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WATER QUALITY DURING STORM EVENTS FROM TWO CONSTRUCTED WETLANDS RECEIVING MINE DRAINAGE[1]

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ABSTRACT: Flow rates, pH, iron concentration, and manganese concentration were measured during several storm events at two constructed wetlands receiving mine water. During a substantial rain event, flow rates at both the wetland outlets surpassed flow rates at the wetland inlets, reflecting incident rainfall and differences in wetland area at the two sites. A significant positive correlation existed between local rainfall and outflow rates at the larger wetland, but not between rainfall and inflow rates. During storm events, outlet pH, relative to inlet pH, was slightly elevated at the larger wetland, and depressed at the smaller wetland. However, over the course of one year, rainfall was uncorrelated to outlet pH in the larger wetland. A substantial rain event at the smaller wetland resulted in a temporary elevation in outlet iron concentrations, with treatment efficiency reduced to near zero. However, in the larger wetland, outlet iron concentrations were not significantly affected by storm events. Although rainfall and outlet iron concentration were not significant correlates at the larger wetland, flow rate was positively correlated to outlet iron concentration. A normal manganese treatment efficiency of 50 percent at the smaller wetland was reduced to zero during a heavy rain.
(KEY TERMS: acid mine drainage; wetlands; storm events; water quality; pH; iron; manganese; water treatment.)

INTRODUCTION

Acidic coal mine drainage results from the exposure and unearthing of pyritic rock in the coal mining process. When such strata are exposed to oxygen and infiltration by water, the oxidation of this material creates large quantities of sulfuric acid that may be laden with iron, manganese, aluminum, and other metals. The solubilities of these metals are generally related to the pH of the water; thus as the production of acid lowers the pH, many of the metals become soluble. The weathering of pyrite (FeS_2) includes the reaction of pyrite with oxygen and water (1), and also the reaction of ferric iron and pyrite (2), both of which generate acidity and ferrous iron (Stumm and Morgan, 1981):

$$FeS_{2(s)} + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (1)$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (2)$$

Microorganisms promote pyrite oxidation by mediating the oxidation of Fe^{2+} to Fe^{3+}, the latter of which becomes a primary oxidant of the pyrite (Equation 2) and subsequently hydrolyzes, resulting in the formation of sulfuric acid. The ferric iron will also precipitate from solution as ferric hydrates at the elevated pH of receiving waters. The generation of acidic mine drainage may persist for decades at abandoned mines. Usually a depressed pH coupled with elevated concentrations of iron and manganese are the principal water quality parameters of concern in coal mine drainage.

Since 1977 the Federal Clean Water Act has required operators to ensure that water leaving the permitted mining area is returned to a circumneutral pH (6.0-9.0), with low mean 30-day concentrations of iron (< 3.5 mg L^{-1}) and manganese (< 2.0 mg L^{-1}; U.S. Code of Federal Regulations, 1981). Conventional water treatment involves the application of alkaline chemicals to elevate pH (e.g., NaOH, Na_2CO_3, CaO,

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$Ca(OH)_2$, NH_3), causing iron and manganese to precipitate from solution upon exposure to oxygen due to the pH-dependent solubility of these metals. Since the recognition that volunteer wetlands receiving mine drainage considerably improved the quality of the water (Wieder and Lang, 1982), the construction of treatment wetlands has increased dramatically in the bituminous coal region of the eastern U.S. (Kleinmann and Girts, 1987).

The advantages of implementing a wetland treatment system in lieu of conventional treatment, assuming each method results in equivalent water treatment, are (1) wetlands are less expensive, especially in the long run (Baker *et al.*, 1991); (2) wetlands require less maintenance; and (3) these treatment wetlands provide habitat for many organisms that in some instances is comparable to those in nonimpacted natural wetlands (Lacki *et al.*, 1990).

There are more than 500 constructed wetlands in the United States receiving mine drainage for treatment purposes (Kleinmann and Hedin, 1993). However, the immediate effects of storm events on the water quality leaving these constructed wetlands is relatively unknown. The quality of water leaving a treatment wetland during storm events has been questioned informally by several workers and regulatory agencies. Some have hypothesized that heavy rains cause a washout of the sediments and consequently result in a release of degraded waters by the wetland. Since discharges are not normally sampled during storm events, published data are few from constructed wetlands.

In Kentucky, several experimental constructed wetlands receiving acid mine water were monitored during a rain event of 2.4 cm over 12 hours (Wieder, 1992). During the rain, (a) outflow rates exceeded inflow rates, (b) no correlation was found between flow rate and outlet total iron concentrations, and (c) no correlation was found between flow rate and outlet particulate iron. These findings led Wieder to conclude that treatment efficiency for iron at these wetlands was not affected by a rain event. However, analyses of effluent water quality at two constructed wetlands in Tennessee reached different conclusions. During storms, total iron, pH, and total suspended solids were elevated above baseline levels, while total manganese increased at one wetland and decreased at the other (Taylor *et al.*, 1993). The present paper describes the effects of several storm events on water quality and flow rates at two constructed wetlands. Site differences were observed and differences in wetland design configuration are offered as a possible explanation for the observed site differences in water quality.

