

Design and performance of the Champion pilot-constructed wetland treatment system

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ABSTRACT: *Pilot wetlands were built at Champion International Corp.'s Pensacola, FL, bleached kraft paper mill to evaluate the potential for final effluent polishing.*

The pilot wetlands began operation July 1, 1991. Monitoring ended June 30, 1993. Removal rates and outflow concentrations for five-day biochemical oxygen demand (BOD₅), total suspended solids (TSS), ammonia nitrogen, total nitrogen (TN), and total phosphorus (TP) depended most on hydraulic loading rates (HLRs). Two-year average removal efficiencies for these constituents were above 67%. Slight color and total dissolved solids reductions were seen at the lower HLRs tested. Deep zones enhanced flow distribution, increased hydraulic residence time, and significantly increased pollutant assimilation in the pilot wetlands. The wetland cells reduced or eliminated chronic toxicity to cladocerans and fathead minnows. The most suitable plant species in the wetlands were cattails, bulrush, and sawgrass.

KEYWORDS: *Aeration tanks, BOD, design, effluent treatment, Florida, land use, operations, pilot plants, plants, suspended solids, waste waters, water quality, wetlands.*

In December 1989, Champion International Corp. entered into a consent order agreement with the Florida Department of Environmental Protection to assess alternatives

for additional effluent treatment and disposal at its Pensacola mill in Cantonment, FL. The use of constructed wetlands for final effluent polishing was one of the alternatives required

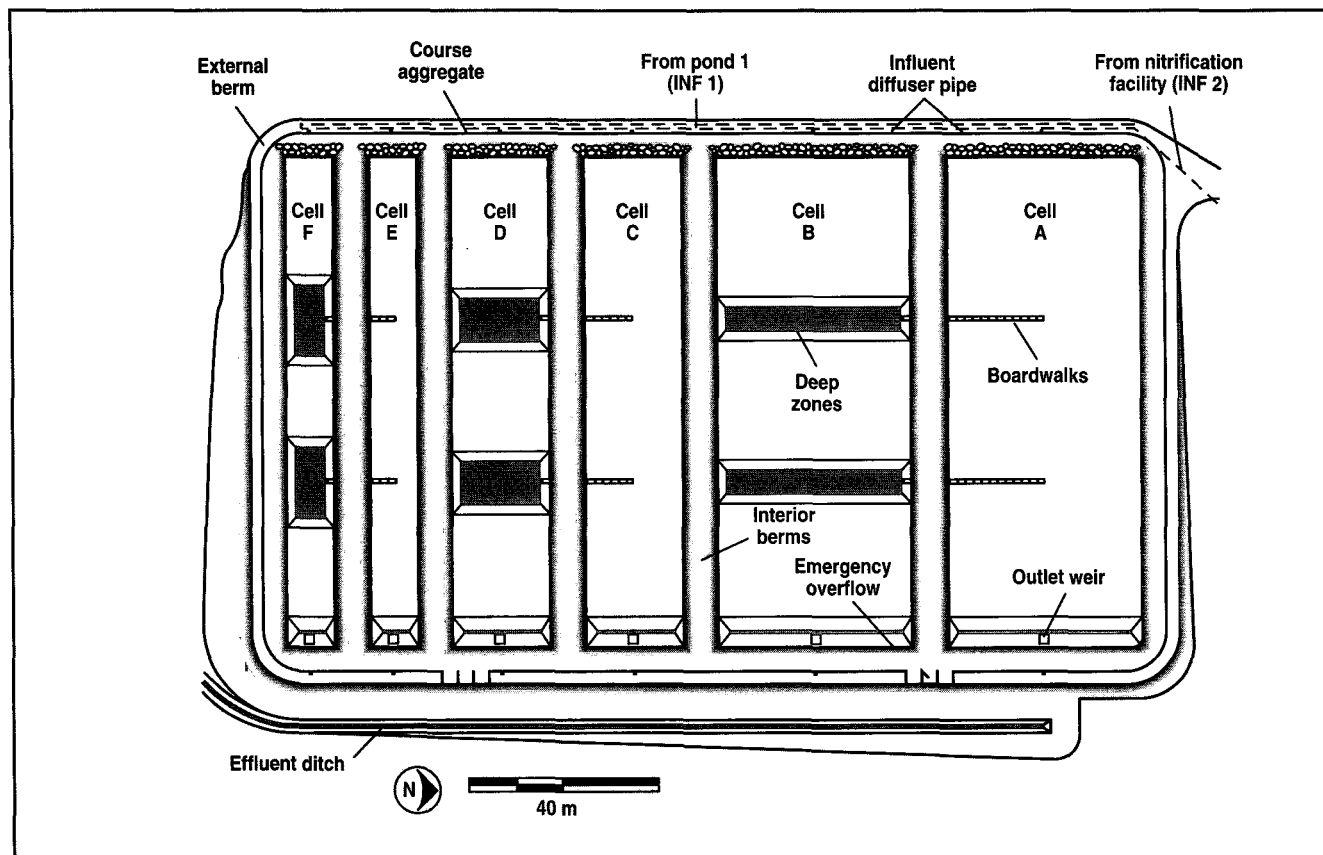
to be studied by the consent order. Interest in using constructed wetlands to treat pulp mill wastewaters was heightened because this technology was successfully used to treat municipal wastewaters at a number of locations in Florida (1, 2) and to treat pulp mill wastewaters elsewhere (3-7).

