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ARIEL IP Address: 130.74.184.144
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ARDT, M. & KREMLING, K,
eawater Analysis, Second Ed
mbH, Weinheim, 419 pp
Vetlands for water polishing
wetlands – In: MITSCH, W J
ands, Old World and New
Science, Amsterdam
LINK, J. G., 1993. *Wetlands* –
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nd Shallow Continental Wa-
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. ROMERO, C. GARCÍA, De-
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A constructed wetland system for treating agricultural waste

Charles M. Cooper, Scott S. Knight and Samuel Testa, III

Introduction

The beneficial role of aquatic plants for improving water quality has been evaluated for decades (BOYD 1970, SHEFFIELD 1967). Re-establishment of wetlands is often recommended (KLOETZLI 1981, JONES & LEE 1980) where water quality has deteriorated since their removal Wetlands can remove nutrients, organic chemicals, heavy metals, and sediments from inflow. SIMPSON et al (1983) and LAN et al (1992) demonstrated the effective role that wetlands play in trapping heavy metals. Research on natural wetlands indicates that physical, chemical, and biological processes that occur in wetlands are similar to those occurring in sewage treatment plants Thus, many recent nutrient uptake and cycling studies conducted on natural and constructed wetlands have been concerned with their potential use for natural sewage treatment (SIMPSON et al. 1983, DOLAN et al. 1981) or as water purifiers (NICHOLS 1983). Over 150 constructed wetland systems are currently in use within the United States for treatment of municipal and industrial wastewater (REED & BROWN 1992)

The focus on applied uses of natural and constructed wetlands (REED 1991) has intensified with little consensus on design Small municipalities have found constructed wetlands an alternative to conventional waste treatment plants (GEARHEART et al. 1989). Several projects for evaluating the ability of constructed wetlands to process animal effluent, a major source of rural water quality deterioration, have been initiated across the United States (HOLMES et al. 1992, ULMER et al. 1992, PAYNE et al. 1992). The Natural Resources Conservation Service (NRCS-Mississippi) and the Agricultural Research Service (ARS) National Sedimentation Laboratory in Oxford, Mississippi, USA, cooperated in constructing and evaluating an on-farm dairy waste treatment project which uses a constructed wetland for processing. The purpose of this paper is to assess the impact of wetland cells as treatment systems for cattle waste.

Study area and methods

A constructed wetland for treatment of dairy wastewater was implemented in DeSoto County, Mississippi, during 1990 on a 100 cow dairy operation The NRCS designed and constructed a 40 m × 52 m primary lagoon and three 6 m × 24 m wetland cells in April, 1990 (Fig 1) All cells were immediately planted with bulrush (*Scirpus validus*) rhizome cuttings at 0 3 m intervals. Standing water (5–10 cm) was maintained in the cells for the remainder of the year. The anaerobic lagoon received direct inputs from milking equipment and tank cleanings, milking barn washings, loafing area runoff, and rainfall Waste production was 10 cu m/day

Plant growth in the cells was rapid By September, 1990, the cells were covered by a uniformly dense monoculture with the majority of culms supporting flowering/seeding heads. Natural senescence occurred in November and December. Re-emergence of bulrushes from rhizomes occurred in February, 1991, through the litter created by the previous year's growth. As the study progressed, the mat of dead plant material restricted plant emergence, and biomass removal was necessary. Duckweed (*Spirodela polyrhiza*) spread to cover nearly all available water surface by May, 1991 In April, gravity flow from the lagoon to the wetland cells began functioning via 7.6 cm diameter PVC pipe to the 3 wetland cells Discharges to each cell were initially calibrated to yield 3.0 L/min

Since both gate and ball valves used for flow regulation caused settling of solids in feeder pipes, threaded end caps with orifices sized to achieve desired flow rates were attached at the end of cell standpipes Using this method, a cell inflow rate of 1.0 L/min was implemented. During summer, 1991, another cell, Cell 4, was constructed in series with Cell 1 to allow greater loading capacity and assessment of further treatment (Fig 1)

A constant head tank was placed on the lagoon levee and attached to the cell effluent pipe cells A timer-controlled electric pump maintained water in the tank, allowing the cells to receive consistent inflow Walk ways were constructed over Cell 2 for sampling in-cell processes with minimum disturbance Lagoon samples were taken from the end of the outflow control platform at a depth of 0.3 m (level of effluent pipe to cells) Water quality parameters were measured according to APHA (1989) guidelines (for further details, see COOPER et al 1993).

