
Civil Issues			
Berm and liner (if used) condition	All berms	Monthly	Monthly
Inlet/outlet condition	All inlet/outlet structures	Monthly	Monthly
Access road condition	All roads	Monthly	Monthly
Solids/peat buildup	Each cell	Annually	Annually
Public Use[1]			
Trail/sign conditions	All trails	Annually	Annually
Number of people	Access points	Annually	Annually

1. If required as part of management plan

Database Maintenance and Analysis

The initial NADB project was initiated in 1991 and ended before completion in September 1993. This project captured a significant fraction of the wetland design and performance information available at that time. However, approximately 100 additional treatment wetlands in the U.S. and Canada were tentatively identified during that effort. It is likely that up to 200 additional North American treatment wetland systems are not currently described in the database. In addition, the coverage and quality of data for those systems that are included in the NADB is often suspect and incomplete in terms of using the data to evaluate system performance.

The depth of existing information displayed in portions of this technology assessment is testament to the potential value of an extensive design and operational performance database for wetland treatment systems. Intra-system data analysis allows determination of the effects of design variables on performance for major constituents of interest. Inter-system data comparisons allow the designer the opportunity to detect regional differences and differences due to variable water sources. The "data cloud" figures presented in this report reassure wetland practitioners that they can expect certain reasonable performance from treatment wetlands.

In spite of the serious limitations of the NADB, it can be used for a variety of purposes. One use is to provide an inventory of how many treatment wetlands are "out there" and how they were built. This knowledge provides an understanding of how important this technology has become and to assess how rapidly it is growing, but does not require detailed operational data. A second goal, more in line with the purpose of a technology assessment, would be to assess accurately wetland performance under a variety of design conditions. The NADB, as it is presently formulated and implemented, falls short of meeting this goal. Insufficient information exists to optimize design of free water surface treatment wetlands. Variability in empirical design relationships cannot be reduced until sufficient wetland data are available to document the effect of all design variables. More complex, multi-parameter design models can only be supported by analysis of detailed information from a number of long-term, research-oriented treatment wetlands. Insuring that complete flow measurements are included for all systems is critical to the utility of the database in evaluating performance.

Additional funding should be sought for reformulating, updating, balancing, and editing the existing NADB. Most of the systems constructed and evaluated in the NADB are lightly loaded systems. Some of these systems have influent BOD and TSS values close to background values, resulting in periods of net negative pollutant removal. Efforts should be made to identify sites with higher loading rates to provide a more balanced view of the potential of the technology to treat wastewater. An initial effort could be completed over a 2-year period. The resulting updated NADB should be analyzed thoroughly and the results widely published. Practitioners in this field should be encouraged to maintain their own project data in an electronic form compatible with the reformulated NADB to allow rapid entry of new information.

Considerations for Minimizing Variability in Effluent Quality

Many items, most of which have been discussed throughout this Technology Assessment, combine to influence the variability of effluent quality from FWS constructed wetlands. These items include design issues covered in Section 5, and information discussed in this section. Following are important design and operational considerations, which can influence and help control variability of effluent water quality, that need to be considered throughout the FWS constructed wetland planning and design process.

1. Ability to buffer weekly fluctuations in effluent flow by use of multiple cells.
2. Ability to store water individually in each wetland cell to allow for longer hydraulic detention times for BOD and TN removal, and quiescent conditions for settling processes.
3. Minimize the amount of emergent vegetation necessary to reach treatment goals. The aquatic vegetation contributes to background BOD, ammonia, and dissolved phosphorus levels in the wetland. The lower the influent BOD, TSS, and TN, the greater potential contribution this background source has to the variation in the effluent value.
4. If wildlife habitat is one of the goals of the project, it is important to have 3 to 7 days detention time of emergent vegetation at the final wetland outlet. This emergent vegetation zone of the wetland has minimal habitat value for migratorial and residential birds (source control), and provides a final clarification/vegetative filter zone.
5. Design final outlet, collection zones, and inlet/outlet structures to minimize open water areas, which attract wildlife and promote phytoplankton and periphyton production.
6. Have a maximum weir overflow length to reduce the velocity field at the inlet and outlet zones of the wetland.
7. Design a solids settling zone across the inlet region of the FWS constructed wetland.

Research Studies

Treatment wetland research studies should be designed to answer specific, design-related questions. The size of wetland research cells, their source of feed water, water depth controls, and sampling can all affect the ability to scale up the conclusions to a full-size treatment wetland. Extremely small FWS wetlands may have edge effects that result in behavior that is unrealistic compared to full-scale wetlands. A pilot system may receive water in batch loads or in a nearly continuous mode, neither of which is typical of most full-scale treatment wetlands. Inlet constituent concentrations may be more constant in some pilot studies than can be expected with a full-scale system. In small pilot wetland cells (mesocosm-scale), sampling including plant harvesting can alter performance significantly.

