Pergamon

Wat. Sci. Tech. Vol. 29, No. 4, pp. 159–168, 1994.

0273–1223/94 $7·00 + 0·00

CONSTRUCTED WETLANDS FOR RIVER WATER QUALITY IMPROVEMENT

R. H. Kadlec* and D. L. Hey**

**Department of Chemical Engineering, Dow Building, The University of Michigan, Ann Arbor, Michigan 48109-2136*
***Wetland Research, Inc., 53 West Jackson Boulevard, Chicago, Illinois 60604*

ABSTRACT

The Des Plaines River Wetlands Demonstration Project has reconstructed four wetlands in Wadsworth, Illinois, USA. The river drains an agricultural and urban watershed, and carries a non-point source contaminant load of sediment, nutrients and agricultural chemicals. Up to 40% of the average stream flow is pumped to the wetlands, and allowed to return from the wetlands to the river through control structures followed by vegetated channels. Native wetland plant species have been established, ranging from cattail, bulrushes, water lilies, and arrowhead to duckweed and algae. Pumping began in the summer of 1989, and has continued during the ensuing spring, summer and fall periods. The experimental design provides for different hydraulic loading rates, ranging from 5 to 60 cm/week. Intensive wetland research began in late summer 1989, and continues to present. Detailed hydrology is measured for each wetland. Sediment removal efficiencies ranged from 86-100% for the four cells during summer, and from 38-95% during winter. Phosphorus removal efficiencies ranged from 60-100% in summer and 27-100% in winter. The river contains both old, persistent and modern, degradable agricultural chemicals. The principal modern pollutant is atrazine, of which the wetlands remove approximately half. The project is successfully illustrating the potential of constructed wetlands for controlling non-point source pollution at an intermediate position in the watershed.

KEYWORDS

Wetlands, river cleanup, wetland restoration, nitrogen, phosphorus, sediments, atrazine, hydrology.

INTRODUCTION

Over the last half century, a great deal of public and private money has been spent to control flooding and achieve clean, ecologically sound streams and rivers in the USA. Return on this investment has been poor because flood control and pollution abatement strategies fail to address the physical conditions of our nation's surface waters. The meandering paths and broad riparian wetlands, characteristic of undeveloped streams, that provided the essential physical setting and biological functions necessary for clean and productive aquatic systems, no longer exist. Without these attributes the national environmental goals of fishable and swimmable streams cannot be reached. The Des Plaines River Wetlands Demonstration Project is a research project designed to produce the criteria necessary for rebuilding our river systems through the use of wetlands and for developing management programs for the continued operation of the new structures. The research program will assess wetland functions through large-scale experimentation, controlled manipulation of flow rates and water depths, testing of soil conditions, and the employment of a wide variety of native plant communities.

The site is located 57 km (35 mi) north of Chicago in the town of Wadsworth, Illinois. It incorporates 4.6 km (2.8 mi) of the upper Des Plaines River and 182 ha (450 ac) of riparian land. The river flows south, draining 537 km^2 (200 mi^2) in southern Wisconsin and northeastern Illinois. Eighty percent of the watershed is agricultural and 20 percent urban. The river is polluted with non-point source contaminants from a variety of land use activities, and point source contaminants from small domestic treatment plants. In support of agricultural uses, low-lying portions of the site were drained by means of tiles. Past uses of the site resulted in the demise of most of the original wetlands and associated fauna and flora.

As the Des Plaines River enters the site from the north, it is relatively wide and shallow for the first 150 m (500 ft) - 30 m (100 ft) wide and about 60 cm (2 ft) deep. Downstream from the confluence with a western tributary, Mill Creek, it becomes sinuous, more narrow (60 feet) and deeper (2.5 feet). Both reaches exhibit channel stability primarily because of the low energy state of the river. Stream velocities average less than 0.3 m/s (1 ft/s). The gradient is 0.2 m/km (1.2 ft/mi).