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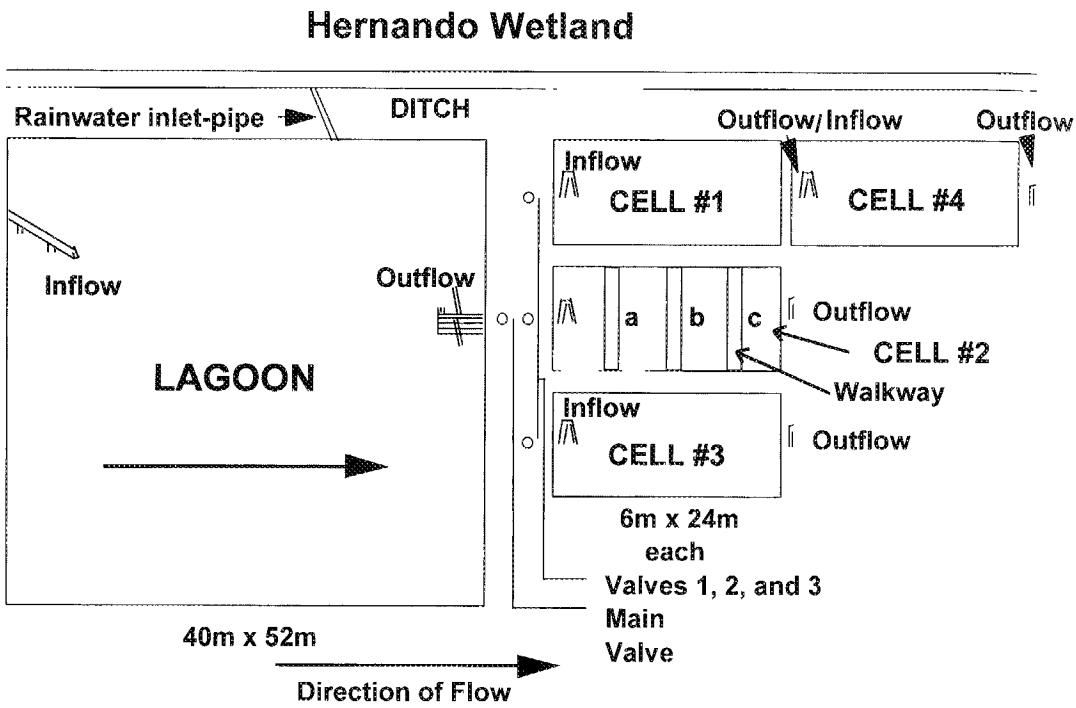

Fig 1 Drawing of lagoon/wetland cell construction at Hernando Wetland on Alan Scott Farm, DeSoto County, Mississippi, USA.

Results and discussion

Measured parameters varied with season and as the system matured. Overall differences in individual parameters were calculated from mean inflow and outflow measurements over the duration of the experiment. Eighteen environmental parameters were monitored at biweekly intervals from May, 1991, to April, 1994 Physical and chemical variables were measured at cell inflow and outflow. Trapping Efficiency (TE) inflow does not attempt to differentiate cell-specific processes. In addition, 3 walkways were constructed equal distances apart in Cell 2 for measurement of in-cell processes. Average rainfall for the study area is 127 cm/yr. Precipitation was 101 cm, 132 cm, and 162 cm for the first, second and third years, respectively. Increasing rainfall amounts through the study period could effect interpretations of seasonal and long-term wetland functioning. Individual rainfall events resulted in temporarily increased discharge from the cells, turbulence, and dilution. Fluctuations in rainfall, variability in waste production, and weather conditions also influenced water depth in the anaerobic lagoon.