After assessing the technical feasibility and costs of various compliance alternatives in April 1990, Champion decided to pilot several end-of-pipe treatment alternatives to develop realistic design criteria for project cost analysis. One of the technologies piloted was surface-flow constructed marshes. This pilot-constructed wetland treatment facility was conceptualized and designed in 1990. Construction was completed in May 1991. Operation of the pilot wetland facility was closely monitored for approximately two years until June 1993. This paper summarizes the pilot wetland design and highlights observations made at the facility during the two-year monitoring period.

System design

From the 1990 feasibility study, it was concluded that constructed wetlands could provide final polishing of the mill's effluent to meet stringent discharge criteria for five-day biochemical oxygen demand (BOD₅),

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total ammonia nitrogen (NH_4), and most other water quality parameters except color and conductivity. The Champion pilot wetland treatment system was designed to provide additional information necessary to implement a cost-effective, full-scale constructed wetland treatment system and to gain experience with system operation and maintenance requirements. For this reason, the pilot-constructed wetland cells were relatively large to test multiple plant species, hydraulic loading rates (HLRs), and water depths, and to observe the response of wildlife populations to the water quality and biological conditions in the pilot wetlands.

The Champion pilot-constructed wetlands receive pretreated effluent

from the existing second aeration stabilization basin (ASB 2) at the Pensacola mill. A pump station at the end of ASB 2 delivers about 1090 m^3/day to six wetland cells (see Fig. 1). The six constructed wetland cells are each 100 m long and are arranged in pairs that are each 40 m (Cells A and B), 20 m (Cells C and D), and 10 m (Cells E and F) wide, respectively.

Table I summarizes the design information for each cell. In each pair of cells, one cell is constructed with two transverse deep zones spaced evenly along the length of the cells, and one cell is constructed without the deep zones. These deep zones are approximately 1 m deeper than the surrounding marsh areas and are progressively wider in the narrower cells. The ratios of open water to

marsh in each of the three cells with deep zones range from 25% to 45%. Water is distributed into the upstream end of the six constructed wetland cells via gated inlet pipes. All of the cells have a narrow final deep zone to help direct water to a single-outlet structure with an adjustable weir.

Each of the wetland cells has a magnetic influent flowmeter. Outflow rate is monitored by a combination horizontal and V-notch weir plate at the outlet of each cell. Water quality is measured at the inflow point, at two intermediate stations accessed by boardwalks, and at the final outlet weirs. Water exiting the wetland cells is collected in a final effluent channel and routed back to the ASB

