ELSEVIER

Ecological Engineering 15 (2000) 41–55

ECOLOGICAL ENGINEERING

www.elsevier.com/locate/ecoleng

Constructed wetlands for livestock wastewater management

Robert L. Knight [a,*], Victor W.E. Payne Jr. [b], Robert E. Borer [c], Ronald A. Clarke Jr. [d], John H. Pries [e]

[a] *2809 N.W. 161 Ct., Gainesville, FL 32609, USA*
[b] *Payne Engineering, 1841 Creekwood Trail, Auburn, AL 36830, USA*
[c] *5225 N.W. 57th LN, Gainesville, FL 32608, USA*
[d] *CH2M HILL, 3011 S.W. Williston Rd., Gainesville, FL 32608, USA*
[e] *CH2M Gore & Storrie, 180 King St. S., Suite 600, Kitchner, Ont. N2J 1P8, Canada*

Received 16 October 1998; received in revised form 4 March 1999; accepted 22 June 1999

Abstract

In 1995, the Gulf of Mexico Program (GMP) sponsored efforts by the Alabama Soil and Water Conservation Committee and the National Council of the Pulp and Paper Industry for Air and Stream Improvement (NCASI) to conduct a review of the literature concerning the use of constructed wetlands for treating concentrated livestock wastewaters. The scope of the literature review and summary of design/operation data included all of North America. Both published and unpublished data have been provided by researchers to be included in the database. The database format used for the GMP project is only slightly modified from the format developed for the US Environmental Protection Agency (EPA) North America Treatment Wetland Database, which includes information from municipal, industrial and stormwater treatment wetlands. The GMP Livestock Wastewater Treatment Wetland Database includes information from 68 sites with a total of 135 pilot and full-scale wetland systems (systems include parallel units at individual research facilities). Types of livestock wastewater being treated by constructed wetlands include dairy manure and milkhouse wash water, runoff from concentrated cattle-feeding operations, poultry manure, swine manure and catfish pond water. Over 1300 operational data records are summarized in the database. These data indicate that removal rates for 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), ammonium nitrogen (NH_4-N), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) and fecal coliforms are potentially very high in constructed wetlands receiving animal wastewaters. Average concentration reduction efficiencies were: BOD_5 65%, TSS 53%, NH_4-N 48%, TN 42%, and TP 42%. Removals are a function of inlet concentrations and hydraulic loading rates. Successful wetland design must include adequate pretreatment to protect the health of the wetland biota and must include adequate wetland area to meet the quality goals.

Keywords: Agricultural engineering; Confined animal feeding operation; Livestock; Nutrient reduction; Treatment wetland; Water quality management

* Corresponding author. Tel.: +1-904-462-1003.
E-mail address: bknight@fdt.net (R.L. Knight)

PII: S0925-8574(99)00034-8

1. Introduction

Pollutants derived from agricultural operations can result in significant impairment of surface and groundwater quality. These pollutants often enter surface waters from diffuse or non-point sources associated with surface runoff and from point sources typically associated with concentrated farming activities such as the production of livestock. Recognition of the impacts that may result from release of concentrated levels of oxygen-demanding organic waste and associated nutrients has led to the investigation of multiple wastewater management alternatives. One alternative receiving increasing consideration is the use of constructed treatment wetlands to intercept and partially renovate wastewaters before they leave the farm as surface runoff or groundwater infiltration, or before they are reused on the farm for irrigation or other activities. Constructed treatment wetlands offer a low-energy alternative to other waste treatment technologies and are compatible with typical farm and ranch operations (Kadlec and Knight, 1996).

Wastewaters derived from livestock (cattle, dairy, swine, poultry, aquaculture, or any other farm-reared animals) operations can often be isolated and treated prior to release or reuse. Because these wastewaters are typically concentrated, they can be conveniently intercepted, pretreated, and subjected to additional advanced treatment in proportion to the desired quality for their ultimate disposal. Pilot and full-scale constructed treatment wetlands have been utilized for livestock wastewater treatment throughout many parts of the USA and Canada.

1.1. Gulf of Mexico Program (GMP)

The GMP was established in 1988 as an interagency effort to improve ecological and economic viability of the Gulf of Mexico. The Nutrient Enrichment Committee of the GMP recognized the potential importance of on-farm treatment wetlands for reducing pollutants entering the Gulf of Mexico watershed (much of the eastern and central USA). Beginning in 1995, the GMP funded a project to assess the effectiveness of treatment wetlands for management of wastewaters from concentrated animal operations and to distribute the resulting assessment to the interested public. This paper was sponsored by the GMP and presented at a workshop on the use of constructed wetlands for treatment of animal wastes in Ft. Worth, TX, in May 1996. Papers from that conference were never published, so this condensed version of the paper is being published here to disseminate information concerning the database and detailed reports issued by the GMP (CH2M HILL, 1997; CH2M HILL and Payne Engineering, 1997; Payne and Knight, 1997).

1.2. Scope of this paper

This paper describes the development of a database to organize information from treatment wetlands receiving wastewaters from livestock operations and presents a preliminary analysis of the data summarized in the database. Results from livestock wastewater treatment wetlands are compared to results from other treatment wetland applications and the North American Treatment Wetland Database (NADB) (Knight et al., 1993) to help transfer technology from the older municipal/industrial treatment applications to the agricultural industry.

2. Treatment wetland overview

More than 400 natural and constructed treatment wetlands in North America receive municipal, industrial, agricultural, or stormwater discharges (Kadlec and Knight, 1996). Since 1976 more than 20 conferences worldwide have addressed treatment wetlands. Published proceedings from many of these conferences provide a wealth of information for treatment wetland designers and owners.

During the past decade, environmental awareness has broadened the focus of water pollution control to include non-point sources. As a result, the agricultural community in North America has actively pursued source controls to prevent the movement of high strength wastewater to surface and groundwater. Contaminated flows not controlled at the source require some treatment. Constructed treatment wetlands for treating high strength agricultural discharges offer a low-cost and low-maintenance alternative. Only during the past 5–10 years has this technology been investigated seriously for treatment of livestock wastewater discharges even though treatment wetlands have been widely used to treat municipal and industrial wastewater for many decades.

The Natural Resources Conservation Service (NRCS), universities in the USA, provincial Conservation Authorities, and Ministries of Agriculture in Canada have been the frontrunners of treatment wetland technology for the agriculture industry. For example, in Kentucky, more than 20 full-scale treatment wetland systems have been installed since about 1992 with assistance from the NRCS. A long-term monitoring program is underway to track the performance of these systems. Several universities including Purdue University, Auburn University, Oregon State University, Texas A&M University, North Carolina State University and the University of Connecticut have carried out testing on treatment wetlands (DuBowy and Reaves, 1994). Some of these sites have multiple wetland systems that are operated at several water depths and varying hydraulic and nutrient loading rates, and are vegetated with a variety of plant species.