Additional, long-term, well-funded research studies would be very valuable for advancing the FWS wetland technology. The Listowel, Ontario, database represents a major contribution for the development of design criteria and operational performance estimates for a cold-climate, cattail-dominated, constructed treatment wetland. Research studies have been performed on the City of Arcata, CA, research wetland cells since 1980, with two major data reports 1983 and 1986, and several papers summarizing research activities and findings. The effects of loading rate, operating depth, and plant types on effluent quality are summarized in the 1983 report (Gearheart et al., 1983). The 4-year time frame of this research project and the excellent monitoring and data reports were essential for maximizing the research benefits this project. It is recommended that regional sponsors be solicited to contribute additional data, following the example established by the Arcata and Listowel project. Several facilities are currently available to provide a cost-effective basis for additional pilot research. These facilities include the Everglades Nutrient Removal test cells, the Champion pilot wetlands in Pensacola, FL, the Tres Rios research wetlands in Phoenix, AZ, the Albuquerque, NM, wetland cells, the Arcata, CA, pilot wetland cells, the Orange County Water District, CA, demonstration wetland, and the Eastern Municipal Water District pilot wetland cells in Hemet, CA.

A common goal of all new and continuing wetland research studies should be the achievement of a high level of quality assurance for all data collected. Water flow and field parameters should be measured using calibrated instruments, and analytical tests should follow accepted testing methods with adequate quality control. All data should be validated prior to analysis and publication. Following good scientific research practices will help to improve our understanding of the transformation processes and will reduce the level of uncertainty in predicting treatment performance of free water surface wetlands in the future.

As part of an ongoing research effort, an interactive communication link for operators, owners, designees, and regulators of FWS constructed wetland should be established. The success of FWS constructed wetlands are not only dependent on good designs but dependent on good operators and management. A forum for discussion of operational issues with treatment wetlands will assure the continued success of this important wastewater treatment technology.

Critical Research Issues

A number of critical research issues requiring additional information and data analysis have been identified in this technology assessment report. These issues deal with the relationships between design variables and system performance. Some of the more pressing issues requiring resolution include the following:

- Specific studies on effluent water quality as a function of characteristics of the inlet and outlet weirs, including number, location, type, spacing, overflow rate, and outlet capacity
- The effect of aspect ratio on internal flow patterns and wetland treatment performance
- Determination of volatile solids destruction and subsequent reuse of soluble biodegradable by-products in the water column
- In depth monitoring of selected full-scale projects to acquire an understanding of systems receiving medium to high organic loads, and of systems in cold climates

- A qualitative description of the factors affecting the high variability of removal rate coefficients
- Detailed data sets for calibration of the sequential performance equations used to describe the nitrogen transformations in FWS treatment wetlands
- The relationship between the settled/decomposing solids and the removal of BOD and ammonia in treatment wetlands
- The spatial distribution of solids removal and nitrogen transformation processes to identify wetland configurations and conditions that optimize performance
- The appropriate use of volumetric removal rate coefficients for treatment wetland data analysis given their dependence on loading rates and water depth
- The importance of dissolved oxygen concentrations in control of wetland performance for BOD and TN removal
- The effect of open/deep water zones on internal flow patterns and treatment performance
- The importance of design criteria such as plant selection and open/deep water zones on wildlife populations in treatment wetlands
- The effects of different plant communities on treatment performance for all major constituents of concern
- The role of substrate surfaces in support of epiphytes and their role in conversion and transformation processes
- Additional information on factors affecting metal removal in treatment wetlands including mass balances over extended operational time periods
- The normal range of quantitative fates and effects of potentially toxic metals and organics in treatment wetland biota
- Normal populations of levels of mosquitoes in treatment wetlands and an understanding of the physical, chemical, and biological factors affecting these populations
- Studies directed at the use of Integrated Pest Management (IPM) for managing mosquito populations in FWS constructed wetlands

Other important issues are more difficult to study in a single research effort, but instead need the collective input from wetland designers and operators of full-scale treatment wetlands. These issues include:

- The optimum design and management of wetlands for multiple uses such as treatment, habitat, and recreation
- The role of dissolved organic carbon generated from the decomposition of detritus in treatment wetlands

- The effect of managing the hydroperiod over a weekly and monthly period on the performance of treatment wetlands
- The role of the full range aquatic microorganisms and aquatic insect larva as they interact with the particulate material (public health significant organisms, plant litter, TSS, etc.) in a FWS constructed wetland

Finally, much effort remains to be done with State and Federal agencies in terms of defining the role and functions of FWS constructed wetlands in the various wetland policies, and in the development of appropriate discharge standards.