I. Summary of design criteria for the Champion pilot-constructed wetland treatment system^a

Design parameter	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Combined system
Flow, m ³ /day	40-480	40-480	20-120	20-120	10-240	10-240	140-1,680
Area, ha.	0.4	0.4	0.2	0.2	0.1	0.1	1.4
Open water, %	5	25	5	35	5	45	18
Emergent areas, %	95	75	95	65	95	55	82
Bottom slope, %	0.02-0.5	0.02-0.5	0.02-0.5	0.02-0.5	0.02-0.5	0.02-0.5	0.02-0.5
Aspect ratio (L/W)	2.5	2.5	5	5	10	10	NA
Volume, m ³							
Mean	1,344	1,937	675	1,142	338	675	6,111
Minimum	125	718	65	532	33	370	1,843
Maximum	2,563	3,156	1,284	1,751	643	980	10,377
Average depth, cm							
Mean	33.6	48.4	33.8	57.1	33.8	67.5	43.7
Minimum	3.1	18.0	3.3	26.6	3.3	37.0	13.2
Maximum	64.1	78.9	64.2	87.6	64.3	98.0	74.1
Hydraulic residence time, days							
Mean	2.8-33.6	4.0-48.4	5.6-158	9.5-57.1	1.4-33.8	2.8-67.5	3.6-43.6
Minimum	0.23-3.1	1.5-18.0	0.5-3.2	4.4-26.6	0.1-3.3	1.5-37	1.1-13.2
Maximum	5.3-64.0	6.6-78.9	10.7-64.2	14.6-87.6	2.7-64.3	4.1-98	6.2-74.1
Hydraulic loading rate, cm/day	1-12	1-12	1-6	1-6	1-24	1-24	1-12
Design influent loading, kg/ha/day ^b							
BOD ₅	2-24	2-24	2-12	2-12	2-48	2-48	2-24
TSS	6-72	6-72	6-36	6-36	6-144	6-144	6-72
TN	1-12	1-12	1-6	1-6	1-24	1-24	1-12
TP	0.1-1.2	0.1-1.2	0.1-0.6	0.1-0.6	0.1-2.4	0.1-2.4	0.1-1.2

^aPlanted species include soft rush, maidencane, sawgrass, canna, fireflag, duck potato, pickerelweed, sand cordgrass, bulrush, and cattail.

^bDesign influent quality was BOD₅ = 20 mg/L; TSS = 60 mg/L; TN = 10 mg/L; and TP = 1 mg/L.

system for final treatment and disposal.

Ten emergent, macrophytic wetland plant species were initially planted in the pilot-constructed wetland system to test their survival and growth in the ASB effluent and to assess their differences in water quality treatment effectiveness. These species were soft rush (*Juncus effusus*), maidencane (*Panicum hemitomon*), sawgrass (*Cladium jamaicense*), canna (*Canna flacida*), fireflag (*Thalia geniculata*), duck potato (*Sagittaria lancifolia*), pickerelweed (*Pontederia cordata*), sand cordgrass (*Spartina bakerii*), bulrush (*Scirpus californicus*), and cattail (*Typha latifolia*). These species were planted in six zones from the influent to the effluent end, beginning with soft rush and sand cordgrass in the first zone; maidencane in the second zone; sawgrass, canna, and fireflag in the

third zone; duck potato and pickerelweed in the fourth zone; bulrush in the fifth zone; and cattail in the final zone.

System operation

ASB 2 effluent pumping into the pilot wetland cells began on April 11, 1991, to provide irrigation water for vegetation establishment. Planting was completed by May 8 and operational monitoring began on July 1, with flows of about 80 m³/day to Cells A and B and 120 m³/day to the other four cells.

Flows and water depths were altered several times during the two-year operational monitoring period to test the effects of variable HLRs and hydraulic residence times (HRTs). On Feb. 8, 1992, flows were maintained at 80 m³/day in Cells A and B; flows were adjusted to 60 m³/day in Cells C and D, and to 30 m³/

day in Cells E and F. Flows were adjusted again on Nov. 1 to about 230 m³/day in Cells A and B, 115 m³/day in Cell C, and 58 m³/day in Cells E and F. Cell D received nitrified influent during this period at a flow rate of about 57 m³/day. On April 27, 1993, flows were altered to about 150 m³/day in Cells A and B, 75 m³/day in Cells C and D, and 38 m³/day in Cells E and F. Water depths were raised during winter months to increase HRT and lowered during summer months to increase the availability of dissolved oxygen to the plant roots.