Across southern Ontario, Canada, the conservation authorities have installed nine treatment wetland systems since 1993 and anticipate preparing a report that will provide guidance for the future direction of this technology in that province. In Nova Scotia, Canada, the Department of Agriculture and Marketing sponsored a 3-day workshop in Fall 1994 during which Department of Agriculture and Marketing engineers attended a training course on the theory and design of treatment wetland systems. Following the seminar, three treatment wetland systems were designed and constructed. In 1996 two livestock treatment wetlands were constructed in Manitoba.

2.1. Treatment wetland design guidance

The use of wetlands for treatment of wastewaters is an emerging technology in North America and worldwide. Existing treatment wetlands have a wide variety of engineering designs, wetted areas, flow rates, inflow water qualities, plant communities, hydrologic regimes, effluent limitations and monitoring requirements. Until recently, an engineer or regulator considering the use of wetland technology for a specific treatment need had to search for information to determine basic area and pretreatment levels necessary to achieve effluent criteria. Several handbooks (US Environmental Protection Agency, 1988; Water Pollution Control Federation, 1990; Davis, 1995; Reed et al., 1995; Kadlec and Knight, 1996) provide useful syntheses of existing knowledge concerning the design of new wetlands. The NRCS has published guidelines for treating livestock wastewaters (US Department of Agriculture Soil Conservation Service, 1992). Efforts are currently in progress to summarize and assess the SF treatment wetland technology and to update the EPA constructed wetland design manual.

2.2. North America Treatment Wetland Database (NADB)

Information on the effects of wetlands on water quality and the effects of these wastewaters on wetland biota have been collected at many operational treatment wetlands. This information was widely scattered in scientific journal articles, monitoring reports to agencies, consultant reports, and private databases. A framework to record and update this expanding knowledge was necessary to make information available to engineers and scientists nationwide to eliminate duplication of effort and to continue to refine the empirical design equations now in use.

During the period 1991–1993, the NADB was used to catalog information from 206 natural and constructed treatment wetlands (Knight et al., 1993). The NADB has been widely distributed to the engineering, scientific, and regulatory communities. The electronic files are available from the EPA (the contact is Don Brown in Cincinnati, OH; tel.: +1-513-569-7630). Version 2.0 of the NADB includes additional information from treatment wetlands, including the data summarized in this paper from livestock wastewater treatment wetlands. NADB version 2.0 is available from EPA through the same source.

Types of information included in the NADB version 2.0 include treatment wetland site locations, population served, capital and operating costs, design details, operating data for water quality, habitat data, data for trace metals and organics, biomonitoring results, human use data, permit conditions, published reports and literature, and key contact people for each system. These data are cataloged into 12 linked data files.

The primary purpose of the wetland treatment database effort was to develop a summary of existing treatment wetland information that could be expanded to accommodate additional information in the future. Design and operational data that affect assimilation rates were summarized for each system to allow regression analysis and the refinement of empirical design equations.

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

3. Livestock Wastewater Treatment Database (LWDB)

The NADB was developed to store and retrieve information about all types of treatment wetlands. The format for the NADB was modified slightly to accommodate the unique characteristics of the livestock wastewater treatment wetland systems described in this paper. Additional fields that were developed for livestock wetlands included types of livestock, numbers of animals and agricultural category (dairy, cattle, swine, poultry, and aquaculture), and operational data categories for conductivity, total dissolved solids (TDS), volatile suspended solids (VSS), chemical oxygen demand, temperature and pH. Because the NADB and LWDB utilized similar data formats, it was relatively easy to combine them in the NADB version 2.0. These data can also be easily separated to conduct analyses for individual treatment wetland categories. For this paper, new data analyses are limited to the LWDB.

3.1. LWDB structure

Six database files with data pertinent to the use of North American wetlands for treatment of high strength livestock wastewaters were developed (CH2M HILL and Payne Engineering, 1997). LWDB files were given names reflective of their contents (within the eight-letter DOS limitation): *sites*, *systems*, *cells*, *operate*, *literat* and *people*. Separate database files were developed because of the hierarchical nature of the data (i.e. one site may have several systems, and one system may have multiple cells). Separate files obviate the need for repetitive (overlapping) data.

The *sites* file ties basic information about each site, such as site name, state, community, and EPA region, to its particular site number. Unique numbers were assigned to wetland sites for this project. The inherent value of any particular number is meaningless; its purpose is to ensure that information about each site remains distinct throughout the tables and that these various database files can be cross-referenced. There are 65 fields containing 239 characters in this file. The 'checkoff' fields are the smallest, with a width of one character. Checkoff fields contain an 'X' to indicate that information for a particular parameter exists in the six files.

The *systems* database file describes each system at a site. Systems are defined as single or parallel wetland treatment areas that have separate outflow monitoring stations. A single system may have multiple cells arranged in series. Information entered here includes site name and number, system name and number, total number of cells, origin, hydrologic type, and design area in hectares (ha) and flow in m^3/day. There are 22 fields and 197 characters in the *systems* file.

The *cells* file contains design information for each cell in a system, including site number, system number, cell number, hydrologic type (surface flow—SF, or subsurface flow—SFF), plant species names for resident vegetation, and cell length and width. Cells are wetland areas that are clearly delineated from other treatment areas by dikes or uplands and that have recognizable inlet and outlet points. There are 33 fields and 364 characters in the *cells* database file.

The *operate* file is the largest of the six linked database files, both in terms of number of records and character widths. It contains all operational data for specific cells within a specific system for a specific time period. Efforts were made to provide average data on a seasonal basis, though data for monthly, annual, or other time periods also were included. Data for 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), NH_4-N, NO_3-N, total nitrogen (TN), organic nitrogen, total phosphorus (TP), dissolved phosphorus, dissolved oxygen (DO), fecal coliforms, conductivity, total dissolved solids (TDS), volatile suspended solids (VSS), chemical oxygen demand (COD) and water temperature are included in this file. There are 110 fields and 904 characters in the *operate* file.

The *literat* file contains selected references to literature documents for systems included in the six database files. Up to three individual authors can be entered, allowing for their selective retrieval. There are 14 fields and 508 characters in the *literat* file.

The *people* file is the smallest of the seven files in terms of number of fields available. One name per record was entered. A coded field ties the recorded individual to his or her involvement with the wetland treatment system, such as researcher, engineer, designer, or operator. There are 13 fields and 325 characters in the *people* file.