Appendix A – References

ADEM (Alabama Department of Environmental Management). 1988. *Natural Treatment Systems for Upgrading Secondary Municipal Wastewater Treatment Facilities.* Prepared by ADEM and the Department of Civil Engineering, Auburn University, Auburn, AL.

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.

Allen, G.H. and R.A. Gearheart. 1988. *Proceedings of a Conference on Wetlands for Wastewater Treatment and Resource Enhancement.* August 2-4, 1988. Humboldt State University, Arcata, CA. 154 pp.

Bastian, R.K. and S.C. Reed, eds. September 1979. *Proceedings of the Seminar on Aquaculture Systems for Wastewater Treatment.* USEPA Publication No. MCD-67.

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.

Benjamin, T.S. 1993. *Alternative Wastewater Treatment Methods as Community Resources: The Arcata Marsh and Beyond.* M.S. Thesis, University of California at Berkely.

Bothner, Brian. 1995. *Assessment of Toxicity in Arcata's Integrated Wastewater Treatment Facility.* Thesis Humboldt State University, Arcata, California.

Bouey, J. 1996. Personal communication.

Brix, H. 1993a. "Macrophyte-Mediated Oxygen Transfer in Wetlands: Transport Mechanisms and Rates." In *Constructed Wetlands for Water Quality Improvement,* G.A. Moshiri, ed. Boca Raton, FL: Lewis Publishers.

Brix, H. 1993b. "Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance." In Moshiri, G.A. (ed) *Constructed Wetlands for Water Quality Improvement,* pp 9-22, Lewis Publishers, Boca Raton, FL.

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

Brix, H. 1994b. "Humedales Artificiales." Lectures on wetland treatment presented in Zaragoza, Spain, 19-30 September, 1994.

Brown, D.S. and J.D. Waterman. 1994. "Wetlands Treatment Database." In *Proceedings WEFTEC 1994, 67th Annual Conference and Exposition.* Vol. 8, Part 1.

Byron Shire Council. Unpublished data.

Campbell, Kenneth, ed. 1995. *Versatility of Wetlands in the Agricultural Landscape.* Proceedings of an international conference sponsored by the American Water Resources Association and American Society of Agricultural Engineers, September 17 to 20, 1995, Tampa, Florida.

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. Chattanooga, TN: TVA Water Quality Department.

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

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

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, UK, September 24-28, 1990. Oxford, UK: Pergamon Press.

Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. *Classification of Wetlands and Deep Water Habitats of the United States.* U.S. Fish and Wildlife Service. FWS/0BS-79/31.

Crites, R.W., G.D. Dombeck, R.C. Watson, and C.R. Williams. 1997. "Removal of Metals and Ammonia in Constructed Wetlands." In *Water Environment Research,* Vol. 69, No. 2.

Crites, R.W., G.D. Dombeck, and C.R. Williams. 1996. "Two Birds With One Wetland: Constructed Wetlands for Effluent Ammonia Removal and Reuse Benefits," in *Proceedings of the WEFTEC 96,* Dallas, TX.

Crites, R.W. and G. Tchobanoglous. 1998. *Small and Decentralized Wastewater Management Systems,* WCB – McGraw-Hill, New York.

Crites, R.W., R.C. Watson, and C.R. Williams. 1995. "Removal of Metals in Constructed Wetlands." In *Proceedings of WEFTEC '95,* Miami, Florida. 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 *Constructed Wetlands for Water Quality Improvement,* G.A. Moshiri, ed. Boca Raton, FL: Lewis Publishers.

DeBusk, T. A., K. R. Reddy, T. D. Hayes, and B. R. Schwegier. 1989. "Performance of a Pilot-Scale Water Hyacinth-Based Secondary Treatment System." In *Journal WPCF,* 61:1218-1224.

Dill, C.H. 1989. "Wastewater wetlands: user friendly mosquito habitats." In *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural,* D.A. Hammer, ed. Chelsea, MI: Lewis Publishers.

Drew, M.A., ed. 1978. *Environmental Quality Through Wetlands Utilization. A Symposium on Freshwater Wetlands.* Sponsored by the Coordinating Council on the Restoration of the Kissimmee River Valley and Taylor Creek-Nubbin Slough Basin. February 28-March 2, 1978, Tallahassee, Florida.