Results

Operational data from the pilot-constructed wetland treatment system were collected for a variety of water quality parameters and for biological indices that would be important in implementing and permitting a full-scale, operational constructed wet-

land. A summary of these data is provided below.

Hydrology

Outflow weir heights were adjusted for all six cells concurrently to regulate seasonal water depths. Because deep zones in several cells varied in proportion, average water depths (and resulting HRTs) were more variable than indicated by stage elevation alone. During the two-year operational period, average water depths were 27 cm for Cell A, 39 cm for Cell B, 26 cm for Cell C, 49 cm for Cell D, 27 cm for Cell E, and 59 cm for Cell F.

Actual HRTs in the six wetland cells were measured with a lithium tracer on two occasions. These measurements indicated that actual HRTs were comparable to theoretical HRTs for the wetland cells. Although the ratio of actual to theoretical residence times was variable (ranging from about 0.5 to 1.4), there was an apparent trend for cells with higher length-to-width ratios and/or with deep zones to have less short-circuiting (ratios closer to 1).

Water balances for the constructed wetland cells were prepared with measured inflows, rainfall, and outflows, and evapotranspiration rates were estimated from lake evaporation values. These water balances indicated that, due to clay soils at the site, infiltration and leakage between adjacent cells were generally negligible, and that the water quality changes measured between the inflow and outflow points for the wetland cells represent actual changes and not dilution.

Water quality

Average water quality conditions in the six pilot-constructed wetland cells during the two-year pilot study are summarized in Table II. Inflow water quality was different between Cells A, B, C, E, and F, which received ASB 2 outflow water, and Cell D, which received ASB 1 outflow that had undergone nitrification in a par-

allel pilot study. Inflow quality for both sources is provided in Table II.

Average HLRs during the two-year study were about 3.2 cm/day in Cells A and B, 4.9 cm/day in Cell C, 4.0 cm/day in Cell D, 7.9 cm/day in Cell E, and 8.2 cm/day in Cell F. These loading rates were equivalent to average HRTs during the two-year study of 5.9 days for Cell A, 11.2 days for Cell B, 4.3 days for Cell C, 12.6 days for Cell D, 2.9 days for Cell E, and 10.4 days for Cell F.

Long-term average outflow concentrations for all measured parameters except pH and dissolved oxygen were lowest from Cell B. Only Cell D achieved lower effluent pollutant concentrations than Cell B during the period it received nitrified influent. Cell B has a relatively small area of deep zones (about 25% by area) and a low HLR. By comparing outflow water quality data between Cells A and B in Table II, it is clear that the presence of the deep zones resulted in a marked increase in treatment performance. Average percent removal efficiencies for Cell B over the two-year monitoring period were as follows: BOD₅: 67%, TSS: 88%, NH₄: 91%, TN: 73%, TP: 71%, color: 14%, and conductivity: 14%.

Comparison of outflow water quality data for Cell D with nitrified influent and the other wetland cells with non-nitrified influent during an operational period with similar HLRs indicated that pretreatment by nitrification further enhanced the final effluent quality achievable with a constructed wetland system. During this period, Cell D achieved the following effluent average concentrations: BOD₅: 6.3 mg/L, TSS: 3.6 mg/L, NH₄: 0.19 mg/L, and TN: 1.67 mg/L. Nitrification pretreatment increased final dissolved oxygen from Cell D by about 0.3 mg/L and increased the TP outflow concentration by about 0.19 mg/L. These data indicate that the wetland treatment area necessary to achieve a given water quality goal could be reduced by using nitrification pretreatment

or that lower specific water quality criteria could be met with a combination nitrification/constructed wetland treatment alternative. However, this improved final effluent quality may be compromised by several factors such as increased system costs and complexity.

Metal concentrations in the ASB 2 effluent were generally quite low, either near or below analytical detection limits. Arsenic, cadmium, chromium, manganese, silver, and zinc were detected in the inflow to the pilot-constructed wetlands at least once during quarterly sampling but were below applicable state water quality standards. The wetlands had a variable effect on these low metal concentrations, with some concentrations decreasing, some remaining the same, and some increasing.