3.2. Database contents

The LWDB includes 68 sites with a total of 135 separate systems. The higher number of systems reflects the presence of multiple systems (separate inflow and outflow points) at a single site. All sites in the LWDB are constructed wetlands. Eighty-three percent of these systems are SF, and the rest are SSF or other. Ninety percent of these systems have marsh vegetation; the remainder are open water, or dominated by floating aquatic plants, shrubs, or of unknown vegetation types. Seventy-two of these systems are research facilities. Many of the others are larger-scale demonstration systems. Most of the systems included in the database are being used for some form of research and technology development.

Of the treatment wetland sites in the LWDB, 38 receive dairy farm wastewaters, 19 receive wastewaters from swine operations, eight receive cattle feeding wastewaters, two are aquaculture systems, and one is a poultry farm operation. Livestock wastewater treatment wetlands occur throughout the USA in most EPA regions (all but regions 2, 8 and 9) and throughout Canada. Region 4 (southeastern USA) has the largest number of sites and systems, followed by Canada.

The LWDB includes design information for 135 systems with a total of 278 individual treatment cells. Multiple cells in a system may function in series or in parallel.

The LWDB includes operational data from 48 treatment wetland systems at 22 sites with a total of 1390 individual records that include data for multiple parameters. Table 1 summarizes the wetland long-term and annual average operational performance data.

The LWDB includes 89 citations to scientific journal articles, system design and data reports, and other documents related to the wetland systems. These literature citations, listed and sorted by site number, should be consulted for more detailed information on each system in the database.

In some cases, no published information is available for operating treatment wetland systems. For these systems, the best sources of more information are (1) the operator or system manager, (2) a researcher working with the system, or (3) the system engineer who will know design considerations and may be involved in performance assessment. The LWDB provides contact information for 37 researchers knowledgeable about the design and operation of these systems.

4. Design summary

4.1. System age

The use of wetlands for treating concentrated animal wastes is a relatively new idea. The oldest recorded system in North America is the Brenton cattle operation in Iowa which started in 1930. All of the other sites are more recent with the oldest being Sand Mountain, AL, started in 1989; and the Newton and Hattiesburg, MS, systems started in 1989. The majority of the other systems started operating in 1993 and 1994. Newer systems constructed in 1995 and 1996, may not have been discovered through the literature review.

4.2. Treatment wetland area and pretreatment

The majority of the wetlands engineered for livestock wastewater treatment are small, with an average system size of 0.6 ha and a median size of 0.03 ha. The majority of the swine, poultry and dairy treatment wetland systems are less than 0.1 ha. Many of these systems were designed for research purposes and not as full-scale installations. Most of the Kentucky swine systems are larger than 1 ha. The only large animal waste treatment wetland in the LWDB is the Brenton Cattle system in Dallas Center, IA, with an area of about 47 ha.

All of the wetland systems in the LWDB have some form of pretreatment. The most common form of pretreatment is a settling basin or anaerobic lagoon. Performance of these facilities was not documented for this study but other published results indicate that 50–75% of the total BOD_5 and TSS in the raw livestock wastewaters is typically removed through pretreatment (US Department of Agriculture Soil Conservation Service, 1992).

4.3. System design flow

Only a few systems report design flow. The majority of these systems had a design flow of less than 10 m^3/day. The swine waste wetland at Delmarva Farms in Maryland reported the highest design flow (103 m^3/day).

Table 1
Average treatment wetland performance for removal of BOD_5, TSS, NH_4-N and TN in the Livestock Wastewater Treatment Wetland Database

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

4.4. Hydraulic loading rate

The average hydraulic loading rate for the treatment wetlands in the database was 4.7 cm/day, and the median was 3.9 cm/day. Average hydraulic loading rates for specific waste categories were 5 cm/day for dairy, 5.5 cm/day for poultry and 3.8 cm/day for swine. Only two experimental cells at Newton, MS, had operational hydraulic loading rates greater than 10 cm/day. The Hernando, MS, and Kellog Wetland in Connecticut, both treating dairy wastewaters, had operational hydraulic loading rates less than 1 cm/day.

4.5. Length-to-width ratio

Length-to-width ratios were reported for 206 wetland cells. The average ratio was 6.5:1, and the median ratio was 5.1:1. The minimum ratio was 0.5:1 and the maximum was 60:1 at the Region of Ottawa-Carlton system in Ontario, Canada.

4.6. Design water depth

Design water depth information was available for 168 wetland cells. The average design depth was 38 cm, and the median was 30 cm. The minimum depth was less than 1 cm, and the maximum design depth was 120 cm.

4.7. Bottom slope

Cell bottom slope was reported for 83 cells. The average slope in the direction of flow was 0.7%, and the median slope was 0.5%. The minimum design slope was 0%, and the maximum was 2%.

4.8. Vegetation

The most commonly used plant species for livestock wastewaters, in order of their occurrence in treatment wetland cells, were cattails (*Typha* spp.), bulrush (*Scirpus* spp.) and common reed (*Phragmites australis*).

5. Performance summary

Operational data from the LWDB for BOD_5, TSS, NH_4-N, and TN are summarized in Table 1. These statistics are global average values and do not necessarily reflect the performance capability of any single system. Carefully designed and operated treatment wetlands would be expected to exceed these performance expectations, while systems with less than optimal plant communities, flow distribution, or water depth control might perform at lower levels.

5.1. Five-day biochemical oxygen demand (BOD_5)

Average inflow and outflow BOD_5 concentrations for the LWDB were 263 and 93 mg/l, for an average concentration reduction efficiency of 65%. Median BOD_5 inflow and outflow concentrations were 81 and 31 mg/l for an efficiency of 62%. The maximum average inlet BOD_5 was 3162 mg/l at the University of Connecticut Kellogg farm receiving dairy wastes.

Fig. 1 summarizes the observed relationship between BOD_5 mass loading and treatment wetland outflow concentration for all of the individual data points in the LWDB. A simple regression equation fitted to these data allows the estimation of the average BOD_5 wetland outlet concentration C_2 based on the inlet concentration (C_1):

$$C_2 = 0.766 C_1^{0.878} \quad (1)$$

where $R^2 = 0.74$, $C_1 = 1–1679$ mg/l, $C_2 = 1–682$ mg/l. The inclusion of hydraulic loading rate (q) in this regression does not improve the value of R^2. Therefore, this equation cannot be used to estimate wetland area for BOD_5 reduction.