The primary water quality problem of the river is associated with turbidity. With a mean concentration of 59 mg/l, over 4540 tonnes (5,000 tons) of suspended solids enter the site per year via the Des Plaines River and Mill Creek. Seventy-five percent of these solids are inorganic and 95 percent are less than 63 mn in size. Other observed water quality problems include violations of the state water quality standards for iron, copper, and fecal coliforms. Although not detected in amounts exceeding the federal Food and Drug Administration's criteria, dieldrin, DDT and PCBs have been found in fish flesh samples. There is a significant nutrient load, as evidenced by nitrate and phosphorus. Agricultural practices within the basin produce atrazine concentrations which peak in excess of the federal drinking water standard. Finally, according to the results of benthic surveys, the stream is classified as semi-polluted.

Site selection was based on criteria ranging from the qualitative state of the river through the degree of channelization, to the extent of riparian land disturbance. In consideration of costs, the land had to be publicly owned. Once the site was selected, Wetlands Research, Inc. was formed and preliminary engineering was undertaken to establish the feasibility of rehabilitating the stream and environs (Hey *et al.*, 1982), constructing wetlands, and conducting the experiments necessary to validate design formulas and management procedures. Once feasibility was firmly established, final design was undertaken and completed (Hey and Philippi, 1985a). At the same time, a detailed survey of the existing physical and biotic conditions was conducted (Hey and Philippi, 1985b). This baseline survey covered topography, hydrology, water quality, geology, soils, vegetation, microorganisms, aquatic invertebrates, terrestrial insects, amphibians, reptiles, fish, birds, mammals, prehistoric uses and public use.

Because of the presence of wetland fragments on the site, a permit from the U.S. Army Corps of Engineers was required for construction. The permit was issued based on the surveys and design. With design, permit, and a grant from the Illinois Department of Energy and Natural Resources in hand, Wetlands Research, Inc. initiated construction in April of 1986.

The first four of eight experimental wetlands, along with the necessary irrigation system, were completed in October, 1988 (Figure 1). Their sizes are: EW3, 2.1 ha (5.2 ac); EW4, 2.3 ha (5.6 ac); EW5, 1.6 ha (4.0 ac); EW6, 2.9 ha (7.2 ac). Each area is designed to have a maximum depth of 0.9 m (3.0 ft), but can be operated at any intermediate level. Experimental wetland areas 3, 4, and 5 all directly discharge to a shallow, constructed channel which runs parallel to the Des Plaines River, and rejoins it just downstream of the wetlands. This new river channel is being used for plant and fisheries research. Experimental wetland area 6 discharges into an abandoned gravel quarry lake. Eight more experimental wetlands were added in 1992.

Research has begun in the four completed experimental areas. Pumping operations for these areas were started in June of 1989. Shortly thereafter, the experimental hydrologic regime, agreed upon by our researchers, was established. This regime represents deep marsh conditions (water depths greater than 2.5 feet) with two areas having high hydraulic loading rates and two having low rates. By the end of December, 1992, over 850 million gallons of river water will have been pumped into these areas.