DuBowy, P. and R. Reaves, eds. 1994. *Constructed Wetlands for Animal Waste Management.* Proceedings of workshop sponsored by the Conservation Technology Information Center, the U.S. Department of Agriculture Soil Conservation Service, U.S. Environmental Protection Agency Region V, and Purdue University Agricultural Research Program, April 4 to 6, 1994, Lafayette, Indiana.

Epibare, R. E. Heidig, and D. W. Gibson. 1993. "Prevention of Mosquito Production At An Aquaculture Wastewater Reclamation plant in San Diego, Ca. using an innovative sprinkler system." In *Bulletin of the Society for Vector Ecology* 18 (1):40-44.

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

Fisk, D.W., ed. 1989. *Wetlands: Concerns and Successes.* Bethesda, MD: AWRA.

Flach, K.W. 1973. "Land Resources." In *Recycling Municipal Sludges and Effluents on Land.* Champaign, University of Illinois.

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

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

Gearheart, R. A. 1993. "Phosphorus Removal in Constructed Wetlands". Presented at the 66th WEF Conference and Exposition, Anaheim, Ca. Oct. 3-7.

Gearheart, 1998, Unpublished data from Arcata Treatment Marshes, California.

Gearheart, R.A. and B. A. Finney. 1996. "Criteria for Design of Free Surface Constructed Wetlands Based Upon a Coupled Ecological and Water Quality Model." Presented at the Fifth International Conference on Wetland Systems for Water Pollution Control, Vienna, Austria.

Gearheart, R.A., R. M. Gersberg, and Mike Ives. 1989. "Pathogen Removal in Constructed Wetlands", presented at International Conference on Wetlands for Wastewater Treatment, Chattanooga, Tennessee June 16-17, 1988. Proceedings published by Ann Arbor Press.

Gearheart, R.A., F. Klopp, and G. Allen. 1989. "Constructed Free Surface Wetlands to Treat and Receive Wastewater Pilot Project to Full Scale". In D.A. Hammer (ed) *Constructed Wetlands for Wastewater Treatment*, pp. 121-137, Lewis Publisher, Inc., Chelsea, MI.

Gearheart, R.A., R. Norman, and L. Finger. 1993. *Review of Wetland Evapotranspiration Literature*. Bullhead Lake, AZ: Bureau of Reclamation

Gearheart, R.A., S. Wilbur, J. Williams, D. Hull, B. Finney, and S. Sundberg. 1983. *City of Arcata Marsh Pilot Project: effluent quality results-system design and management. Final report*. Project No. C-06-2270, State Water Resources Control Board, Sacramento, California. 127 pp.

Gearheart, R.A., Williams, J., Holbrook, H., and Ives, M. 1986. *City of Arcata Marsh Pilot Project Wetland Bacteria Speciation and Harvesting Effects on Effluent Quality*. Environmental Resources Engineering Department, Humboldt State University, Arcata, California.

Gersberg, R. M., S.R. Lyons, B. V. Elkins, and C. R. Goldman. 1984. "The Removal of Heavy Metals by Artificial Wetlands." In *Proceedings Water Reuse Symposium III*. Vol. 2, American Water Works Association Research Foundation, p. 639-648.

Gersberg, R. M., B.V. Elkins, R. Lyons, and C. R. Goldman. 1985. "Role of Aquatic Plants in Wastewater Treatment by Artificial Wetlands." In *Water Research*, 20:363-367.

Gersberg, R.M., R.A. Gearheart, and M. Ives. 1989. "Pathogen Removal in Constructed Wetlands." In *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural*, D.A. Hammer, ed. Chelsea, MI: Lewis Publishers.

Godfrey, P.J., E.R. Kaynor, S. Pelczarski, and J. Benforado, eds. 1985. *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters*. New York: Van Nostrand Reinhold Company.

Greeson, P.E., J.R. Clark, and J.E. Clark, eds. 1978.*Wetland Function and Values: The State of Our Understanding*. Minneapolis, MN: American Water Resources Association.

Hall, B.R. and G.E. Freeman. 1994. "Study of Hydraulic Roughness in Wetland Vegetation Takes New Look at Manning's n." In *The Wetlands Research Program Bulletin* 4(1):1-4. USACOE, Waterways Experiment Station, Vicksburg, MS.

Hammer, D.A. and R.L. Knight. 1994. "Designing Constructed Wetlands for Nitrogen Removal." In *Water Science and Technology* (29) 15-27.

Hammer, D.A. 1992. *Creating Freshwater Wetlands*, Lewis Publishers, Boca Raton, FL.