Inflow rates to the cells for most of the study period were targeted at 1.0 L/min. Actual inflows fell between 0 75 and 1.25 L/min at 84 % of sampling visits. The wetland cells did not discharge continually. Outflow was observed at 103 out of 181 sampling visits (57 % frequency). Of these 103 observations, 57 (55 %) were at a rate of less than 0.75 L/min, and 83 (81 %) at less than 1.25 L/min. Discharges in excess of 1.0 L/min were always associated with rainfall events. When no outflow occurred, measurements were taken after tilting the outflow standpipe until discharge resulted, and the pipe was flushed. This allowed within-cell reduction efficiencies to be calculated without the necessity of outflow. Parameters which showed little change as waste processing occurred are simply listed in Table 1.

Temperatures (Temp) at outflows from the constructed wetland were 10.9 % lower than at inflow stations because of shading by wetland plants and the shallower mass of water within

Table 1 Summary v

	TEMP	CON
Mean	17 8	343
Min	5 4	28
Max	30 3	773

	TEMP	CON
Mean	15 9	245
Min	1 5	103
Max	27 3	785

TEMP	CON
11%	28%

	TEMP	CON
Mean	15 1	174
Min	4 6	77
Max	26 0	356

11%	52%

1%	23%

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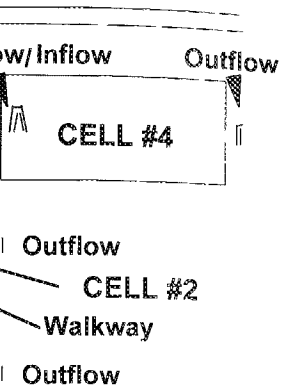

Table 1 Summary values for inflow and outflow stations.

	TEMP	COND	DO	PH	RED	TS	DS	SS	FOP	TP	NH3	NO3	CHL	BOD	COLIF
ALL INFLOWS															
Mean	17 8	343	3 7	7 0	-48	484	364	122	9 6	15 9	7 0	0 1	306	35 1	14526
Min	5 4	28	0 0	5 7	-259	176	72	0	0 9	1 3	0 1	0 0	0	9 7	40
Max	30 3	773	14 2	8 5	311	749	573	466	24 0	69 0	30 8	0 9	1505	80 0	101000
ALL OUTFLOWS															
Mean	15 9	245	1 9	6 3	18	331	285	49	5 5	7 4	1 3	0 1	65	8.9	1586
Min	1 5	103	0 0	5 7	-270	149	60	0	0 1	0 3	0 0	0 0	1	0 3	20
Max	27 3	785	7 3	7 4	395	605	554	332	15 5	22 8	10 8	3 3	759	48 0	19700
OVERALL REDUCTION															
	11%	28%	48%	10%	-1	32%	22%	60%	42%	53%	82%	-14%	79%	75%	89%
CELL 4 OUTFLOW															
Mean	15 1	174	3 1	6 7	115	239	192	49	2 4	4 5	0 4	0 1	45	5 9	2534
Min	4 6	77	0 3	6 0	-197	124	87	0	0 1	0 4	0 0	0 0	0	2 0	0
Max	26 0	356	12 5	7 8	340	506	357	308	9 0	16 0	1 2	0 6	721	17 2	19700
1i - 4o REDUCTION															
	11%	52%	28%	5%	-2058%	51%	49%	62%	80%	76%	94%	52%	88%	83%	79%
DIFFERENCE															
	1%	23%	-21%	-5%	-1921%	20%	27%	2%	37%	23%	13%	66%	10%	9%	-10%

Alan Scott Farm, DeSoto

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the wetland cells (Table 1). In winter, outflow water temperatures averaged 21 % lower than inflow temperatures.

Conductivity (Cond) decreased 28.5 % with passage through the constructed wetland cells. Greatest reductions occurred during the winter and spring seasons. Reductions increased each year of the study to a peak during spring of 1994 at 44 %. Conductivity declined from an inflow mean of 343 µmhos/cm to an outflow mean of 245 µmhos/cm.

Dissolved oxygen (DO) concentrations decreased by nearly half (49 %) when passed through the wetland cells. Increases were measured only during the initial three months of operation. Reduced oxygen levels were attributable to biochemical oxygen demand and duckweed which quickly colonized open water surface. Measurements during the study period declined from a mean of 3.7 mg/L for inflows to 1.9 mg/L at outflows.