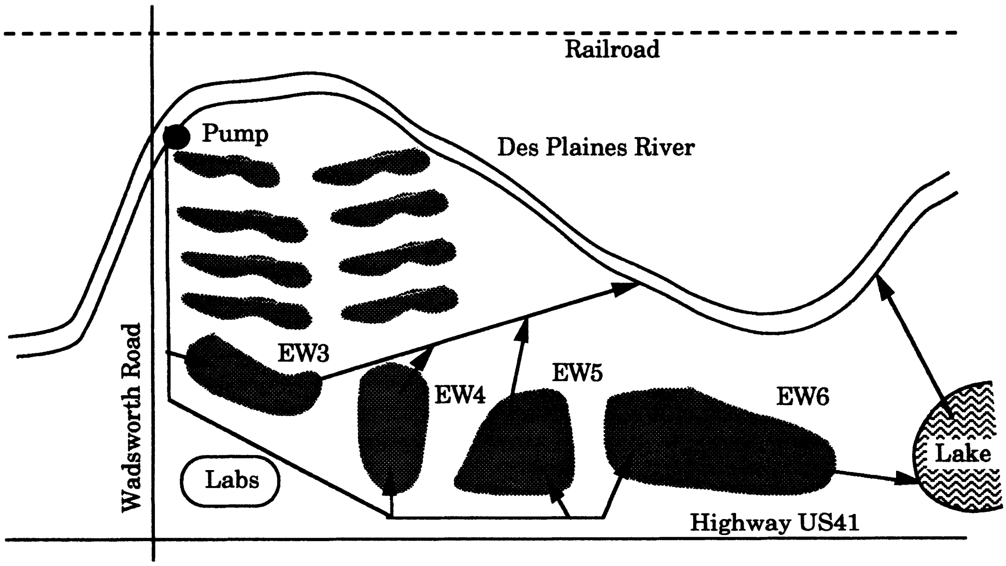

Fig. 1. Des Plaines River demonstration site: experimental wetlands.

The project is estimated to cost $13.5 million; approximately half of the budget has been secured. Construction is the largest cost component followed by research, then land acquisition. At the outset of the project, these cost components were allocated to both public and private interests - the logic being that both will benefit from the results of the project. In terms of meeting their allocation, state and local contributors rank first and second. Private industry falls third and the federal government is fourth.

HYDROLOGY

The irrigation system provides flow control to and through the experimental wetland areas. The system will help overcome the vagaries of precipitation, evapotranspiration, and associated fluctuations in streamflow, so that experimentation can continue despite adverse hydrologic conditions. Further, movement of water through the experimental wetland areas needs to be carefully controlled and monitored to test water quality and biological responses to various flow regimes. A submersible pump supplies water at rates up to 34 m^3/min (20 cfs). The pumping capacity is approximately 25 percent of the mean annual flow of the Des Plaines River at the point of withdrawal. The pump is a low head, propeller type, driven by 480 volt, 3-phase induction motors. The pump is connected to a 36 inch header pipe which directs the flow to the experimental wetland areas.

Acoustic velocity meters measure the volume and velocity of incoming water. The sum of the flow entering the wetland areas and the sum of the flow leaving the pumping station (measured by two meters on either side of the header) serves to check for leakage in the delivery system and to check pumpage. Parshall flumes and weirs are used to measure the flow leaving each experimental area.

Hydrologic budgets are constructed for the four wetlands of the Des Plaines River Wetlands Demonstration Project for each water year. The hydrologic budget includes the following components: pumped inflow, precipitation, evapotranspiration, seepage, flood inflow, siphonage, and discharge. The budget was constructed via the following procedure. For each wetland, water flow rate for each component was measured, calculated or estimated on an hourly timestep. The resulting flow time series were stored in a hydrologic simulation program -FORTRAN (HSPF) Time Series Store. A computer simulation program was developed which read, for each successive timestep, each flow component. Flow rates were converted to volumes and added or subtracted (as appropriate) to storage volume computed for the previous time step. Discharge over the weir during the timestep was computed using water surface elevation at the end of the previous timestep and the depth-discharge relationship. This procedure produced the volume of water and, using depth-area and depth-storage relationships, the water surface elevation in each wetland at the next time step. This simulation of hydrologic conditions produced an hourly time series of calculated water surface elevations, which were compared with measured (or observed) water surface elevations to evaluate accuracy of the simulation.

Commonly accepted procedures were used to quantify components in the budget. The site engineer recorded times at which the pump was turned on and off each day. Another hourly time series was constructed which contained the fraction of the hour the pump was operating, thus defining volume inflow into each wetland during every hour. A weighing-bucket precipitation gauge was installed on the site at the climate station. Strip charts were removed and replaced every 1-3 weeks and read by hand using an hourly time step.

Evapotranspiration (ET) was estimated using measurements of solar radiation, air temperature, relative humidity and wind speed. Hourly average values of these variables were recorded by the weather tower on site. The wind speed was projected from the 9 m (30 ft) weather tower to the value at 15 cm (6 in), needed for the calculation. Meteorological data was also obtained from Waukegan Airport, about 5 km (3 mi) east of the site. The airport monitors hourly air temperature, wind speed, cloud cover and dew point from 6 am to 6 pm every day. During periods when the weather station was inoperative, airport data was used. When neither site, nor airport data were available, missing values were estimated by interpolating between the closest preceding and succeeding available values. Solar radiation was estimated from potential solar radiation multiplied by hourly cloud cover data.