Biological responses

During field surveys, a total of 48 plant species were identified in one or more of the pilot wetland cells. Of the 10 original species planted in the wetland cells, all grew well with the exception of maidencane, canna, and fireflag. Duck potato, pickerelweed, and sawgrass grew relatively slowly, and the first two species were easily outcompeted by cattails. Sawgrass developed viable, monospecific stands in the wetland cells. After two years of operation, cattails and bulrush were the dominant species in the wetland cells. Other important dominants that were not initially planted were duckweed (*Lemna* spp.) and water hyacinth (*Eichornea crassipes*). The apparent limiting factors that affected the growth of sensitive plant species were the high water temperatures (up to 39°C) resulting from colored water in a shallow basin during initial plant establishment and flooded conditions with low dissolved oxygen concentrations after the first winter dieback of herbaceous species.

II. Summary of pilot-constructed wetland treatment system performance averages for July 1991 through June 1993

Parameter	Units	Inflow		Cell outflows					
		A,B,C,E,F	D	A	B	C	D	E	F
Average flow	m ³ /day	-	-	128	137	97.8	80.7	79.1	82.3
HLR	cm/day	-	-	3.2	3.2	4.9	4.0	7.9	8.2
Average depth	cm	-	-	27	38	25	48	27	58
Water temperature	°C	28.1	27.7	23.6	23.4	22.9	22.7	22.7	23.2
Dissolved oxygen	mg/L	2.4	3.1	3.2	3.4	3.4	2.8	2.7	3.1
pH	(none)	7.8	7.8	7.9	7.8	7.8	7.8	7.7	7.8
Total suspended solids	mg/L	58.6	50.7	10.1	6.9	11.5	6.1	12.9	13.6
Volatile suspended solids	mg/L	43.3	36.7	7.8	5.2	9.2	5.2	9.6	10.3
Alkalinity	mg/L as CaCO ₃	418	408	373	372	396	385	412	398
Total ammonia N	mg/L	3.35	1.79	0.70	0.31	1.20	0.94	1.96	2.01
Total Kjeldahl N	mg/L	8.08	6.18	3.36	2.36	3.75	2.84	4.46	4.53
Nitrate	mg/L	0.89	3.98	0.13	0.11	0.20	0.15	0.13	0.12
Total N	mg/L	9.09	10.34	3.52	2.48	4.04	3.07	4.66	4.74
Organic N	mg/L	5.31	4.83	2.62	1.98	2.51	2.14	2.70	2.92
Total P	mg/L	0.97	0.99	0.37	0.28	0.54	0.79	0.58	0.59
BOD ₅	mg/L	21	16	10	7	11	8	13	13
Total organic C	mg/L	73	66	64	61	66	63	69	66
Turbidity	JTU	27	24	14	11	18	11	17	18
Total dissolved solids	mg/L	1460	1448	1359	1341	1433	1370	1427	1378
Color units	mg/L	386	357	341	331	383	365	398	408
Conductivity	µmhos/cm	2126	2119	1881	1831	1982	1934	1991	1966

Four tree species were also tested in two of the wetland cells. Of these species, pond cypress (*Taxodium ascendens*) and black gum (*Nyssa biflora*) grew better than bald cypress (*Taxodium distichum*) and pop ash (*Fraxinus caroliniana*).

Invertebrate populations in the wetland cells were sampled twice during the first year of pilot wetland operation. Between 21 and 41 species of benthic macroinvertebrates were identified in each cell during these sampling events with Shannon-Weaver diversity values ranging from a low of 0.98 to a high of 2.98 for individual cells. Dominant invertebrate groups that were observed were midges, aquatic bugs (especially backswimmers), dragonflies, damselflies, and aquatic beetles. Mosquito larvae and pupae were infrequently encountered during routine sampling.

Vertebrates observed using the constructed wetlands included three amphibian species, three reptile species, about 31 species of birds, three fish species purposely introduced into the wetlands, and two mammal species. About 490 mosquitofish

were initially introduced into the constructed wetland cells in May 1991. By January 1992, the average density of mosquitofish in the wetland cells was about 9.2 fish/m² for a total estimated population of about 129,000.