Hammer, D.E. and R.H. Kadlec. 1986. "A Model for Wetland Surface Water Dynamics." In *Water Resources Research*. 22(13): 1951-1958.

Hammer, D.A., ed. 1989. *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural*. Chelsea, MI: Lewis Publishers.

Herskowitz, J. 1986. *Listowel Artificial Marsh Project Report*. Prepared for Reasearch Advisory Committee, Ontario Ministry of the Environment, Water Resources Branch, Toronto. Project No. 128RR, October 1986.

Herskowitz, J.,S. Black, and W. Lewandowski. 1987. "Listowel Artificial Marsh Treatment Project." In K. R. Reddy and W. H. Smith (ed) *Aquatic Plant for Water Treatment and Resource Recovery,*. Magnolia Publishing, Inc., Orlando, FL, p 248-254.

Hovorka, R.B. 1961. *An Asymmetric Residence-time Distribution Model for Flow Systems*, Dissertation, Case Institute of Technology.

IAWQ (International Association on Water Quality). 1994. *Proceedings of the Fourth International Conference on Wetland Systems for Water Pollution Control*, November 6 to 10, 1994, Guangzhou, China. Guangzhou, P.R. China: Center for International Development and Research, South China Institute for Environmental Sciences.

Ives, M. 1988. "Viral Dynamics in Artificial Wetlands." In *Proceedings of a Conference on Wetlands for Wastewater Treatment and Resource Enhancement*, G.H. Allen and R.A. Gearheart, eds. Arcata, CA: Humboldt State University.

Kadlec, R.H. 1994. Personal communication.

Kadlec, R.H., W. Bastiaens, and D. T. Urban, 1993. "Hydrological Design of Free Water Surface Treatment Wetlands." In *Constructed Wetlands for Water Quality Improvement*, G.A. Moshiri, ed. Boca Raton, FL: Lewis Publishers.

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

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*.

Kadlecik, Laura. 1996. *Organic Content of Wetland Soils, Arcata Enhancement Marsh*, Special Project ERE Department Wetland Workshop. Arcata, CA.

Kays, W.B. 1986. *Construction of Linings for Reservoirs, Tanks, and Pollution Control Facilities*. 2nd ed., Wiley-Interscience, New York, NY.

Knight, R.L. Unpublished data from Champion pilot wetlands.

Knight, R.L. and K.A. Ferda. 1989. "Performance of the Boggy Gut Wetland Treatment System, Hilton Head, South Carolina." In *Proceedings of the Symposium on Wetlands: Concerns and Successes*, D. Fisk, ed. Bethesda, MD: American Water Resources Association.

Knight, R.L., J. Pries, R. Borer, R. Clarke, and V. Payne. 1996. *Constructed Wetlands for Livestock Wastewater Management. Literature Review, Database, and Research Synthesis.* Prepared for the Gulf of Mexico Program.

Knight, R.L., R.W. Ruble, R.H. Kadlec, and S.C. Reed. 1993. "Wetlands for Wastewater Treatment Performance Database." In *Constructed Wetlands for Water Quality Improvement*, G.A. Moshiri, ed. Boca Raton, FL: Lewis Publishers.

Knight, R.L., R.W. Ruble, R.H. Kadlec, and S.C. Reed. September 1993. *Database: North American Wetlands for Water Quality Treatment. Phase II Report.* Prepared for U.S. Environmental Protection Agency.

Lakshman, G. 1982. *A Demonstration Project at Humboldt to Provide Tertiary Treatment to the Municipal Effluent Using Aquatic Plants.* Saskatchewan Research Council, SRC Publication No. E-820-11-B-28.

Martin, C.V. and B.F. Eldridge. 1989. "California's Experience with Mosquitoes in Aquatic Wastewater Treatment Systems." In *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural*, D.A. Hammer, ed. Chelsea, MI: Lewis Publishers.

McAllister, Lynne S. 1993. *Habitat Quality Assessment of Two Wetland Treatment Systems in the Arid West – A Pilot Study.* Corvallis, OR: U.S. Environmental Protetion Agency, Environmental Research Laboratory. EPA/600/R-93/117.

Meyers, J. 1998. Personal communication.

Mitsch, W.J., ed. 1994. *Global Wetlands: Old World and New.* Amsterdam: Elsevier.

Mitsch, W.J. and J.G. Gosselink. 1993. *Wetlands.* New York: Van Nostrand Reinhold.

Mitsch, W. and X. Wu. March 1995. *Olentangy River Wetland Research Park at the Ohio State University. Annual Report 1994.* Columbus, OH: Ohio State University School of Natural Resources.