Seepage was estimated using a procedure developed by Dr. Bruce Hensel of the Illinois State Geologic Survey. The procedure relates seepage rate per unit area to groundwater elevation in groundwater observation well 14 (near McCarty Road bridge) and water surface elevation in the wetlands. Briefly, the procedure divides groundwater elevation into five regimes and water surface elevations into four regimes. For each combination of groundwater and EWA elevation regime, a curve relating seepage to EWA elevation was constructed. The curves were linearized and slope and intercept of each line were used to calculate seepage. Studies indicated seepage rates in EW3 and EW4 were negligible. Seepage was non-zero in EW5 and EW6.

TABLE 1. Water Budget Components (annual metres) for the Four Experimental Wetlands

	EWA3	EWA4	EWA5	EWA6
Inflows				
Surface Inflow	19.5	5.3	18.3	10.2
Precipitation	1.0	1.0	1.0	1.0
Outflows				
Discharge	19.5	5.3	17.5	1.3
Evapotranspiration	1.0	1.0	1.0	1.0
Seepage	0.0	0.0	0.8	8.9

During floods in March and May, 1990, the river rose to an elevation at which water flowed backwards over the outlet weirs into the wetlands. The amount of inflow from flooding was estimated by manually measuring water surface elevation during these times. Inflow volume to each wetland was calculated from elevation increase. Flow rate was calculated by dividing inflow volume by the time between elevation readings. As the river subsided, there were times when the elevation, while not great enough to cause inflow, caused backwater which inhibited the discharge of the weir. Outflow during these conditions was estimated using the same method as for flood inflow. Because the wetlands are hydraulically connected through the pipeline, if there was an elevation difference, water flowed from one wetland to another when the pump was off. Check valves were installed in 1991 to prevent siphoning between wetlands.

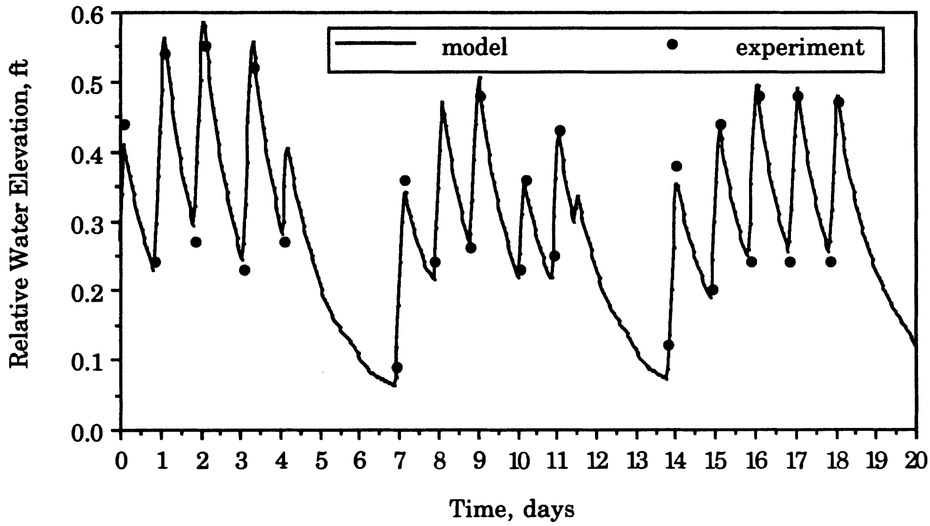

Fig. 2. Dynamic water budgets for June 2-23, 1991.

The water budgets for the water year 1990 (Oct-Sept) are presented in Table 1. Results are reported as equivalent metres of water applied to or removed from a wetland via each component. Agreement between observed and calculated water surface elevations was good (Fig. 2).