METHODS AND SITE DESCRIPTIONS

The Simco Wetland

A deep mine discharge developed in 1980 at the Simco No. 4 mine in Coshocton County, Ohio. After several alternatives were explored to treat the mine water, a wetland treatment system was completed in November 1985. It initially consisted of three wetland cells in sequence separated by small settling pools (Stark *et al.*, 1988). The substrate consisted of a layer of crushed limestone (15 cm) covered with a layer of spent mushroom compost (45 cm). The total initial area of the system was 2623 m^2 (cell 1 = 850 m^2, cell 2 = 771 m^2, and cell 3 = 1002 m^2). Bed slope was 1 percent. *Typha latifolia* L. (common broad-leaved cattail) rhizomes were transplanted at an initial density of 3-4 m^{-2}. This species has remained the dominant plant species, with a mean shoot density in 1990 of 14.8 m^{-2}. Following the addition of a fourth cell in 1989 and including the source pool, the pools below cells 1 and 2, and the ditches around cells 1 and 2, the total wetland area from inlet to outlet totaled 4,138 m^2 (Figure 1). Ditches around the site prevent most surface water flows from entering the wetland.

Mean inlet and outlet water quality parameters are given in Table 1. This wetland retained about 81 percent of the iron that it received from February 1, 1990, to March 1, 1991. Since the Simco wetland was built (nine years), it has retained about 75 percent of the iron received, with no sign of declining performance (Stark *et al.*, 1994).

The Hartzfeld Wetland

Also constructed in 1985, the Hartzfeld wetland is located near Luthersburg in central Clearfield County, Pennsylvania. The discharge developed on the periphery of a reclaimed surface mine. The pH of the seep was circumneutral, and concentrations of metals were relatively low (up to 10 mg L^{-1} iron; up to 7 mg L^{-1} manganese) in the study period (1988-89). Nine wetland cells are located in a terraced sequence interrupted by limestone rocks (Figure 2). The wetland substrate was composed of a mixture of topsoil, manure, and straw, with a depth of approximately 50 cm. The initial planting was *Typha latifolia*; however, each cell has become variously colonized by vegetation ranging from an almost pure stand of *Equisetum arvense* (horsetail) in the upper cells, through associations of sedges, grasses, and *Typha latifolia* in the lower cells. Total wetland area was 450 m^2, of which greater than 80 percent is vegetated. For the year of

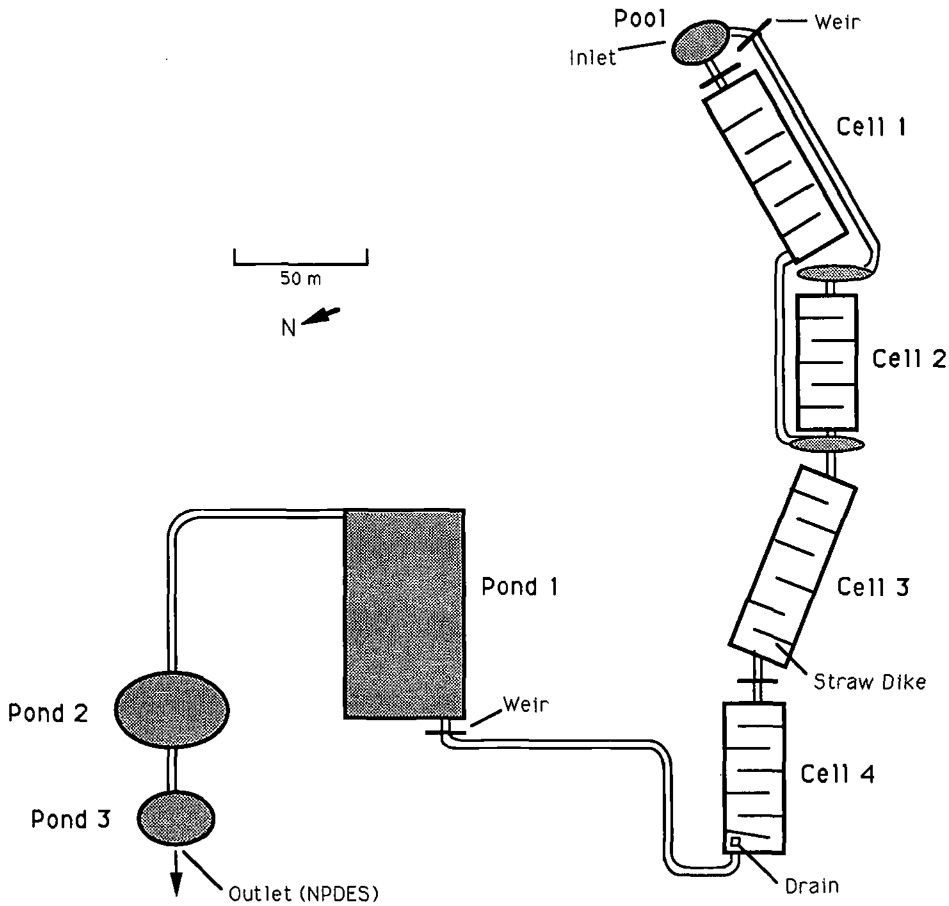


Figure 1. Configuration of the Simco Wetland.

TABLE 1. Mean (± 1 S.D.) Water Quality at the Simco Wetland, February 1, 1990, to March 1, 1991.

Parameter	Inlet	Outlet	N
Flow Rate (L min^{-1})	606.8 ± 258.0	648.4 ± 264.8	254
pH (S.U.)	6.68 ± 0.12	6.93 ± 0.14	26
Acidity (mg L^{-1})	147.6 ± 22.3	29.5 ± 4.8	26
Alkalinity (mg L^{-1})	86.4 ± 19.6	58.3 ± 14.8	26
Total Fe (mg L^{-1})	69.5 ± 8.9	13.5 ± 6.1	26
Total Mn (mg L^{-1})	1.34 ± 0.18	1.45 ± 0.24	26
Sulfate (mg L^{-1})	863 ± 110	824 ± 109	26
Conductivity (μmhos cm^{-1})	1538 ± 155	1459 ± 131	26
Total Suspended Solids (mg L^{-1})	33.7 ± 11.5	22.9 ± 10.0	26
Temperature (°C)	12.4 ± 0.9	11.7 ± 6.8	24

study, mean inlet and outlet water quality parameters are given in Table 2. On average, 79.4 percent of the iron and 47.9 percent of the manganese was retained.