5.2. Total suspended solids

Average inflow and outflow TSS concentrations for the LWDB were 585 and 273 mg/l, for an average concentration reduction efficiency of 53%. Median TSS inflow and outflow concentrations were 118 and 51 mg/l for a reduction efficiency of 57%. The maximum average inlet TSS was 11,300 mg/l at Norwood Dairy Farms in LaGrange, TN.

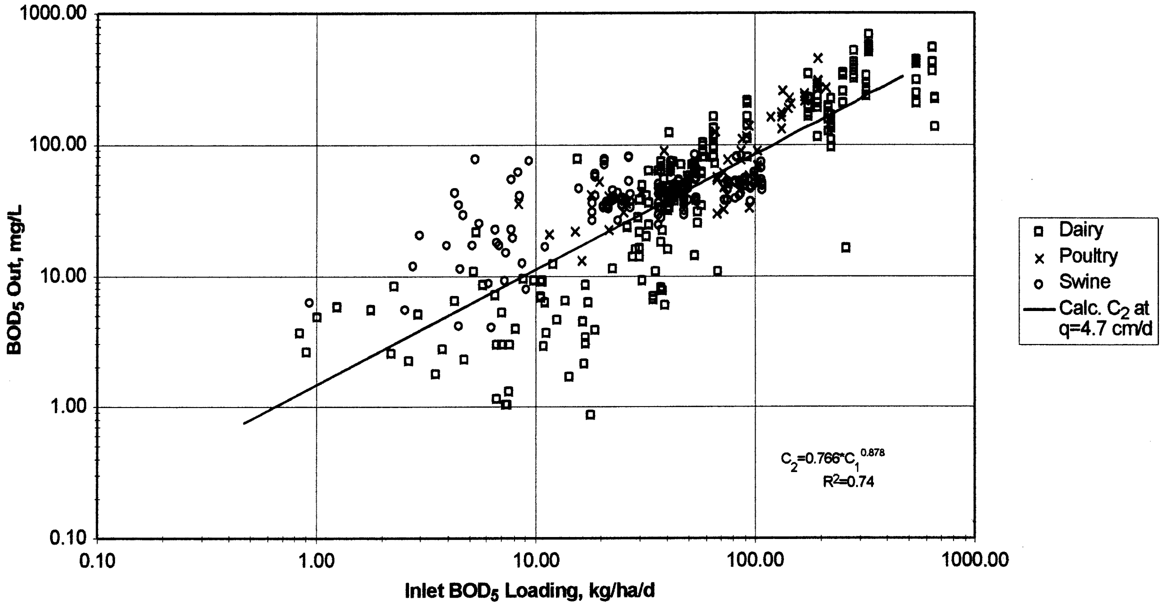

Fig. 1. Observed relationship between BOD_5 mass loading to livestock wastewater treatment wetlands and BOD_5 outlet concentration for average data in the LWDB.

Fig. 2 summarizes the observed relationship between TSS mass loading and treatment wetland outflow concentration. A simple regression equation was applied to these data to estimate the average TSS wetland outlet concentration C_2 based on the inlet concentration (C_1) and the average inlet hydraulic loading rate (q):

$$C_2 = 2.334C_1^{0.582}q^{0.227} \quad (2)$$

where $R^2 = 0.30$, $C_1 = 4–1270$ mg/l, $C_2 = 2–641$ mg/l, $q = 0.3–49$ cm/day. This low R^2 value suggests a poor fit of a line to the data points, and therefore the use of the equation for estimating C_2 should be used with caution.

5.3. Nitrogen

Several forms of nitrogen are important in concentrated animal wastewaters. The majority of the TKN in most of the livestock wastewater systems is in the ammonium form. At the Auburn poultry system, ammonium averaged 84% of the TKN. At LSU, the ammonium fraction was 73%. At Pontotoc, the fraction was 86%, and at Sand Mountain, AL, the ammonium fraction averaged 82%.

The average inlet and outlet ammonium nitrogen concentrations for all of the systems in the LWDB were 122.2 and 63.7 mg/l, respectively; average reduction was 48%. The median values were 59.8 and 18.9 mg/l for an efficiency of 68%.

The average NH_4-N concentrations for cattle feeding are for only one wetland site, and are not typical of intense cattle feeding operations.

Inlet NO_3-N concentrations were generally low at most sites, which would be expected because of the anaerobic conditions found in most pretreatment systems. Average inflow and outflow concentrations were 3.6 and 2.3 mg/l for an average concentration reduction efficiency of 35%. The median concentration was reduced from 1.1 to 0.9 mg/l.

Average TN inflow and outflow concentrations were 254.1 and 147.5 mg/l, respectively, and the average TN concentration reduction efficiency was 42%. Median concentrations were 273.6 and 98.9 mg/l for a concentration reduction efficiency of 64%.

Fig. 3 summarizes the observed relationship between NH_4-N mass loading and treatment wetland outflow concentration. A simple regression equation fitted to these data results in a relatively good fit of a line to the data ($R^2 = 0.87$). Therefore, one can make an estimate of the average NH_4-N wetland outlet concentration C_2 based on the inlet concentration (C_1) and the average inlet hydraulic loading rate (q):

$$C_2 = 0.682 C_1^{0.874} q^{0.319} \quad (3)$$

where $R^2 = 0.87$, $C_1 = 3–1122$ mg/l, $C_2 = 0.6–951$ mg/l, $q = 0.3–48$ cm/day.

Fig. 4 summarizes the observed relationship between TN mass loading and treatment wetland outflow concentration. A simple regression equation fitted to these data allows the estimation of the average TN wetland outlet concentration C_2 based on the inlet concentration (C_1) and the average inlet hydraulic loading rate (q):

$$C_2 = 0.358 C_1^{1.016} q^{0.226} \quad (4)$$

where $R^2 = 0.81$, $C_1 = 21–1127$ mg/l, $C_2 = 4–958$ mg/l, $q = 0.3–7.8$ cm/day.

5.4. Phosphorus

Animal wastes typically contain organically bound phosphorus and dissolved inorganic phosphorus. These organic and inorganic forms can be analyzed together as TP. Both TP and dissolved phosphorus are reported in the LWDB. Fig. 5 summarizes the observed relationship between TP mass loading and treatment wetland outflow concentration. A simple regression equation fitted to these data allows the estimation of the average TP wetland outlet concentration C_2 based on the inlet concentration (C_1) and the average inlet hydraulic loading rate (q):

$$C_2 = 0.511 C_1^{1.008} q^{0.170} \quad (5)$$

where $R^2 = 0.70$, $C_1 = 3.5–107$ mg/l, $C_2 = 0.6–92$ mg/l, $q = 0.3–7.8$ cm/day.