Whole-water toxicity was measured quarterly in the inflow and outflow of selected wetland cells with cladocerans (*Ceriodaphnia dubia*) and fathead minnows (*Pimephales promelas*) during the first operational year. No acute toxicity to either cladocerans or fathead minnows was detected in any of the samples analyzed. Influent samples (ASB 2 outflow) were all chronically toxic to the cladoceran with measured chronic values ranging from less than 12.5–65% influent. Chronic toxicity was reduced by passage through the wetlands in 10 of 11 test comparisons, with no observable chronic toxicity in samples collected at the Cell B outflow. Inflow samples were chronically toxic to fathead minnows in two out of three samples tested. No chronic toxicity to fathead minnows was observed in any of the wetland outflow samples tested.

Conclusions

Knight (7) has summarized operational data from six pulp and paper facilities that use wetlands on an experimental or full-scale basis for final effluent polishing. BOD₅ removal efficiency was found to be inversely correlated with HLR in these wetland treatment systems. Data from the Champion project indicate that BOD₅ outflow concentration can be further reduced by including a relatively small area of deep water zones that help reduce short-circuiting and increase HRT.

TSS removal in constructed wetlands is relatively independent of loading rates up to mass loadings as high as 150 kg/ha/day (8). At the pilot wetlands, loading had a slight effect on TSS reduction. Also, the lowest TSS outflow concentrations were obtained from cells with a relatively small deep-zone area. Average TSS removal efficiencies were between 40% and 80% at all of the pulp and paper mill wetlands tested (9), confirming the consistent effectiveness of these passive treatment systems for polishing TSS in pulp and paper mill effluents.

TN is removed in wetland treatment systems through ammonification, nitrification, and denitrification. In addition, particulate nitrogen is trapped in the wetland and subject to these chemical transformations over a longer time period. These processes appear to be effective at reducing the mass of nitrogen in pulp and paper mill effluents routed through treatment wetlands. Average TN removal efficiency is typically between 35% and 75% (9) and is inversely related to HLR. The pilot wetlands indicate that TN outflow concentrations are also further reduced by the presence of a relatively small area of deep zones. Our results, as well as data from other studies, indicate that there is a recalcitrant organic nitrogen fraction that cannot be effectively removed in wetlands. At the Pensacola mill, this fraction is equal to about 2 mg/L of organic nitrogen.

Color was found to be a relatively conservative constituent in pulp and paper mill wastewaters and is not generally reduced through biological treatment systems. Although color removal efficiency at the pilot wetlands was relatively low, these data, as well as data from other wetland systems summarized by Knight (9), indicate that color removal does increase at lower HLRs. Color data, in conjunction with observed reductions in conductivity and lithium through the pilot wetland cells, may suggest that there are compartments (plants, deep zones, and sediments) that may temporarily or permanently sequester these conservative constituents. Research is currently underway at the Pope and Talbot pilot wetlands in Halsey, OR, to develop techniques to enhance this natural color removal potential of wetlands (10).

Constructed wetlands clearly have the potential to further polish certain nonconservative constituents remaining in treated pulp and paper mill effluents. This potential may be important to mills that have suffi-

cient land area to construct wetlands and must meet increasingly stringent mass removals for BOD₅ and TSS. For example, it is estimated that about 200 ha (500 acre) of constructed wetlands would be required to remove an additional 50% of the BOD₅ remaining in the secondary effluent of a mill with an average flow of 76,000 m³/day. Based on a typical wetland construction cost of about US\$ 37,000/ha for large-scale systems, a 200-ha project would cost about US\$ 7,400,000.

Constructed wetlands can reduce concentrations of nutrients, such as nitrogen and phosphorus, lower concentrations of metals, and reduce or eliminate whole effluent toxicity of pulp and paper mill effluents. Constructed wetlands have the advantages of avoiding residual solids management and of enhancing wildlife habitat and providing limited public use. Disadvantages of constructed wetlands for effluent polishing are the large land area requirements and the low degree of operational control. These advantages and disadvantages of constructed wetlands for pulp and paper mill effluent polishing should be compared to the merits of conventional treatment technologies on a case-by-case basis to provide final selection of the most appropriate alternative for a given mill. □

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Received for review Jan. 7, 1994.

Accepted Feb. 14, 1994.

Presented at the TAPPI 1994 Environmental Conference.