Field Sampling

At the Simco wetland, daily measurements of outflow, inflow (beginning June 14, 1990), pH, total iron, and temperature were taken at the NPDES (National

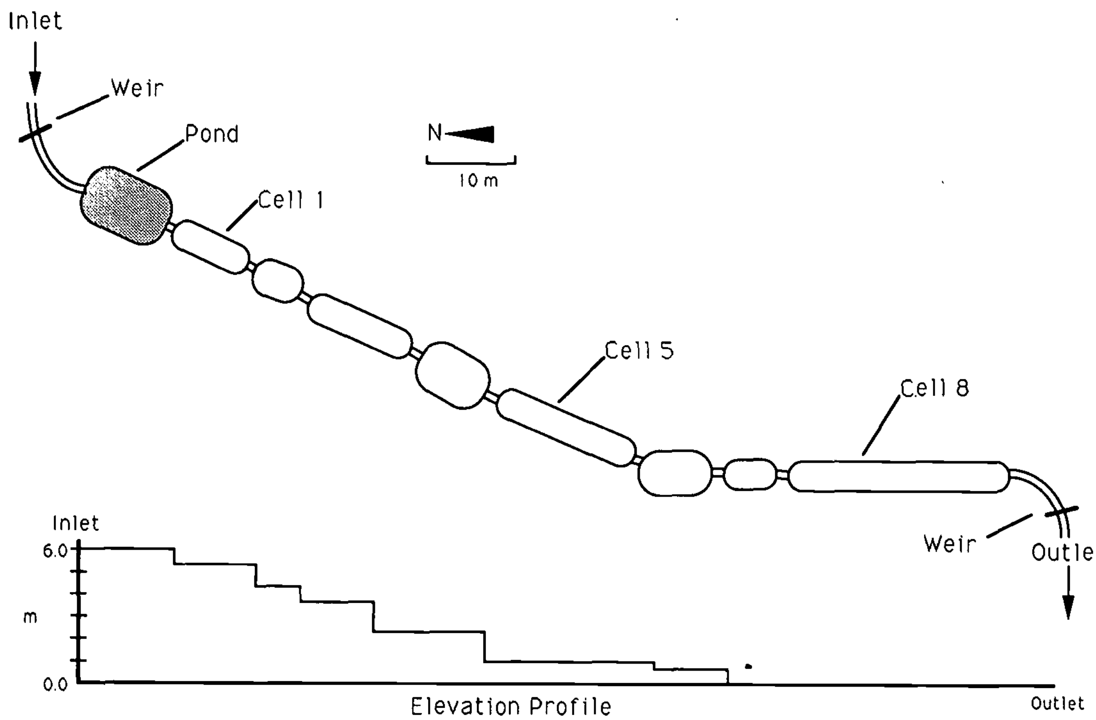


Figure 2. Configuration of the Hartzfeld Wetland.

TABLE 2. Mean Water Quality at the Hartzfeld Wetland, July 14, 1988, to June 16, 1989 (NA = not analyzed).

Parameter	Inlet	Outlet	N
Flow Rate (L min^{-1})	124.2 ± 95.4	100.8 ± 81.0	14
pH (S.U.)	5.71 ± 1.67	6.73 ± 0.42	14
Acidity (mg L^{-1})	NA	NA	NA
Alkalinity (mg L^{-1})	66.0	54.0	1
Total Fe (mg L^{-1})	6.0 ± 3.9	1.4 ± 2.5	14
Total Mn (mg L^{-1})	5.1 ± 1.8	3.2 ± 1.8	14
Sulfate (mg L^{-1})	415.0	395.0	1
Conductivity (μmhos cm^{-1})	717 ± 134	693 ± 122	14
Total Suspended Solids (mg L^{-1})	NA	NA	NA
Temperature (°C)	NA	NA	NA

Pollutant Discharge Elimination System) sampling point (outlet, Figure 1) for a period of 13 months (February 1, 1990, through March 1, 1991). The pH and temperature were taken electrometrically, total iron was determined with a field test kit (Hach model MD2, to the nearest 0.1 mg L^{-1}), and flow rates were taken by measuring water depths in the permanent weirs at the wetland inlet and outlet. Iron concentrations measured with the field test kit were within 1 mg L^{-1} of duplicate samples that were analyzed in the laboratory using atomic absorption (as per APHA, 1985).

At the Hartzfeld wetland, water samples and flow rates were taken during two storms: October 2, 1988, and May 11, 1989. For the rain event of October 2, samples and flows were taken on the days immediately preceding and following the storm. For the rain event of May 11, samples and flows were taken on that date only. Flow rates, pH, conductivity, dissolved iron, and dissolved manganese were sampled at the wetland inlet, outlet, and at the outfalls of individual wetland cells within the system. Flows were measured by permanent weirs, pH and conductivity were analyzed electrometrically, and metals were analyzed by atomic absorption following filtration (0.45 μm) and acidification.

RESULTS

Simco Wetland

Although the outlet is located below the wetland proper outlet (Figure 1), it represents the last point before the treated mine water enters the watershed from the permitted area (the NPDES station). Therefore the quality and quantity of water at this station is critical to downstream waters. Four storm events illustrate how flow rates, pH, and total iron vary in response to rain. Storm and rain events are defined here as either a single continuous event or an intermittent precipitation event over the course of several days.