It is noted that treatment efficiency for phosphorus may be higher during the initial years of operation and decline to a lower level at system maturity (Kadlec and Knight, 1996). The coefficient of determination ($R^2 = 0.70$) suggests the use of caution when using this equation to predict long-term, ongoing results.

5.5. Fecal coliforms

Fecal coliform bacteria are a component of wastewaters derived from warm-blooded animals and are used as an environmental indicator of poorly treated or untreated wastewater. Fecal col-

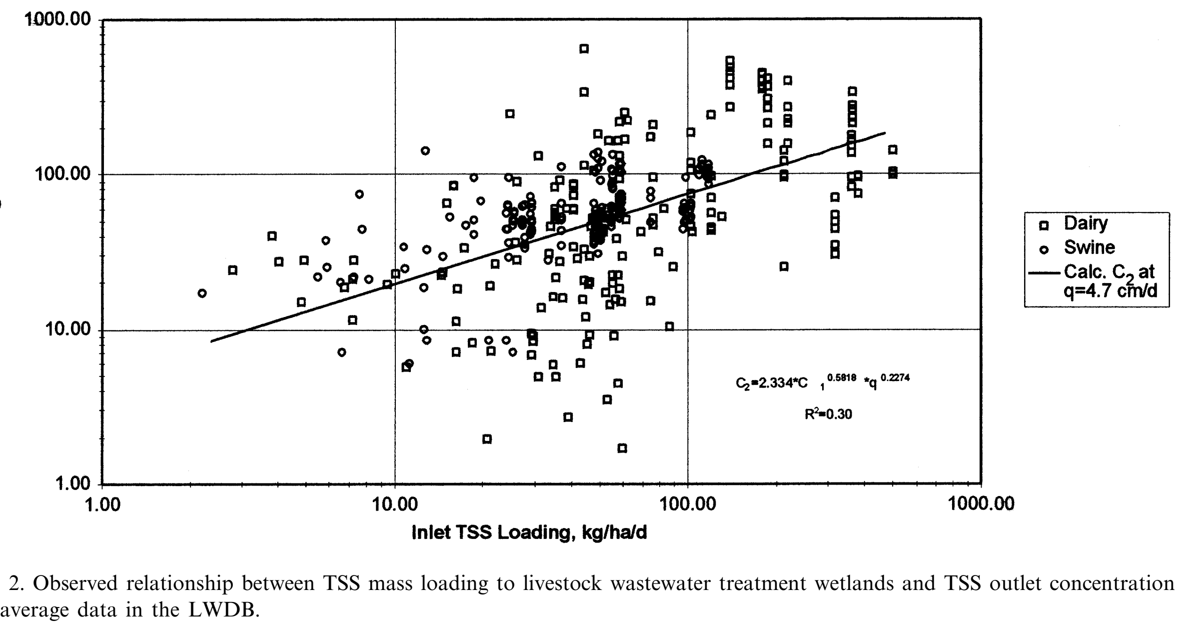

Fig. 2. Observed relationship between TSS mass loading to livestock wastewater treatment wetlands and TSS outlet concentration for average data in the LWDB.

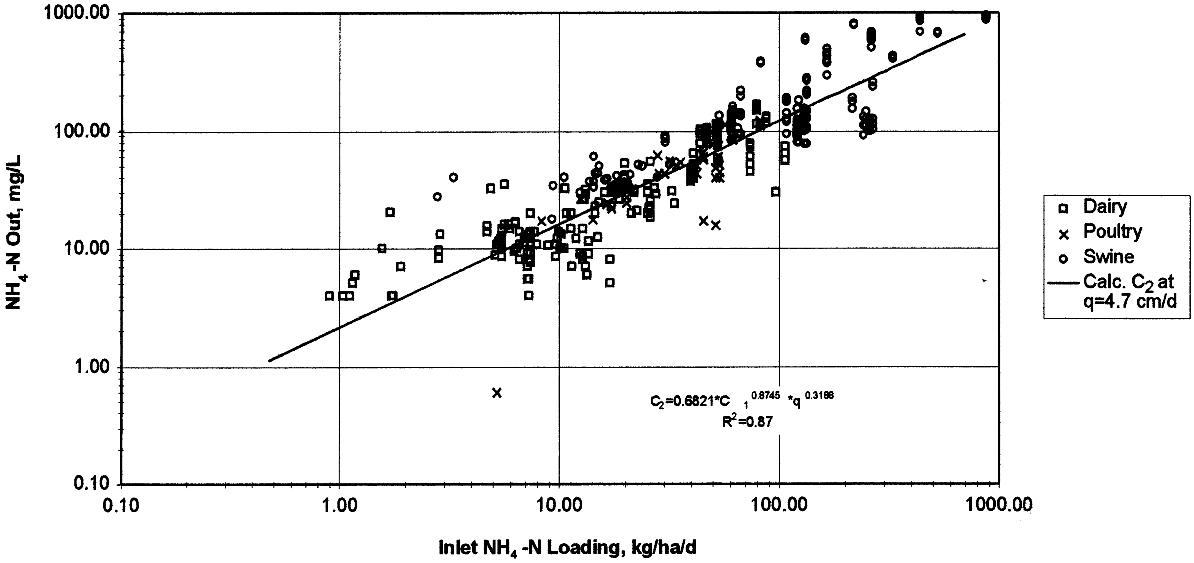

Fig. 3. Observed relationship between total ammonia nitrogen mass loading to livestock wastewater treatment wetlands and total ammonia nitrogen outlet concentration for average data in the LWDB.

iform densities in raw wastewaters are typically high and can be reduced before wetland discharge by pretreatment or dilution. Inlet fecal coliform densities in the LWDB are highly variable, ranging up to a system average of 1,030,000 col/100 ml in one dairy system. The average wetland reduction for fecal coliforms was from 160,477 to 13,424 col/100 ml for an efficiency of 92%. The median concentrations were 1742 col/100 ml and 55 col/100 ml for a reduction efficiency of 97%.

Planners and designers should be aware that any discharge to receiving streams would probably not be allowed in most states with these high outlet concentrations. It is imperative that discharge criteria be checked with the state regulatory agency before designing for a discharge.

5.6. Salts

The general salt content of concentrated animal wastewaters can be surmised by measuring conductivity and TDS. Treatment wetlands have little effect (other than dilution or concentration by precipitation/evapotranspiration) on concentrations of these environmentally conservative parameters. Average concentration reduction efficiencies were 21% for conductivity ($n = 31$) and 15% for TDS ($n = 19$).