Redox potential (Red) in the wetland cells increased an average of 137 %. Inflow measurements ranged from (−)259 to (+)311 with a mean value of (−)48.39. Outflow measurements ranged from (−)270 to (+)395 with a mean of (+)18. Research by ROGERS et al. (1991) suggested that increased redox potential in wetland waste treatment systems is due to plant presence, while a decrease in redox occurs in unplanted systems.

Dissolved solids (DS) removal was low (21.8 %), while suspended solids (SS) removal was relatively high at 60.5 %. Total solids (TS) were reduced by 31.6 % (Table 1) during the three year evaluation. Suspended solids reduction in the wetland cells exhibited distinct seasonal changes linked to plant growth/senescence and plant biomass accumulation/decay. Since much of the suspended solids contained in the waste settled in the lagoon, dissolved solids were the major component entering the wetland. Dissolved solids during the study had a mean of 364 mg/L at inflow and 285 mg/L at outflows.

Total phosphorus (TP) removal averaged 53.2 % for the three year study period. TE climbed from slightly above 50 % during the initial season of operation to near 85 % after 9 months of system operation TE declined during the next 6 months to 44 % removal (summer, 1992). Inflow TP concentrations ranged from a minimum of 1.32 mg/L to a maximum of 69.04 mg/L (mean = 15.86). Principal phosphorus removal mechanisms were probably precipitation and adsorption to sediments although plant uptake accounted for some removal. SPANGLER et al. (1976) found 30 to 66 %

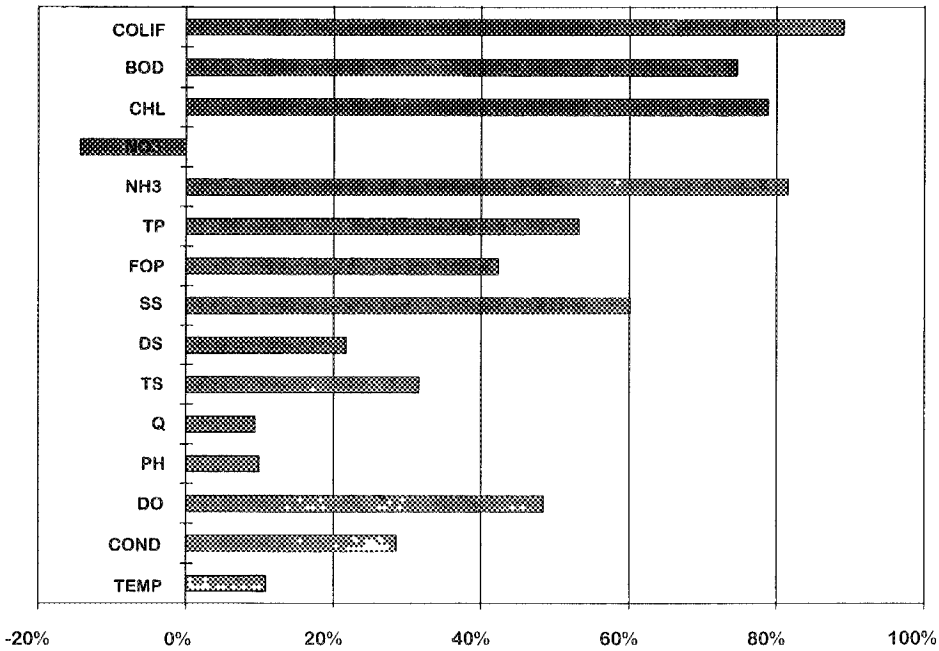

Fig 2 Overall reduction efficiencies for each parameter

of the total phosphorus in bulrush wetland cells was associated with substrate. Phosphorus is immobilized in organic materials and saturation is reached rapidly (HAMMER & KADLEC 1983). Filterable ortho-phosphorus (FOP) removal efficiency averaged 42 4 % (Fig 2). FOP trapping by the system was near 70 % during the initial season of operation and peaked at 85 % during the second season. TE declined nearly linearly from that point during the next 12 months to 31 % in fall 1992, and averaged 37 % afterward.