Moshiri, G.A., ed. 1993. *Constructed Wetlands for Water Quality Improvement.* Boca Raton, FL: Lewis Publishers.

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.

NAWCC (North American Wetlands Conservation Council). 1995. *Wastewater Applications of Wetlands in Canada.* Prepared by CH2M HILL and Canadian Wildlife Service. Sustaining Wetlands Issues Paper No. 1994-1.

Nolte and Associates. 1989. *Harwich Septage Treatment Pilot Study - Evaluation of Technology for Solar Aquatic Septage Treatment System.* Prepared for Ecological Engineering Associates, Marion, MA.

Nolte and Associates. 1997. *Sacramento Regional Wastewater Treatment Plant Demonstration Wetlands Project - 1996 Annual Report*. Prepared for the Sacramento Regional County Sanitation District, Elk Grove, CA.

Nolte and Associates. 1998. *Constructed Wetlands Demonstration Project. 1997 Annual Report*. Prepared for SacramentoRegional County Sanitation District, Elk Grove, CA.

O'Connor, D.J. and W.E. Dobbins. 1958. "Mechanism of Reaeration in Natural Streams." In *ASCE Transactions*, Paper No. 2934, pp. 641-684.

Odum, H.T. 1985. *Self-Organization of Estuarine Ecosystems in Marine Ponds Receiving Treated Sewage. Data From Experimental Pond Studies at Morehead City, North Carolina, 1968-1972. A Data Report*. University of North Carolina Sea Grant Publication #UNC-SG-85-04.

Ogden, M.C. 1994. Personal Communication.

Olson, R.K., ed. 1992. "The Role of Created and Natural Wetlands in Controlling Non-Point Source Pollution." Proceedings of a U.S. EPA Workshop, Arlington, VA, 10-11 June, 1991. In *Ecological Engineering*. 1(1/2) 170 pp.

Phelps, Earle B. 1944. *Stream Sanitation*. New York, NY: John Wiley and Sons.

PBSJ (Post, Buckley, Schuh, and Jernigan). 1991. *Orlando Easterly Wetlands: 1990 Monitoring Report*, to City of Orlando, FL.

Pilgram, D., Chairman. 1992. *Wetland Systems in Water Pollution Control*. Proceedings of the International Association on Water Quality (IAWQ) Specialist Conference, November 30 to December 3, 1992, Sydney, Australia.

Pullin, B.P. and D.A. Hammer. 1991. "Aquatic Plants Improve Wastewater Treatment." In *Water Environmental Technology*. March: 36-40.

Pullin, B.P. and D.A. Hammer. 1989. "Comparison of Plant Density and Growth Forms Related to Removal Efficiencies in Constructed Wetlands Treating Municipal Wastewaters," Preprint of paper presented at 62nd Annual Conference WPCA, San Francisco, CA, October 1989.

Reckhow, K. and Song S. Qian. 1994. "Modeling Phosphorus Trapping in Wetlands Using General Models". In *Water Resources Research*, Vol. 30 No. 11, pp. 3105-3114.

Reddy, K.R. and E.M. D'Angelo. 1994. "Soil Processes Regulating Water Quality in Wetlands." In *Global Wetlands: Old World and New*, W. Mitsch, ed. Amsterdam: Elsevier.

Reddy, K.R. and W.H. Smith, eds. 1987. *Aquatic Plants for Water Treatment and Resource Recovery*. Orlando: Magnolia.

Reddy, K.R. 1984. "Nutrient Transformations in Aquatic Macrophyte Filters Used for Water Purification," in Proceedings of Water Reuse III, Vol. 2, American Water Works Association.

Reed, S.C. 1992. "Subsurface Flow Constructed Wetlands for Wastewater Treatment - Status and Prospects." In *Wetland Systems in Water Pollution Control*, D. Pilgram, Chairman. Proceedings of the International Association on Water Quality (IAWQ) Specialist Conference, November 30 to December 3, 1992, Sydney, Australia.

Reed, S.C., R.W. Crites, and E.J. Middlebrooks. 1995. *Natural Systems for Waste Management and Treatment*. 2nd Ed. New York: McGraw-Hill.

Richardson, B., ed. 1981. *Selected Proceedings of the Midwest Conference on Wetland Values and Management*, St. Paul, MN, June 17-19, 1981. Navarre, MN: Freshwater Society.

Sartorius, J., et al. 1999. "Investigations of Nitrogen Transformations in a Southern California Constructed Wastewater Treatment Wetland." presented for publication to *Ecological Engineering*.