TABLE 2. Suspended Solids Reduction in the Des Plaines Wetlands

		Inlet	EWA3	EWA4	EWA5	EWA6
FA 89	mg/l	8.0	2.0	2.4	2.6	3.0
	%		75	70	68	63
WI89	mg/l	7.1	5.0	3.6	4.2	3.0
	%		29	49	41	58
SP90	mg/l	24.2	5.5	4.5	2.9	3.3
	%		77	82	88	87
SU90	mg/l	47.7	5.7	14.9	4.3	13.9
	%		88	69	91	71
FA90	mg/l	50.1	10.8	7.4	5.4	4.4
	%		78	85	89	91
WI90		-------------No Pumping-------------				
SP91	mg/l	63.9	5.8	7.4	2.4	6.2
	%		91	88	96	90
SU91	mg/l	123	6.0	6.8	3.2	7.7
	%		95	94	97	94
FA91	mg/l	66.0	10.8	6.7	25.8	NF
	%		84	90	61	--
AVG	mg/l	48.8	6.5	6.7	4.9	6.1
	%		**87**	**86**	**90**	**87**

WATER QUALITY

The observed changes in water quality and improvements to the general environment were impressive. Analyses indicate that the experimental areas trapped about 88 percent of the sediments contained in the incoming river water (Table 2). There are no seasonal changes in the exit total suspended solids (TSS) concentrations; the high values in summer 1990 may be due to bioturbation by carp. There are seasonal and yearly changes in the incoming TSS, and therefore the percentage removals also change in response. Typically, there are lower levels of TSS in winter, and the highest values occur at summer low flow conditions. There are not large differences in the performance of the different wetland cells, even though these have different shapes and hydraulic loading rates. Detailed examination of inlet zones indicates that the wetlands trap river sediments near their inlets, thus size and loading are unimportant. Column studies showed that river sediments settle (90%) in under 6 hours. There is a large vertical sediment flux within the wetlands (Mitsch, 1991). This is balanced by a large sedimentation rate, and only a small differential amount remains in the water column and is available for export. Further, the exported sediments are probably in part those which originate within the wetlands.

TABLE 3. Total Phosphorus Concentration Reduction in the Des Plaines Wetlands

		Inlet	EWA3	EWA4	EWA5	EWA6
FA 89	mg/l	0.052	0.018	0.013	0.014	0.018
	%		65	74	73	66
WI89	mg/l	0.073	0.053	0.030	0.058	0.024
	%		28	59	21	68
SP90	mg/l	0.057	0.044	0.015	0.017	0.023
	%		23	74	70	61
SU90	mg/l	0.117	0.038	0.055	0.035	0.062
	%		68	54	71	47
FA90	mg/l	0.131	0.024	0.007	0.017	0.011
	%		82	95	87	91
WI90		-------------No Pumping-------------				
SP91	mg/l	0.089	0.003	0.002	0.001	0.002
	%		97	98	99	98
SU91	mg/l	0.166	0.030	0.011	0.008	NF
	%		92	92	92	--
FA91	mg/l	0.115	0.037	0.014	0.060	0.061
	%		68	88	48	47
AVG	mg/l	0.100	0.031	0.018	0.026	0.029
	%		**69**	**82**	**74**	**71**
1990 Loading, kg/ha/yr			10.6	3.5	13.4	4.1
1991 Loading, kg/ha/yr			14.1	2.3	13.7	3.3

Relatively small amounts of phosphorus travel with the river and are thus available to be pumped to the wetlands. An average of 100 ppb in the incoming waters is reduced to 25 ppb in the discharges from the wetlands, for an average immobilization of about three-quarters of the incoming phosphorus (Table 3). This phenomenon is possibly temporary, since much of the phosphorus is being utilized to build the developing live and dead plant tissues, as indicated by the phosphorus loadings (Table 3). This idea is further supported by the higher removals of phosphorus during the summer season, despite higher incoming concentrations during that time of the year. The current cumulative phosphorus loading rate is removed to the sediments as particulate phosphorus, to the establishment of biomass not previously present, and to the formation of new organic sediments. Sustainable P-removal is due entirely to sediment accretion in the wetlands, currently under study.