TE for ammonia nitrogen (NH_3) averaged 81.6 % overall. Reductions exceeded 90 % during the first year of operation, then declined to an average of 81 % for the next 5 seasons of the study (summer 1992 through summer 1993). TE exceeded 90 % again in fall 1993. Reduction declined to 57 % (winter 1993) and was 65 % during the final season of the study period (spring 1994). Ammonia nitrogen concentrations entering the cells varied from a low of 0.14 mg/L to a high of 30.8 mg/L (mean = 6.95). Minimum outflow concentrations reached undetectable levels (<0.01 mg/L) while the maximum outflow concentration measured was 10.78 mg/L (mean = 1.3).

Nitrate nitrogen concentrations entering and leaving the wetland treatment system were low (means = 0.09 and 0.10 mg/L, respectively). Concentrations indicated a net export of nitrate 14.4 % higher than inflow, though actual concentrations were nearly negligible. Seasonal nitrate-N processing began with a 28 % reduction for the first two seasons of treatment, followed by two seasons of 270 % export. The system then fluctuated between net reduction and net export during the following 15 months (summer 1992 through summer 1993, averaging 5 % reduction overall), before exhibiting >50 % reduction in nitrate-N for the last three seasons of the study (fall 1993 through spring 1994). Inflow nitrate nitrogen ranged from undetectable (<0.01 mg/L) to 0.87 mg/L. Outflow concentrations also ranged from undetectable levels to 3.31 mg/L. Nitrate concentrations decreased an average of 27.7 % in cells 1 and 2 but showed an increase of 211 % in cell 3. Inflow concentrations exhibited occasional spikes but generally were lowest during summer. An expected seasonal release of nitrate from senescent and decaying plants occurred most noticeably in cell 3 during the fall and winter, 1991, and spring, 1992, resulting in large negative TE during win-

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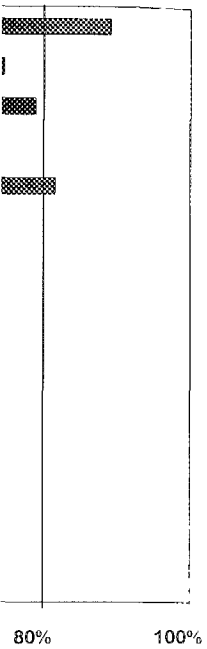

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ter and spring months. Nitrate concentrations also rose within cell 2 during the same periods but decreased to below inflow levels before discharge from the cell.

Five-day oxygen demand (BOD_5) was reduced consistently by about 80 % following the first season of operation, in which there was only a 42 % reduction (overall 74.6 % reduction).

Although seasonal fluctuation was greater than for BOD_5, total chlorophyll (CHL) was reduced by 78.8 %. Mean inflow concentration was 306 mg/L with a minimum of <0.01 and a maximum of 1505 mg/L total chlorophyll. In-cell production was minimal because of plant shading.

Coliform bacteria (COLIF) were abundant in pre-treatment lagoon wastewater; yet our data showed there was an 89 % reduction in total coliforms with passage through the wetland cells. Inflow concentrations had a mean of 14,525 colony forming units (CFU)/100 ml, with a minimum of 40 and a maximum of 101,000 CFU/100 ml. Outflow mean concentration was 1585 CFU/100 ml, with a minimum observed of 20 and a maximum of 19,700 FU/100 ml. Maximum seasonal inflow occurred during winter while maximum outflows occurred during the fall.

Use of catwalks in Cell 2 (Fig. 1; e.g. Stations 2 a, 2 b, and 2 c) allowed assessment of in-cell processing. Because of the length : width ratio, our constructed wetland cells were assumed to have plug flow (Reed 1988). A dye study confirmed this to be true. Several parameters showed sharp declines in the first portion of the cell. Values for BOD_5 decreased more than one half in the first half of cell 2. Little change was measured from 2 b to 2 c, but a further reduction occurred from 2 c to outflow that resulted in a 76 % reduction overall. Mean chlorophyll concentrations entering cell 2 decreased sharply near inflow and then decreased gradually until export for a 75 % TE. Shading from bulrushes and duckweed reduced photosynthesis while physical and biological trapping reduced inflowing concentrations. Coliform bacteria concentrations declined abruptly from inflow levels to 2 a near the front of the cell. After this reduction, however, concentrations remained nearly uniform until outflow, but at a level less than one seventh that of inflow concentrations Fecal coliforms exhibited a decline from inflow to 2 a and reached outflow levels by 2 b. BOD_5 and chlorophyll exhibited similar longitudinal patterns in the cell, decreasing distinctly by 2 a, declining further by 2 b, and slightly increasing at 2 c before reaching lowest levels at outflow.