5.7. Other parameters

Temperature data were reported for some of the treatment wetland systems. The typical effect of the wetland on water temperature is an approach to ambient air temperature. The net effect average temperature change noted in the LWDB was a decrease of about 1°C.

Average wetland inlet pH values ranged from 6 to 8.4 units. In most cases, pH changed very little between the inlet and outlet wetland stations.

Dissolved oxygen concentrations are typically below saturation in wetland surface waters. This observation was true in the concentrated livestock wastewater treatment wetlands with low dissolved oxygen at both the wetland inlet and outlet. The average dissolved oxygen concentration declined from 2.5 to 1.6 mg/l for the livestock wastewater treatment systems.

Few data were reported on changes in chemical oxygen demand (COD) through treatment wetlands. Average concentrations decreased from 1004 to 536 mg/l for a reduction efficiency of

47%. The highest average COD reduction occurred for dairy wastes from 2003 to 946 mg/l for an efficiency of 53%; COD for one poultry facility declined from 405 to 290 mg/l for an efficiency of 28%.

Fig. 6 summarizes the observed relationship between COD mass loading and treatment wetland outflow concentration. Outlet COD concentration is clearly leveling out at a 'background' concentration of about 50–100 mg/l at low input loadings. A simple regression equation fitted to these data allows the estimation of the average COD wetland outlet concentration C_2 based on the inlet concentration (C_1) and the average inlet hydraulic loading rate (q):

$$C_2 = 1.042 C_1^{0.851} q^{0.259} \tag{6}$$

where $R^2 = 0.89$, $C_1 = 49–3810$ mg/l, $C_2 = 34–2172$ mg/l, $q = 0.7–6.5$ cm/day.

6. First-order model reaction rates

Typical treatment wetland concentration profiles decline over distance from the inlet in an approximately exponential pattern. Pollutant concentrations follow this pattern over time in batch experiments and with distance from inlet to outlet. Some pollutant concentrations decline to near-zero values while others level off to some background concentration. The few transect water quality data from livestock wastewater treatment wetlands follow this same exponentially-declining pattern (CH2M HILL and Payne Engineering, 1997).

The simplest model that summarizes this behavior is a first-order reaction with a zero-order return (Kadlec and Knight, 1996):

$$J = k(C - C^*) \tag{7}$$

where J is constituent reduction rate (g/m²/year), k is first-order rate constant (m/year), C is constituent concentration (mg/l) and C^* is background constituent concentration (mg/l).

The plug flow integration of Eq. (7) is (Kadlec and Knight, 1996):

$$\ln \frac{C_2 - C^*}{C_1 - C^*} = -\frac{k}{q} \tag{8}$$

where C_1 is inlet concentration (mg/l), C_2 is outlet concentration (mg/l) and q is hydraulic loading rate (m/year).

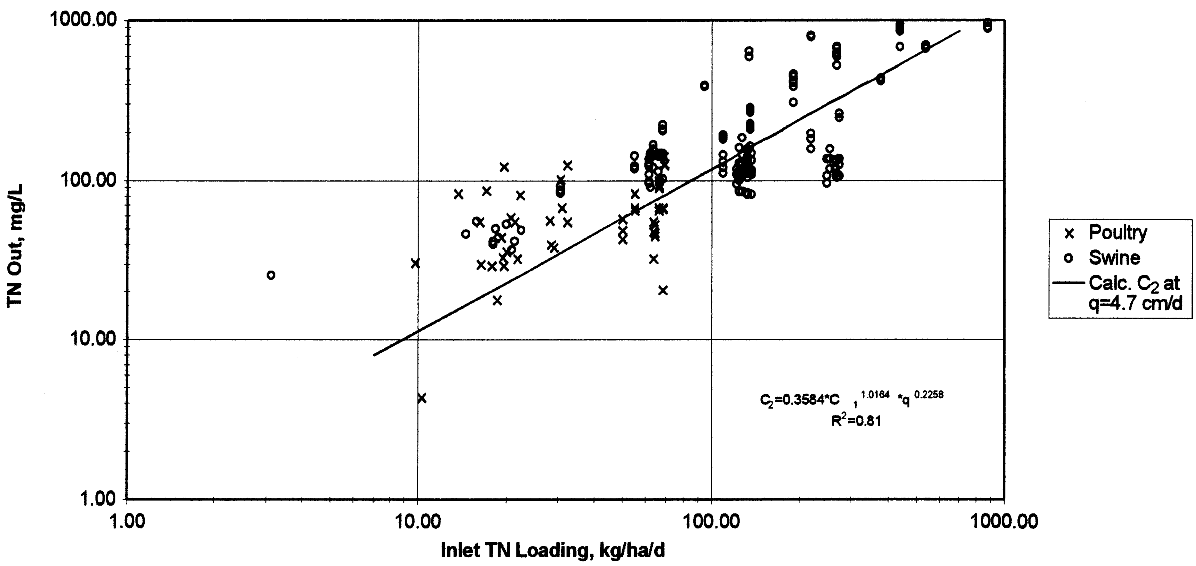

Fig. 4. Observed relationship between TN mass loading to livestock wastewater treatment wetlands and TN outlet concentration for average data in LWDB.