There are a variety of nitrogen forms in the river water. About 0.6 mg/l of organic nitrogen enter the wetlands, and the same amount leaves. Very low ammonium nitrogen concentrations are found in both river and wetland waters: ca 0.05 mg/l. Nitrate varies seasonally in the river, in response to urban and agricultural practices. High spring and fall concentrations are echoed by similar variations in the nitrate content of the wetland effluent waters (Figure 3). However, Table 4 demonstrates that a considerable amount of the incoming nitrate is removed, presumably due to denitrification. This microbially mediated process appears to be more efficient in the wetlands with lower hydraulic loading rate, which is equivalent to increased detention time, since depths are comparable. Thus the overall effect of the wetlands is to control the nitrate in the water, when sufficient contact time is available.

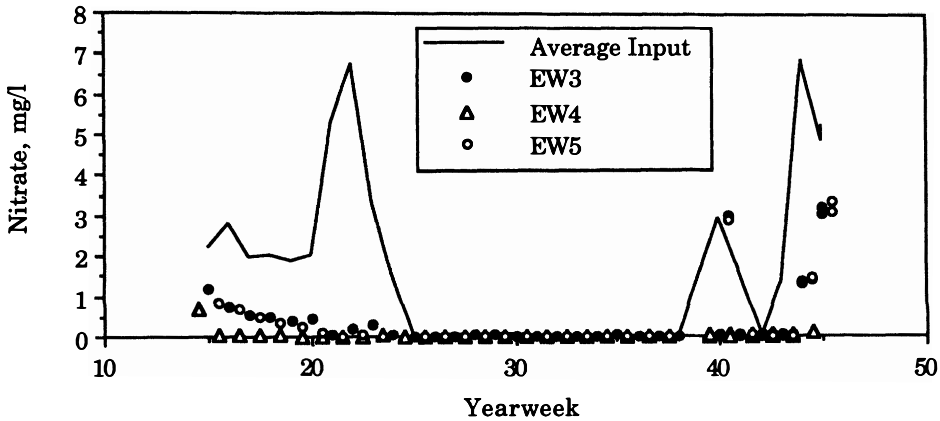

Fig. 3. Nitrate exiting wetlands (1991).

TABLE 4. Nitrate Reduction in the Experimental Wetlands, HLR is Approximate

		EWA3	EWA4	EWA5	EWA6
1989	mg/l	2.36 1.05	2.28 0.11	2.32 1.39	2.28 0.16
	%	55	95	40	93
1990	mg/l	1.87 0.54	1.87 0.24	1.87 0.53	1.87 0.32
	%	61	87	72	83
1991	mg/l	1.22 0.23	1.22 0.10	1.22 0.18	1.22 0.18
	%	81	92	85	85
Average	%	**66**	**91**	**66**	**87**
HLR	cm/day	4.9	1.5	4.9	2.2
1990 Loading, kg/ha/yr		581	152	523	204
1991 Loading, kg/ha/yr		147	36	134	39

Atrazine, a triazine herbicide, exists in many streams in the upper midwestern part of the United States, including the Des Plaines River, due to use patterns in the watershed. The atrazine-wetland interaction is very complex, including removal from the area by convection in the water, loss of chemical identity by hydrolysis to hydroxytriazine and dealkylation, and sorption on wetland sediments and litter. Atrazine transport, sorption and identity loss were studied at the site, and in accompanying laboratory work (Kadlec and Alvord, 1992). Sorption followed a 0.8-power law for several sediment types, but the more organic materials, such as litter, showed a stronger affinity for atrazine than the mineral soils of the wetland cells at Des Plaines.

Atrazine was found to degrade on those sediments according to a first-order rate law. Therefore, outflows from the Des Plaines wetland cells contained reduced amounts of atrazine compared to the river water inputs. During 1991, atrazine peaked in the river due to two rain events (Figure 4). Only about 25% of the incoming atrazine was removed in wetland cell EW3, but 95% was removed in wetland cell EW4. The explanation is again to be found in the fact that the detention time in EW4 is larger than in EW3.