Dissolved oxygen concentrations did not display linear decreases, but declined abruptly after water entered the cell. The mean decrease from cell inflow to the nearest sampling site, 2 a, was 2 3 mg/L, and to cell outflow was 1.9 mg/L, showing that a slight increase in oxygen concentration in the outflow region after the initial oxygen depletion.

Total solids (Ts) were reduced 32 % overall during passage through the cell. Overall reduction of suspended solids (ss) was 56 %. Seasonal trends along the cell length indicated that sedimentation was augmented by adsorption-driven particle building/flocculation.

Filterable ortho-phosphorus and total phosphorus decreased similarly through the cell in a nearly linear manner, but with a greater proportion of ortho-phosphorus leaving the cell (only 44 % TE versus 55 % trapping for total phosphorus). The greater retention measured for total phosphorus was because of "non-bioavailable" phosphorus which may be trapped in sediment and soils, while ortho-phosphorus is cycled biologically in the cell. Ammonia decreased nearly linearly to mid-cell (2 b), then reduction slowed to outflow. Nitrate nitrogen was present in inflowing water in low concentrations (<0.1 mg/L) but increased sharply in the first portion of the cell to a concentration nearly 2.5 times that of inflow as ammonia was converted to nitrate. Concentration declined steadily as wastewater passed through the cell until discharge, at which point the concentration was generally below inflow level; there was significant cell to cell variation in nitrate uptake, depending on conversion rates. Most in-cell processes were explained by the physical processes of sedimentation, adsorption (electrostatic attraction, Van der Waals forces), or filtration, and the chemical mechanisms of chemical adsorption (covalent bonding, hydrogen bond formation), decomposition, and chelation.

Doubling the length of cell treatment by adding an identical companion cell for assessment (Fig. 1) during 1992 and 1993 showed the following improvements in water quality as compared to original cell results: an added 23 % drop in conductivity; a 20 % increase in dis-

solved oxygen; a 20 % added TE in total solids; and a 27 % additional decrease in dissolved solids Nutrients were also positively affected: 37 % more filterable ortho-phosphorus reduction and 23 % additional reduction of total phosphorus concentrations, 13 % greater reduction of ammonia-nitrogen; and nitrate-nitrogen concentrations decreased 52 % as opposed to a 14 % increase in original cells. BOD_5 and total chlorophyll concentrations decreased by over 9 %; while total coliforms were only slightly changed. Greatest reductions in the three original treatment cells were seen for coliform bacteria (86 %), ammonia (82 %), chlorophyll concentrations (76 %), and, to a lesser degree, for biochemical and chemical oxygen demand (76 and 64 % respectively), suspended solids (58 %), and total and filterable ortho-phosphorus (53 and 42 % respectively). The system functioned adequately during all seasons. Biomass buildup from decaying bulrushes was the major problem encountered during the study. In view of the relatively small size of the treatment cells involved (6 × 4 × 24 m), the measured reduction in pollutants indicated a successful point source management plan

As researchers continue to search for methods of treating agricultural and other contaminants using wetlands, more efficient and ecologically sound designs and maintenance programs will certainly be forthcoming. Long term effects on surface and ground water, adjacent land, wildlife, and humans have yet to be explored. Our system has proven to be effective for the treatment of concentrated on-farm animal waste, and following subsequent evaluation and modification, may provide further useful information for a variety of applications.

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References

APHA, 1989· Standard Methods for the Examination of Water and Wastewater. – APHA, Washington, DC, 1268 pp.

Boyd, C E, 1970· Vascular aquatic plants for mineral nutrient removal from polluted waters - *Econ Bot* **24**: 95–103.