The Effect of Precipitation on Flow Rates. A plot of daily outflow rates and precipitation from February 1990 through February 1991 illustrates the relationship between flow and storm events (Figure 3): rainfall and outflow rate are positively correlated over this period ($r = +0.26$; $P < 0.0001$; $N = 235$). Each significant precipitation event corresponded with a sudden increase (spike) in the outflow rate. Successive spring rains in late April and early May 1990 resulted in higher flows from the wetland. Dry periods in July and August 1990 resulted in gradually declining outflows. Unlike outflow rates, inflow rates at Simco were not significantly correlated to local rainfall over this period ($r = 0.03$; $P < 0.71$; $N = 152$). Regressions of outflow on precipitation and of inflow on precipitation yielded similar probability values.

Inflow and outflow rates are plotted during a major three-day summer storm event totaling 14.2 cm, a minor summer storm event totaling 4.6 cm over 16 days, an early fall storm event totaling 4.6 cm over six days, and a late fall fairly heavy storm event totaling 4.1 cm over two days (Figure 4). Rain immediately elevated outflow rates during and shortly following

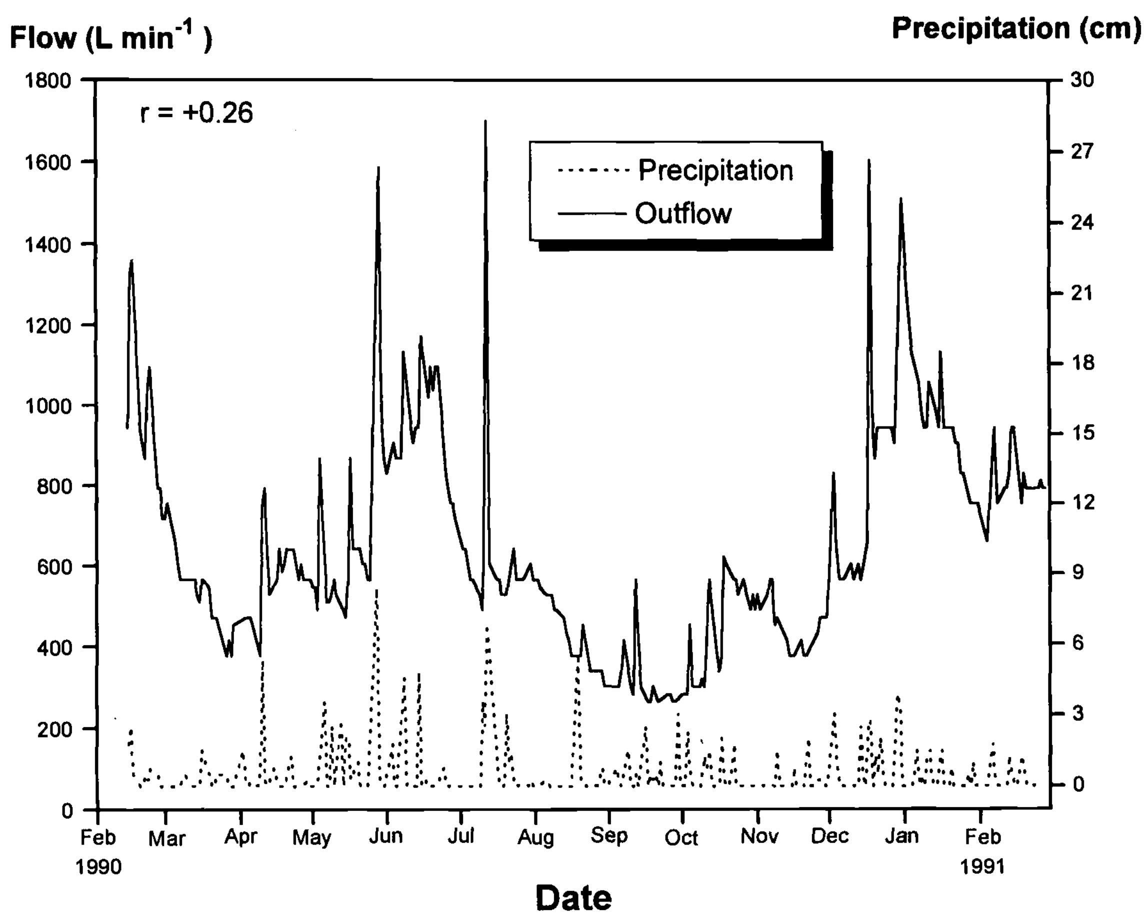


Figure 3. The Relationship Between Outflow Rate and Local Precipitation at the Simco Wetland.

the storm event, provided the rainfall exceeded about 1.27 cm on that day.

On July 12, 1990, a heavy rain of 6.86 cm fell on the Simco wetland (Figure 4A), which was preceded by two days of rain totaling 6.10 cm. While the inflow rate rose from 491 to 756 L min-1 over this three-day period, the outflow rate increased from 491 to 1701 L min^{-1} over the same period, increases of 54 percent and 246 percent, respectively. During the minor summer storm event including a total of 4.57 cm of rain over two weeks, inflow and outflow rates were similar (Figure 4B). During the early fall storm event totaling 4.58 cm over a period of six days, both inflow and outflow rates increased from 378 L min^{-1} on October 17 to 548 L min^{-1} on October 25 (Figure 4C). While inflow and outflow rates were equivalent when the precipitation began and three days after the storm event, outflow exceeded inflow by about 25 percent during the rains and until two days following the rains. In the late fall rain event, two successive days of rain in early December totaling about 4 cm resulted in an immediate increase in both outflow and inflow rates (Figure 4D). However, as in the other storm events, outflow rates exceeded inflow rates by a distinct margin. Following these two days of rain, outflow continued to exceed inflow for six days during which no further rain occurred. It was not until December 11, 1990, that outflow and inflow rates were once again equivalent. Therefore, it appears that rain events at Simco influence the outflow rate by immediately increasing it over the short term, while exerting less of an influence on the inflow rate.