SCDHEC (South Carolina Department of Health and Environmental Control). 1992. *Grant for Development of a Wetlands Classification and Standards System, Effluent Criteria, and Criteria for Other Activities in Wetlands*. Final Report. Columbia, SC.

Schwegler, B. R. 1978. *Effects of Sewage Effluent on Algal Dynamics of a Northern Michigan Wetland*. M.S. Thesis. The University of Michigan, Ann Arbor, 53 pp.

Seidel, K., 1976. "Macrophytes and Water Purification." In *Biological Control of Water Pollution*, J. Tourbier and R.W. Pierson, Jr., eds. Philadelphia: University of Pennsylvania Press.

SFWMD (South Florida Water Management District). Unpublished data from Everglades Nutrient Removal Project.

Small, M. and C. Wurm. 1977. *Data Report. Meadow/Marsh/Pond System*. Brookhaven National Laboratory. BNL 50675.

Steele, Kenneth, ed. 1995. *Animal Waste and the Land-Water Interface*. Boca Raton, FL: Lewis Publishers.

Stefan, et al. 1994. "Influence of Macrophytes on Nitrate Removal in Wetlands". In *Ambio* Vol. 23, No. 6.

Steiner, G.R. and R.J. Freeman, Jr. 1989. "Configuration and Substrate Design Considerations for Constructed Wetlands Wastewater Treatment." In *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural*, D.A. Hammer, ed. Chelsea, MI: Lewis Publishers.

Stephenson, M., G. Turner, P. Pope, J. Colt, A. Knight, and G. Tchobanoglous. 1980. *The Use and Potential of Aquatic Species for Wastewater Treatment*, Appendix A, "The Environmental Requirements of Aquatic Plants," Publication No. 65, California State Water Resources Control Board, Sacramento, CA.

Stowell, R., R. Ludwig, J. Colt, and G. Tchobanoglous. 1980. "Towards the Rational Design of Aquatic Treatment Systems." Presented at the American Society of Civil Engineers Spring Convention, Portland, OR. April 14-18, 1980. 43 p.

Stowell, R., 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 *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters.* P.J. Godfrey, E.R. Kaynor, S. Pelczarski, and J. Benforado, eds. New York: Van Nostrand Reinhold Company.

Sutherland, J.C. and R.H. Kadlec, eds. 1979. *Freshwater Wetlands and Sanitary Wastewater Disposal.* Conference Abstracts. Higgins Lake, Michigan.

Tchobanoglous, G. 1993. "Constructed Wetlands and Aquatic Plant Systems: Research, Design, Operational, and Monitoring Issues." In G.A. Moshiri (ed) *Constructed Wetlands for Water Quality Improvement*, pp. 23-34, Boca Raton, FL: Lewis Publishers.

Tchobanoglous, G., R. Gearheart and R. Crites. 1991. "System Operation and Monitoring," presented at the Natural/Constructed Wetland Treatment Systems Workshop, sponsored by the U.S. Environmental Protection Agency, Region VIII and the Colorado Department of Health, Denver, CO. September 4-6.

Tchobanoglous, G., R. Stowell, R. Ludwig, J. Colt, and A. Knight. 1979. "The Use of Aquatic Plants and Animals for the Treatment of Wastewater: An Overview." In *Aquaculture Systems for Wastewater Treatment: Seminar Proceedings and Engineering Assessment*, R.K. Bastian and S.C. Reeds, eds. Washington, D.C.: U.S. Environmental Protection Agency. EPA 430/9-80-006.

Tilton, D.L., R.H. Kadlec, and C.J. Richardson, eds. 1976. "Freshwater Wetlands and Sewage Effluent Disposal." In *Proceedings of NSF/RANN Conference.* Ann Arbor, Michigan: The University of Michigan. NTIS PB259305.

Tojimbara, T. 1986. *A Quantitative Study of Periphyton Colonized on Artificial Substrates at the City of Arcata's Marsh Pilot Project.* M.S. Thesis. Arcata, CA: Humboldt State University.

TVA (Tennessee Valley Authority). 1990. Unpublished data from Benton, KY.

U.S. Environmental Protection Agency. 1983a. *The Effects of Wastewater Treatment Facilities on Wetlands in the Midwest.* EPA 905/3-83-002.

U.S. Environmental Protection Agency. 1983b. *Freshwater Wetlands for Wastewater Management. Region IV Environmental Impact Statement. Phase I Report.* EPA 904/9-83-107.

U.S. Environmental Protection Agency. 1984. *The Ecological Impacts of Wastewater on Wetlands: An Annotated Bibliography.* EPA 905/3-84-002.