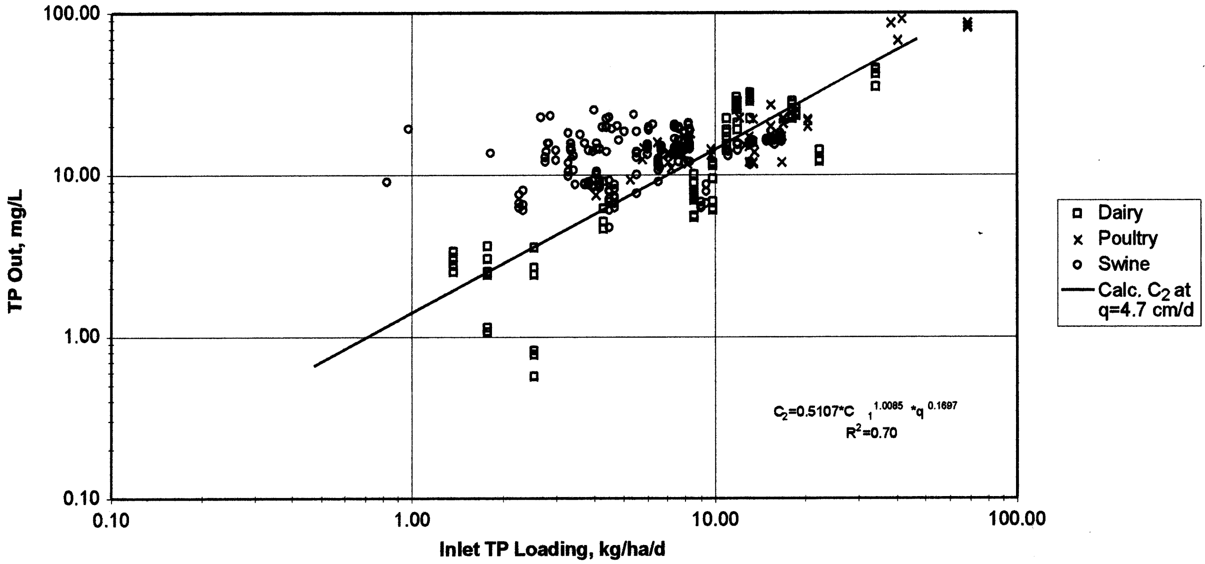

Fig. 5. Observed relationship between TP mass loading to livestock wastewater treatment wetlands and TP outlet concentration for average data in LWDB.

While treatment wetland hydraulic efficiency is typically intermediate between complete mix and plug flow (approximated by three complete-mix tanks in series; Kadlec, 1994), the area-based, first-order rate constant k derived using Eq. (8) is conservative. As long as k values in Eq. (8) are used to predict treatment wetland performance for a wetland at least as efficient hydraulically as the typical system used to generate the rate constant, these rate constants can be used for design.

The area-based first order rate constant derived using Eq. (8) is typically based on time-averaged data to eliminate variability due to short-term variation of inflow and outflow quality and changing flow patterns. For this study, monthly or longer averaging periods were used for data analysis.

Water temperature is known to affect some treatment wetland rate constants. This effect can be modeled as a modified Arrhenius equation as follows (Kadlec and Knight, 1996):

$$k_T = k_{20}\theta^{T-20} \quad (9)$$

where $k_{20} = k$ at 20°C (m/year), $k_T = k$ at T°C (m/year), θ is theta value (dimensionless), T is water temperature (°C).

A spreadsheet routine (solver on Excel) can be used to simultaneously solve for k_{20}, C^* and θ values that minimize the sum of squares between actual and predicted C_2 when a detailed treatment wetland data set is available. For the concentrated animal waste treatment wetlands represented in the LWDB, sufficient data were available to make these estimates only for livestock treatment wetlands at Auburn, AL, Newton and Pontotoc, MS, Purdue, IN and Corvallis, OR.

6.1. Five-day biochemical oxygen demand (BOD)

Table 2 summarizes the values of $k_{20\,\mathrm{BOD}}$, C^*_{BOD}, and θ_{BOD} derived from concentrated livestock wastewater treatment wetlands. The average value for $k_{20\,\mathrm{BOD}}$ was 22 m/year with individual system values ranging from 7 to 68 m/year. C^*_{BOD} could not be accurately determined from these high concentration data sets and an estimate of 8 mg/l was used for model calibration. Temperature had a slight positive effect on the first-order rate constant for BOD_5 with an overall average value of $\theta_{\mathrm{BOD}} = 1.03$. The range of estimated θ values was from 0.94 to 1.07. Kadlec and Knight (1996) reported an average k_{BOD} from systems in the

NADB as 34 m/year with $C^* = 3.5 + 0.053C_1$ where C_1 is inlet BOD concentration. θ_{BOD} was reported as approximately 1.00 for treatment wetlands receiving lower BOD_5 mass loadings.

6.2. Total suspended solids

Table 2 provides a summary of the estimated k–C^* model parameter values for TSS from the LWDB. The average $k_{20\,TSS}$ was 21 m/year with individual system values ranging from 3 to 51 m/year. A C^*_{TSS} value of 20 mg/l was used for model calibration. Temperature had little apparent effect on TSS reduction in the LWDB treatment wetlands ($\theta_{TSS} = 1.01$). Kadlec and Knight (1996) reported that k_{TSS} is highly variable for different waste types and not affected by temperature ($\theta_{TSS} = 1.00$).

6.3. Nitrogen

Apparent rate constants were calculated for NH_4-N reduction in treatment wetlands (Table 2). These rate constants may be lower than actual NH_4-N rate constants that incorporate the sequential transformation of organic N to NH_4-N. The average estimated value of $k_{20\,AN}$ equals 10 m/year with individual system values ranging from −1 to 26 m/year. Temperature does have an effect on the removal rate of NH_4-N with an average value of $\theta_{AN} = 1.05$. A C^*_{AN} value of 3 mg/l was used for model calibration. Kadlec and Knight (1996) reported an average of 18 m/year with a C^*_{AN} of about zero and $\theta_{AN} = 1.04$.

TN rate constants were estimated at three sites: Auburn Poultry, Pontotoc Swine and Purdue Swine. Table 2 summarizes these parameter estimates. The average $k_{20\,TN}$ was about 14 m/year with individual system estimates ranging from 5 to 32 m/year. A C^*_{TN} value of 10 mg/l was used for model calibration. The average effect of temperature on the TN rate constant was estimated as $\theta_{TN} = 1.06$. Kadlec and Knight (1996) reported an average $k_{20\,TN}$ from systems in the NADB as 22 m/year with $C^*_{TN} = 1.5$ mg/l and $\theta_{TN} = 1.05$.