Only one sampling point is available on the day of an appreciable snow event. On February 14, 1991, 5.08 cm of snow fell, followed by zero precipitation on the next day, and subfreezing temperatures. Neither inflow nor outflow rates were affected. On both days, inflow rates were 926 L min^{-1} and outflow rates were 945 L min^{-1} (i.e., flows were roughly equal).

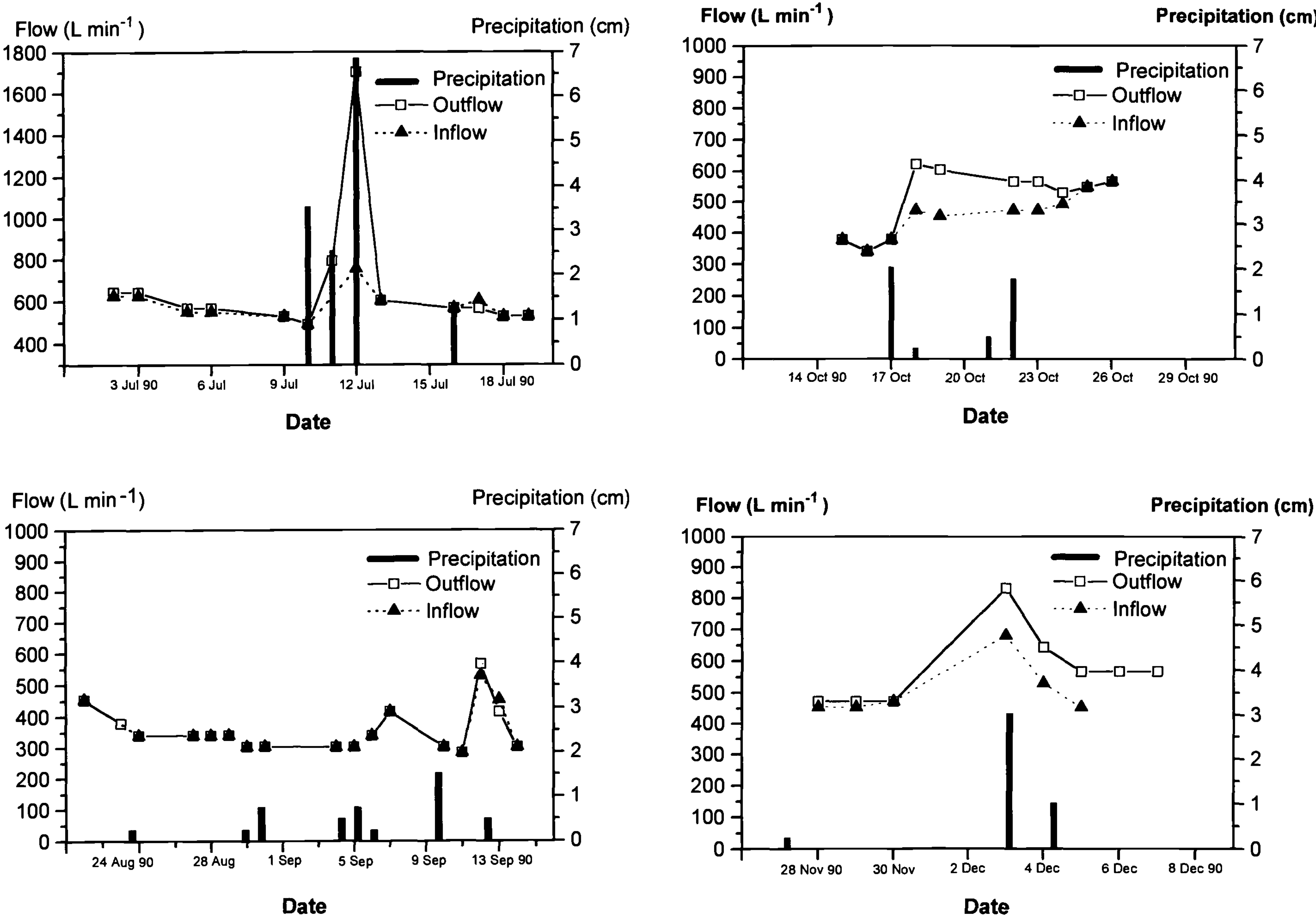
The Effect of Precipitation on Outlet pH. As the outflow rate increased to over 1512 L min^{-1} during the major summer storm event, outlet pH increased slightly from 7.0 to 7.3 on the second rain day, then declined to 7.0 on the last rain day (Figure 5A). During the minor summer storm event, a similar pattern in pH occurred (Figure 5B): during a two-day rain of 1.02 cm accumulation, pH increased from 6.8 to 6.9 on the first day of rain, declining to pre-rain pH on the second day of rain. A few days later, a three-day rain, also of 1.02 cm accumulation, resulted in an increase in pH at the wetland outlet from 6.80 to 6.87 on the second day of rain, followed by a decline to pre-rain pH on the third day of rain. In both cases, pH dropped to pre-rain levels following an initial increase in pH during the rains. This pattern was not detected in the early fall storm event (Figure 5C): a drop in outlet pH was observed from 6.78 to 6.6 on the day of heaviest accumulation. However, in the late fall storm event, pH was elevated a tenth of a unit during the first day of rain; then pH dropped below pre-rain pH levels on the second day of rain (Figure 5D). Following this rain, outlet pH rose appreciably during the immediate dry period.