U.S. Environmental Protection Agency. 1985. *Freshwater Wetlands for Wastewater Management Handbook.* EPA 904/9-85-135.

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

U.S. Environmental Protection Agency. 1988b. *Report on the Use of Wetlands for Municipal Wastewater Treatment and Disposal.* EPA 430/09-88-005.

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

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

U.S. Environmental Protection Agency. 1999. *Manual for Constructed Wetlands Treatment of Municipal Wastewater.* Cincinnati, OH: Technology Transfer Branch (in preparation).

van Oostrom, A.J. and R.N. Cooper. 1990. "Meat Processing Effluent Treatment in Surface-Flow and Gravel-Bed Constructed Wastewater Wetlands." In *Constructed Wetlands in Water Pollution Control,* P.F. Cooper and B.C. Findlater, eds. Oxford, UK: Pergamon Press.

Valelia, I., S. Vince, and J.M. Teal. 1976. "Assimilation of Sewage by Wetlands in Estuarine Processes." In *Volume 1: Uses, Stresses, and Adaptations to the Estuary,* M. Wiley, ed. New York, NY: Academic Press, pp. 234-253.

Vela, G.R. 1974. "Effect of Temperature on Cannery Waste Oxidation." In *Journal of WPCF,* Vol. 46. No. 1, pp. 198-202.

Walker, L.P. and M.R. Walker. 1990. *City of Gustine Marsh Evaluation Study.* Report to the City of Gustine. Davis, CA: Larry Walker Associates, Inc.

Walton, W.E., E.T. Schreiber, and M.S. Mulla. 1990. "Distribution of *Culex tarsalis* Larvae in a Freshwater Marsh in Orange County, California." In *Journal of the American Mosquito Control Association.* 6:539-543.

Wass, R. 1997. *Tres rios Demonstration Constructed Wetland Project – 1996/1997 Operation & Water Quality Report.* Prepared for the City of Phoenix, SROG, and Bureau of Reclamation. Phoenix, AZ.

Water Environment Federation (WEF). 1999. *Natural Systems for Wastewater Treatment, 2nd ed.* (in preparation). Alexandria, VA. Washington, DC: WEF.

Water Pollution Control Federation (WPCF). 1989. *Natural Systems for Wastewater Treatment.* Manual of Practice FD-16. Alexandria, VA. Washington, DC: WPCF.

Watson, J.T., S.C. Reed, R.H. Kadlec, R.L. Knight, and A.E. Whitehouse. 1989. "Performance Expectations and Loading Rates for Constructed Wetlands." In

Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural, D.A. Hammer, ed. Chelsea, MI: Lewis Publishers.

Watson, J.T., F. D. Diodato, and M. Launch. 1987. "Design and Performance of the Artificial Wetlands Wastewater Treatment Plant at Iselin, Pennsylvania." In K.R. Reddy and W. H. Smith (eds) *Aquatic Plants for Water Treatment and Resource Recovery.*

Weber, A.S. and G. Tchobanoglous. 1986. "Prediction of Nitrification in Water Hyacinth Treatment Systems." In *Journal WPCF.* 58(5):376-380.

Western Consortium for Public Health with EOA, Inc. 1996. *Total Resource Recovery Project, Final Report,* prepared for the City of San Diego, CA. Oakland, CA.

Wieder, R.K., G. Tchobanoglous, and R.W. Tuttle. 1989. "Preliminary Considerations Regarding Constructed Wetlands for Wastewater Treatment." In *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural,* D.A. Hammer, ed. Chelsea, MI: Lewis Publishers.

Wile, I., G. Miller, and S. Black. 1985. "Design and Use of Artificial Wetlands." In *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters,* P.J. Godfrey, E.R. Kaynor, and S. Pelczarski, eds. New York: Van Nostrand Reinhold.

Wilhelm, M. S.R. Lawry and D.D. Hardy. 1989. Creation and Management of Wetlands Using Municipal Wastewater in Northern Arizona: A Status Report, in D.A. Hammer (ed) *Constructed Wetlands for Wastewater Treatment,* p. 179-185, Lewis Publishers, Inc., Chelsea, MI.

Williams, C.R., R.D. Jones, and S.A. Wright. 1996. "Mosquito Control in a Constructed Wetlands." In *Proceedings of WEFTEC 96,* Dallas, TX.

Wilson, B.A., K.R. Townsend, and T.H. Anderson. 1987. "Mosquito and Mosquitofish Responses to Loading of Water Hyacinth Wastewater Treatment Ponds." In *Aquatic Plants for Water Treatment and Resource Recovery,* K.R. Reddy and W.H. Smith, eds. Orlando: Magnolia.