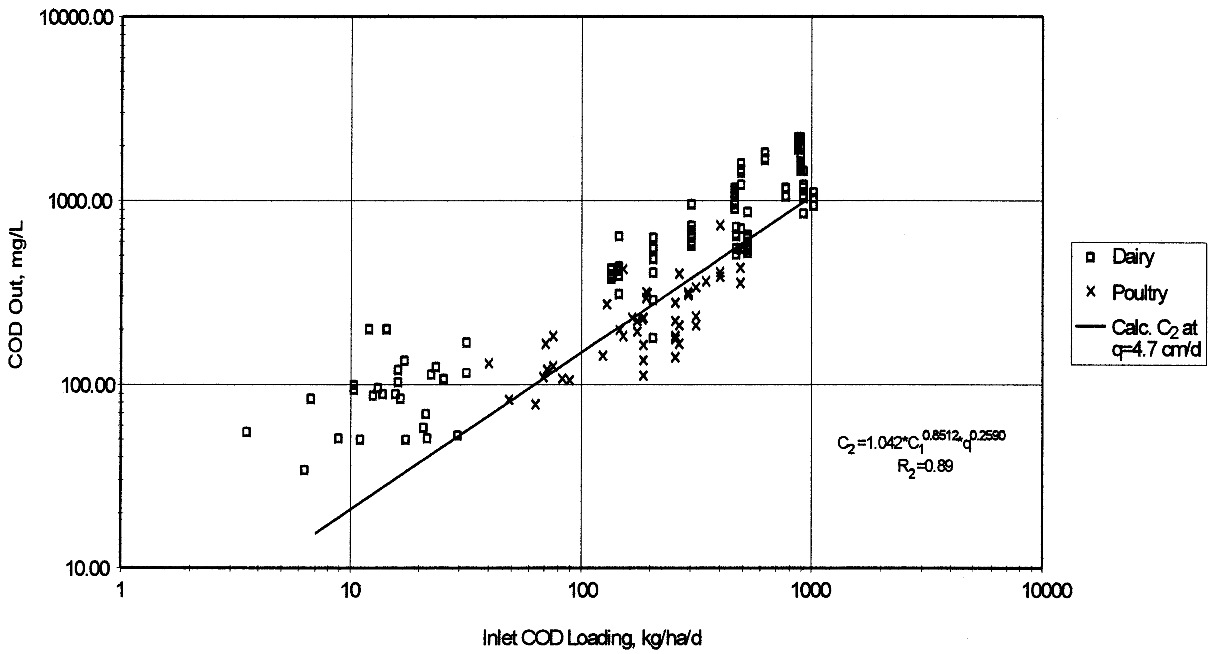

Fig. 6. Observed relationship between COD mass loading to livestock wastewater treatment wetlands and COD outlet concentration for average data in the LWDB.

Table 2
Summary of parameter values for use in the k–C^* model for sizing livestock wastewater treatment wetlands

Parameter	Livestock treatment wetland data			Kadlec and Knight (1996)		
	k	C^*	θ	k	C^*	θ
BOD_5	22	8	1.03	34	$3.5+0.053C1$	1.00
TSS	21	20	1.01	1000	$5.1+0.16C1$	1.00
NH_4-N	10	3	1.05	18	0.00	1.04
TN	14	10	1.06	22	1.50	1.05
TP	8	2	1.05	12	0.02	1.00

6.4. Total phosphorus (TP)

TP parameter values were estimated at four treatment wetland sites (Table 2). The average value of $k_{20\ TP}$ was about 8 m/year with a range of estimated values from 2 to 18 m/year. A C^*_{TP} value of 2 mg/l was used for model calibration. The average effect of temperature on the TP rate constant was estimated as $\theta_{TP}=1.05$ with a range of estimates from 0.99 to 1.14. Kadlec and Knight (1996) reported an average $k_{20\ TP}$ from systems in the NADB as 12 m/year with $C^*_{TP}=0.02$ mg/l and $\theta_{TP}=1.0$.

7. Conclusions

The development of the treatment wetland technology for the agricultural industry reflects the collective efforts of scientists and engineers who have designed and studied pilot and full-scale wetland treatment systems. Historical studies, full-scale projects, published literature, and conferences have been key to providing a scientific basis for the technology's development.

Constructed and natural wetlands are being used to treat wastewaters from a variety of types of concentrated livestock operations. This technology is relatively new for these applications; however, at least 68 separate sites are currently using treatment wetlands and more are being constructed each year. The livestock industry has the distinct advantage of being able to draw upon the considerable data available from other treatment wetland applications. The development and analysis of the LWDB and the NADB have indicated that a number of the principal pollutants typical of livestock wastewaters are removed in treatment wetlands at about the same rate as these constituents in other wastewater types. Thus, recently published design methods described by Kadlec and Knight (1996) can be applied with some confidence to the preliminary design of wetlands treating livestock wastewaters.

Considerable published data exist for the design, construction and early years of operation of many livestock wastewater treatment wetlands. Increasing knowledge about removal rate constants, background concentrations and temperature effects on removal should be a goal of ongoing and future research in this field. As these systems mature and steady-state data become available, findings should be re-analyzed and published to provide further design and operational guidance. Also, more complex, multi-parameter models should be developed to incorporate apparent effects of dissolved oxygen, pH, plant populations and other environmental factors on treatment wetland performance.

Acknowledgements

Funding for this research was provided by the Gulf of Mexico Program (GMP), Nutrient Enrichment Committee. Dr Douglas Lipka was the acting director or the GMP. Co-chairs of the nutrient enrichment committee were Lon Strong of the Natural Resources Conservation Service and Dugan Sabins of the Louisiana Department of Environmental Quality. The US Environmental Protection Agency (EPA) provided financial support for this project under the GMP. The EPA project officer was Lloyd Wise. This research was completed by CH2M HILL under a contract with the National Council of the Paper Industry for Air and Stream Improvement (NCASI). Dr Robert Fisher was project manager at NCASI. A portion of this research was funded through the Alabama Soil and Water Conservation Committee (ASWCC). Stephen Cauthen was executive director of ASWCC.

References

CH2M HILL, 1997. Constructed Wetlands and Wastewater Management for Confined Animal Feeding Operations. Gulf of Mexico Program Public Information Center, Stennis Space Center, MS.

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

Davis, L., 1995. Agricultural Wastewater. In: A Handbook of Constructed Wetlands. A Guide to Creating Wetlands in the Mid-Atlantic Region, vol. 3. US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS).

DuBowy, P., Reaves, R. (Eds), 1994. Constructed Wetlands for Animal Waste Management. Proceedings of workshop sponsored by the Conservation Technology Information Center, the US Department of Agriculture Soil conservation Service (USDA), US Environmental Protection Agency (EPA) Region V, and Purdue University Agricultural Research Program, 4–6 April 1994, Lafayette, IN.

Kadlec, R.H., 1994. Detention and mixing in free water wetlands. Ecol. Eng. 4, 1–36.

Kadlec, R.H., Knight, R.L., 1996. Treatment Wetlands. Lewis Publishers, Boca Raton, FL.

Knight, R.L., Ruble, R.W., Kadlec, R.H., Reed, S.C., 1993. In: Moshiri, G.A. (Ed.), Wetlands for Wastewater Treatment Performance Database. Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL, pp. 35–58.

Payne, V.W.E., Knight, R.L., 1997. Constructed Wetlands for Animal Waste Treatment. A Manual on Performance, Design, and Operation With Case Histories. Gulf of Mexico Program, Stennis Space Center, MS.

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

US Department of Agriculture (USDA) Soil Conservation Service (SCS), 1992. Agricultural Waste Management Field Handbook. SCS, Washington, DC.

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

Water Pollution Control Federation (WPCF), 1990. Natural Systems for Wastewater Treatment. Manual of Practice FD-16. WPCF, Washington, DC.