Despite apparent effects during rainstorms on outlet pH described above, outlet pH and precipitation were not significantly correlated ($r = 0.03$; $P < 0.66$; $N = 225$) at Simco over the 13-month period, indicating that pH fluctuations were probably only mildly affected by local rainfall events. A regression of pH on precipitation yielded similar probability values.

The Effect of Local Precipitation on Outlet Total Iron. Total iron was increased at the wetland outlet from 0.8 to1.4 mg L^{-1} during the heavy summer storm event (Figure 6A). However, it was not until the third day, when the heaviest accumulation occurred, that iron levels increased. During the first two days of rain, iron concentrations were essentially unchanged at 0.8 mg L^{-1}. During the minor summer storm event (Figure 6B), total iron increased from 0.8 to 1.0 mg L^{-1} during the first rainstorm but was unchanged at 0.8 mg L^{-1} during the second rainstorm. The early fall rain event resulted in a slight increase in outlet iron: total iron increased from 0.8 to 0.9 mg L^{-1}, and from 0.8 to 1.0 mg L^{-1} during successive rains (Figure 6C). However, during the heavy late fall rain event, total iron at the wetland outlet increased from 1.2 to 2.2 mg L^{-1} (Figure 6D).

Because a positive correlation existed between precipitation and flow rates at Simco (as noted earlier), in light of the above trends for iron it was expected that a similarly positive correlation may exist between outflow rate and outlet iron concentration. Indeed, this is the case, although the strength of the correlation was surprising: $r = +0.55$; $P < 0.0001$; $N = 244$ (Figure 7). Although outflow rate appears to be a partial function of local rainfall, outlet iron concentrations and rainfall were not significantly correlated ($r = -0.02$; $P < 0.71$; $N = 225$).

Outflow rates are influenced to a greater extent by incident rainfall than are inflow rates. However, inflow rates largely determine outflow rates ($r = +0.90$; $P < 0.0001$; $N = 164$; $r^2 = 0.81$) and probably represent the effects of local rainfall, but on a delayed basis. Therefore, a regression of outlet iron concentration as a function of inflow and outflow rates may be useful: $[Fe]_{outlet} = -0.4183 + 0.0011(\text{Inflow Rate}) + 0.0024(\text{Outflow Rate})$; $r^2 = 0.36$.



4A (TOP) – 4B (BOTTOM)

4(C) (TOP) – 4D (BOTTOM)

Figure 4 (A-D). The Relationship Between Local Precipitation on Flow Rate During Four Storm Events at the Simco Wetland. Daily rainfall totals indicated by vertical bars.