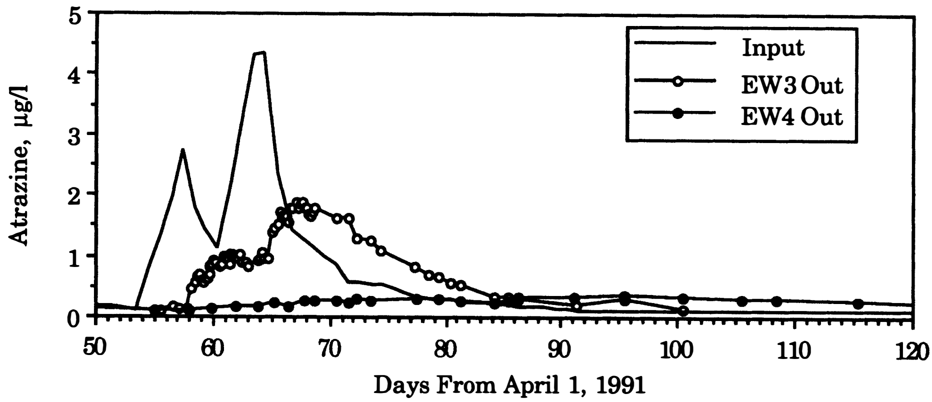

Fig. 4. Atrazine entering and leaving EW3 and EW4 during summer 1991.

Neither plug flow nor well mixed flow patterns explain the water quality data for these wetlands (Kadlec and Bastiaens, 1992). Figure 5 shows the response of wetland EW3 to a single impulse addition of lithium, a non-reactive tracer, in the form of lithium chloride. This response is explainable only with an intermediate flow pattern, which may be modeled as a series/parallel network of flow elements. Although the nominal residence time was seven days, the entire flushing of the added tracer required three weeks, and the shape of the curve indicates a very large degree of mixing. The wetlands are neither close to plug flow, nor close to being perfectly mixed. More sophisticated techniques of data interpretation, which incorporate imperfect mixing, must therefore be used.

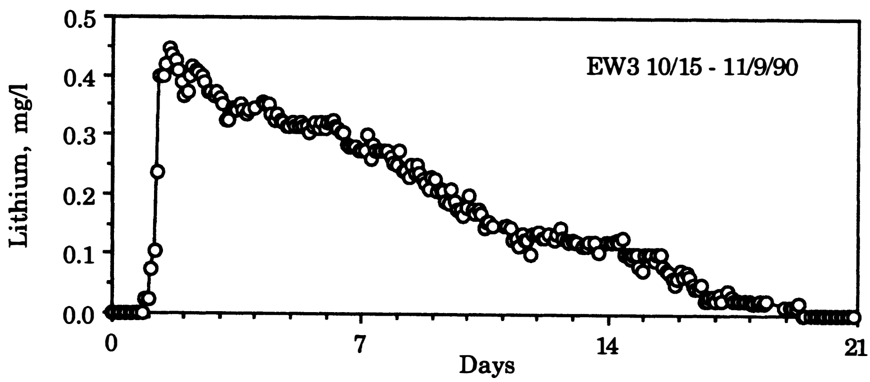

Fig. 5. Response of EW3 to a pulse injection of lithium at time zero.

BIOTA

Efforts at vegetation establishment were thwarted by the extreme drought conditions of 1988. The planting of white water lily (*Nymphea odorata*) showed small success, and American water lotus (*Nelumbo lutea*) did not survive.

The development of the macrophyte plant communities was monitored from project start up (Mitsch, 1991). Sixteen 2m x 2m permanent quadrats were established in each wetland cell. Data were acquired on species composition and biomass for all plants in each quadrat. Plants were individually measured, and a correlation between dry weight and leaf size was developed. Thus biomass could be determined non-destructively. There was an overall increase in species as volunteer wetland vegetation replaced the terrestrial vegetation of pre-pumping (Table 5). Fourteen species were observed in 1990 that were not present in 1989, and ten species from 1989 did not reappear; these later being mostly upland species.