Cooper, C M, Testa, S III & Knight, S S, 1993· Evaluation of ARS and SCS constructed wetland/animal waste treatment project at Hernando, Miss in cooperation with the Miss Soil Conservation Service 1991–1992 – *National Sedimentation Laboratory Research Rpt.* No 2., Oxford, Mississippi, 55 pp

Dolan, T J, Bayley, S. E, Zoltfck, J Jr & Herrmann, A J, 1981· Phosphorus dynamics of a Florida freshwater marsh receiving treated wastewater. - *J. Appl Ecol.* **18**: 205–219

Gearheart, R A, Klopp, F. & Allen, G., 1989: Constructed free surface wetlands to treat and receive wastewater Pilot project to full scale – In. Hammer, D. A. (ed.). *Constructed Wetlands for Wastewater Treatment* 121–138 Lewis Pub., Chelsa, MI.

Hammer, D. & Kadlec, R. H, 1983 *Design Principles for Wetland Treatment Cells* EPA 600/S2-83-026.

Holmes, B. J., Massie, L R., Bubenzer, G D. & Hines, G, 1992 Design and construction of a wetland to treat milkhouse wastewater. 1992 Intl Winter Meeting – *Am Soc Agric Engrs*

Jones, R. A & Lee, G F., 1980· An approach for the evaluation of efficiency of wetlands-based phosphorus control programs for eutrophication related water quality improvement in downstream water bodies – *Water Air Soil Pollut* **14**: 359–378.

Kloetzli, F., 1981. Some aspects of conservation in over-cultivated areas of the Swiss Midlands *Intl J Ecol Environ Sci* **7**: 15–20

Lan, C., Guizhu, C., Li, L & Wong, M H, 1992. Use of cattails in treating wastewater from a Pb/Zn mine. – *Environ Management.* **16** (1): 75–80

Nichols, D S, 1983 Capacity of natural wetlands to remove nutrients from waste water. – *J. Water Poll Control Fed* **55** (5)· 495–505.

Payne, V. W E, McCaskey, T A & Eason, J T., 1992 Constructed wetland for treating swine lagoon effluent 1992 Intl. Winter Meeting. – *Am Soc of Agric. Engrs*

Reed, S C, 1991. Constructed Wetlands for Wastewater Treatment – *Biocycle* **32** (1): 44–49.

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ntl Winter Meeting. – *Am*

ucted Wetlands for Waste-
iocycle **32** (1)· 44–49

Reed, S. C & Brown, D. S., 1992 Constructed wetland design – the first generation. – *Water Environment Research* **64**: 766–781

Reed, S. C, Middlebrooks, E. J. & Crites, R. W., 1988 *Natural Systems for Waste Vater and Treatment* - McGraw-Hill, New York.

Rogers, K. H., Breen, P. F. & Chick, A J., 1991· Nitrogen removal in experimental wetland treatment systems: evidence for the role of aquatic plants – *J Water Poll Control Fed* **63**: 934–994

Sheffield, C. W., 1967: Water hyacinth for nutrient removal. – *Hyacinth Control J.* **6**: 27–30.

Simpson, R L, Good, R. E., Walker, R & Frasco, B R, 1983: The role of Delaware River USA fresh water tidal wetlands in the retention of nutrients and heavy metals. – *J Environ. Qual* **12** (1): 41–48

Spangler, F L, Sloey, W E & Fetter, C. W., 1976. Experimental use of emergent vegetation for the biological treatment of municipal wastewater in Wisconsin. – In: Tourbier, J & Pierson, R W. Jr (eds.): *Biological Control of Water Pollution:* 161–171. Univ of Pennsylvania Press, Philadelphia, PA.

Ulmer, R, Strong, L, Cathcart, T, Pote, J. & Davis, S, 1992 Constructed wetland site design and installation 1992 Intl. Winter Meeting – *Am Soc Agri Engrs.*

Authors' address

C M. Cooper, S. S. Knight, S Testa III, Water Quality and Ecological Processes Research Unit, USDA-Agricultural Research Service, National Sedimentation Laboratory, Oxford, Mississippi, USA