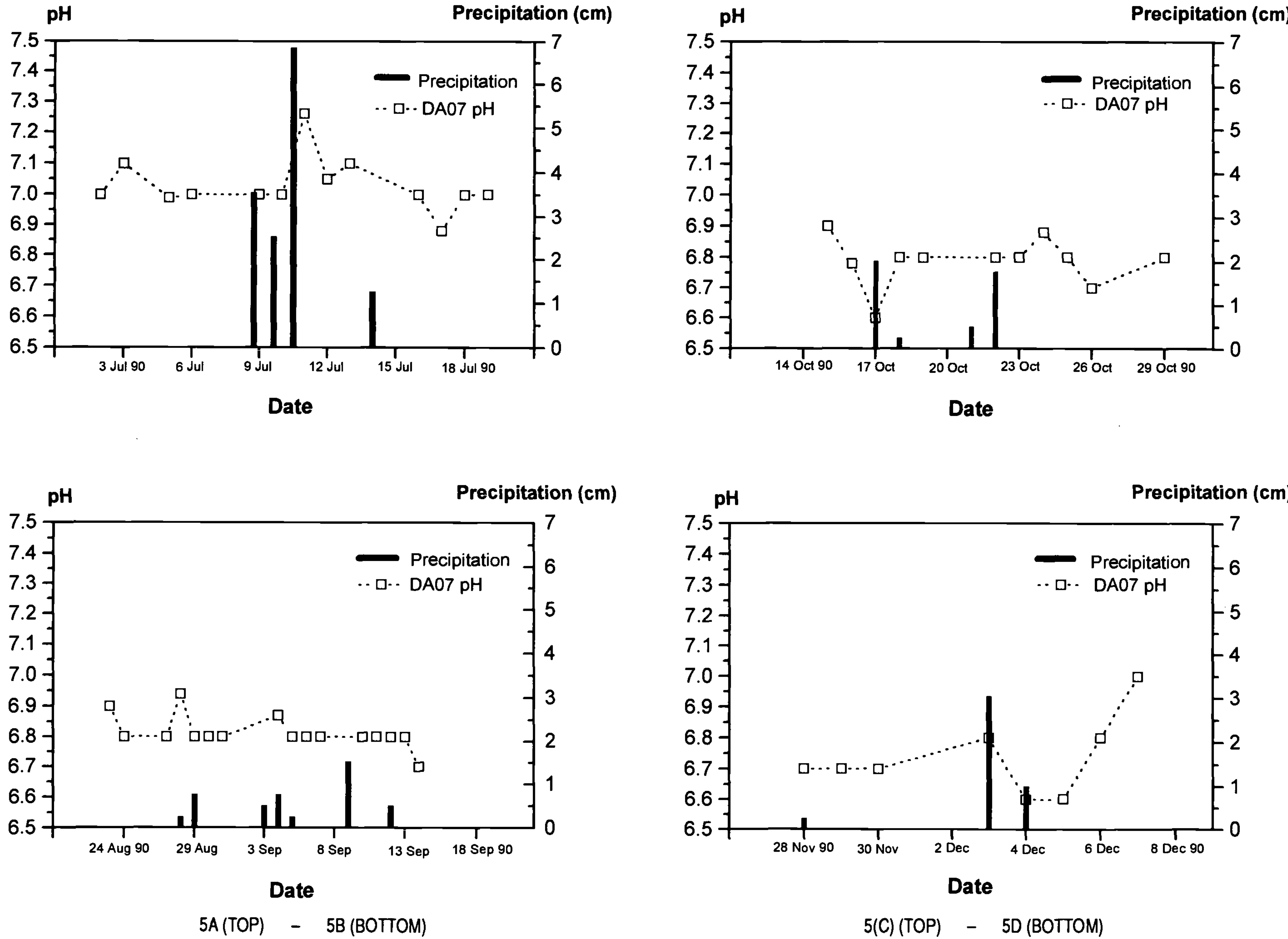
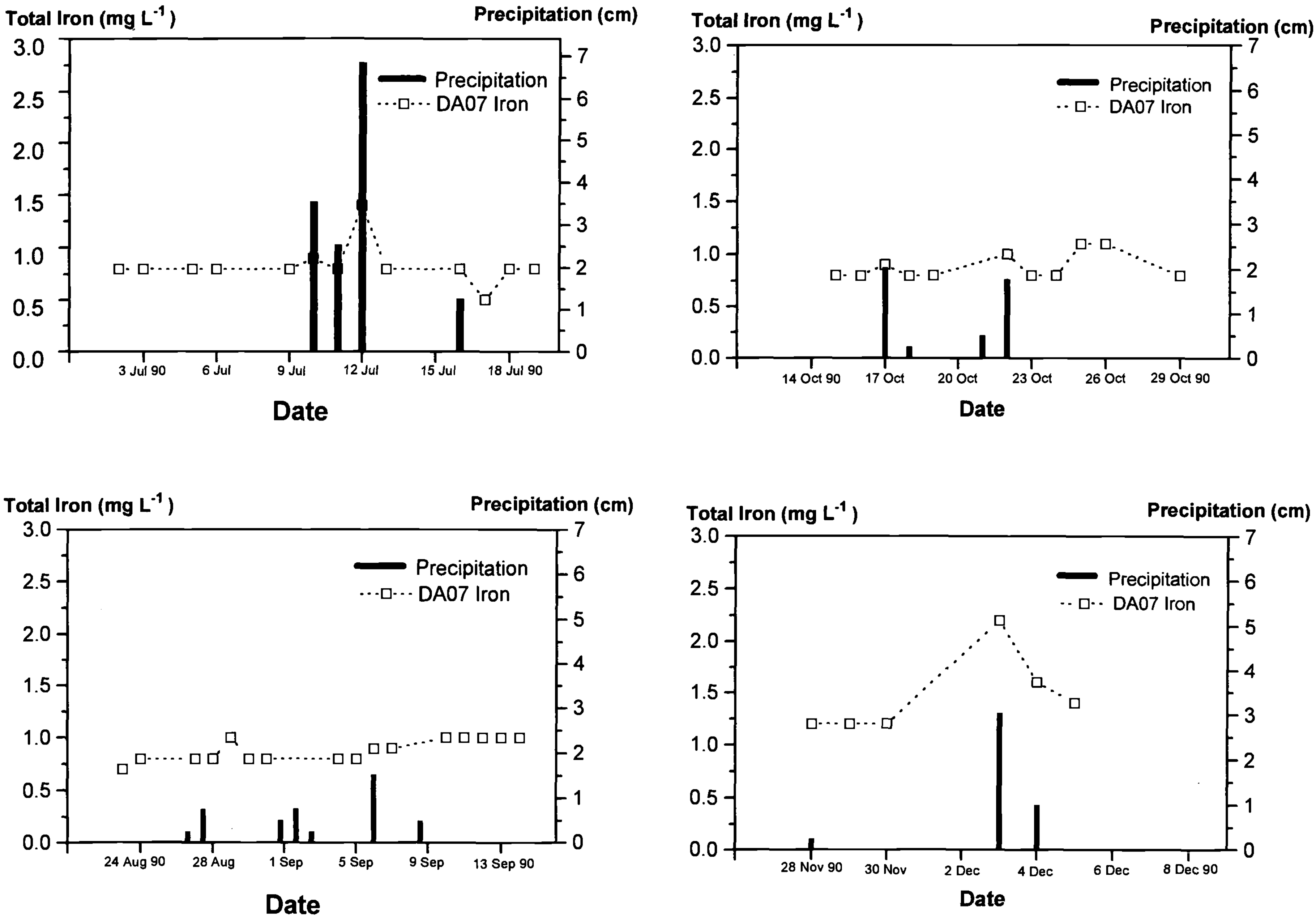


Figure 5 (A-D). The Relationship Between Local Precipitation on Outlet pH During Four Storm Events at the Simco Wetland.
Daily rainfall totals indicated by vertical bars.



6A (TOP) – 6B (BOTTOM)

6(C) (TOP) – 6D (BOTTOM)

Figure 6 (A-D). The Relationship Between Local Precipitation on Outlet Total Iron During Four Storm Events at the Simco wetland. Daily rainfall totals indicated by vertical bars.