The first year of inundation caused the death of many upland species, such as cottonwood (*Populus deltoides*). The growing seasons of 1989, 1990 and 1991 all displayed an increase in the amount of cattail (*Typha* spp.). Productivity increased from 200-400 dry grams per square metre in 1989 to 600-800 in 1990. The growing season of 1990 produced extensive blooms of macrophytic algae, predominantly *Cladaphora* sp.

TABLE 5. Species Counts for Macrophytes in the Experimental Wetlands

	Total	EWA3	EWA4	EWA5	EWA6
1989	30	9	19	14	15
1990	34	26	28	20	24

The fall 1990 bird survey turned up a number of interesting species, including the state endangered pied-billed grebe and black-crowned night heron, and also the great egret, American bittern, and the sharp-shinned hawk. The state-endangered yellow-headed blackbird and least bittern nest successfully at the site. For migratory waterfowl, there has been a 500% increase in the number of species, and a 4500% increase in the number of individuals from 1985 to 1990 (Hickman and Mosca, 1991). Forty-seven species of birds nested on the site in 1990, a 27% increase over preproject numbers. Muskrats moved in during the summer and fall and constructed dwelling houses, in separate experimental areas. Beaver paid frequent visits to the wetlands. They chewed off quadrat corner posts, and attempted to dam the wetland outflows.

Carp pose a serious threat to wetland and stream environments. Their feeding behavior, which results in disturbance of bottom sediments and resuspension of solids in the water column, interferes with food chains through the destruction of the habitats of bottom-dwelling organisms and through disruption of photosynthetic activity because of greater turbidity. Carp in the wetland cells were believed to have caused lessening of the sediment removal by late 1990. Consequently, the wetlands were drawn down in late winter 1991, causing death of all resident carp. This procedure also caused great damage to frog populations.

CLOSURE

The results to date indicate that wetlands are good candidates for river water quality improvement. Solids and nutrients are removed, and agricultural herbicides are attenuated. Hydraulic loading rate is of great importance for nitrate and herbicide reduction, but not as important for sediment removal. These unplanted wetlands have been developing, in terms of vegetation, for three years; but it appears that process may be reaching completion. Important benefits will come from the project's research program and its demonstration of the wetland re-creation model. The restored site will serve as a living laboratory for the participating scientists and engineers to evaluate a wide variety of techniques for creating wetlands in ecologically degraded urban and agricultural environments. The project will provide new and greatly needed information about how and at what cost natural wetland processes can be used to manage water and wildlife resources. This information will be applicable throughout the nation, wherever wildlife habitat, pollution abatement and flood storage are scarce and in demand.

REFERENCES

Hey, D. L. and Philippi, N. S. (1985). *Baseline Survey, Volume II; and Design, Construction Specifications and Site Management*, Volume III, Wetlands Research, Inc., Chicago, IL.

Hey, D. L., Stockdale, J. M., Kropp, D. and Wilhelm, G. (1982). *Creation of Wetland Habitats in Northeastern Illinois*, Illinois Department of Energy and Natural Resources, Document No. 82/09, Springfield, IL.

Hickman, S. C. and Mosca, V. J. (1991). *Improving Habitat Quality for Migratory Waterfowl and Nesting Birds at the Des Plaines River Wetlands Demonstration Project*, Technical Paper No. 1, Wetlands Research, Inc., Chicago, IL.

Kadlec, R. H. and Alvord, H. H. (1992). Fate and transport of atrazine in the Des Plaines River and experimental wetlands 1990-91. In: *Report on the Des Plaines River Wetlands Demonstration Project*, from Wetlands Research, Inc. to USEPA, May 1992.

Kadlec, R. H. and Bastiaens, W. V. (1992). The use of residence time distributions (RTDs) in wetland systems. In: *Report on the Des Plaines River Wetlands Demonstration Project*, from Wetlands Research, Inc. to USEPA, May 1992.

Mitsch, W. J. (1991). Chapter 3 In: *Progress Report on the Des Plaines River Wetlands Demonstration Project*, from Wetlands Research, Inc. to USEPA, March 1991.