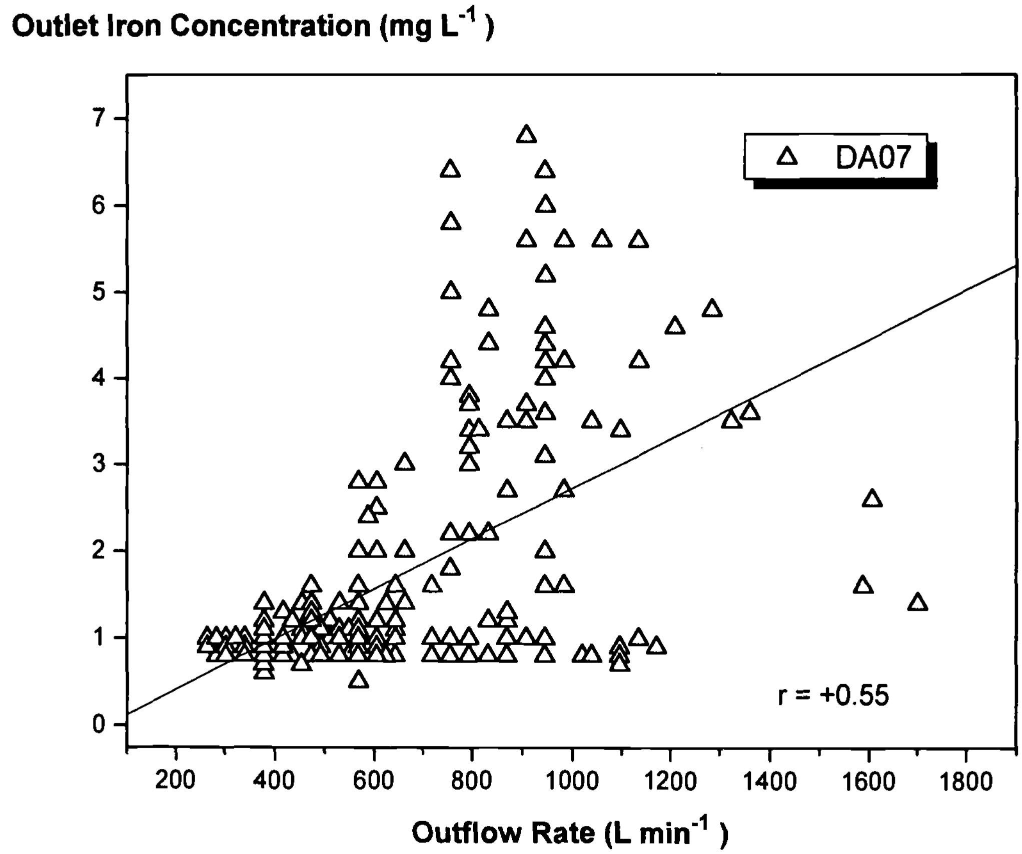


Figure 7. Correlation Between Outflow Rate and Outlet Total Iron Concentration at the Simco Wetland.

Hartzfeld Wetland

The Effect of Local Precipitation on Flow Rates. The storm event of October 2, 1988, registered 0.2 cm. Before the storm, inflow exceeded ouflow by approximately 6.0 L min^{-1}. During the storm, outflow exceeded inflow by 4.2 L min^{-1} (14 percent). On the day after the storm, inflow once again exceeded outflow, but only by 3.6 L min^{-1} (Table 3). During the heavier rainstorm of May 11, 1989, when rain was falling at the rate of 0.13 cm hr^{-1}, outflow exceeded the inflow rate by 10 percent (Table 4). Outflow rate during the spring storm was 6.6 times greater than the outflow rate during the fall storm (227.4 vs 34.2 L min^{-1}). Since flow data are not available for dates preceding or following the storm of May 11, 1989, it is not possible to separate the storm effects on surface and ground water flows.

The Effect of Local Precipitation on pH. Normally, pH is elevated by the Hartzfeld wetland from about 5.7 to about 6.7 (Table 2). During the fall 1988 rain event of 0.2 cm, pH patterns at the site were unaffected (Table 3). However, during the heavier rain event of spring 1989, the capacity to elevate pH may have been reduced (Table 4): pH was elevated only from 6.3 to 6.5.

The Effect of Local Precipitation on Dissolved Iron. Before and after the fall rain, outlet dissolved iron concentrations were 0.1 mg L^{-1}. During the rain event, outlet concentrations increased to 0.4 mg L^{-1} (Table 3). During the heavy spring rain, inlet and outlet dissolved iron concentrations were essentially equivalent (Table 4); treatment efficiency dropped to near zero during this heavy rain.

The Effect of Local Precipitation on Dissolved Manganese. During the light fall rain, manganese concentrations at the inlet or outlet of the wetland were apparently unaltered (Table 3). However, during the heavy spring rain, a small export of manganese occurred (Table 4). Treatment efficiency for manganese, normally near 50 percent, dropped to zero during this rain.

TABLE 3. Water Quality and Flow Rates at the Hartzfeld Wetland Before (October 1, 1988), During (October 2, 1988), and After (October 3, 1988) a Storm Event of 0.2 cm.

Parameter	Time	Inlet	Outlet
Flow Rate (L min^{-1})	Pre-Rain	30.0	22.8
	Rain	30.0	34.2
	Post-Rain	26.4	22.8
pH (S.U.)	Pre-Rain	6.4	7.3
	Rain	6.5	7.3
	Post-Rain	7.0	7.1
Dissolved Iron (mg L^{-1})	Pre-Rain	4.6	0.1
	Rain	5.2	0.4
	Post-Rain	5.0	0.1
Dissolved Manganese (mg L^{-1}	Pre-Rain	5.1	2.8
	Rain	5.3	2.4
	Post-Rain	4.3	2.1

TABLE 4. Water Quality and Flow Rates at the Hartzfeld Wetland During a May 11, 1989, Rain Event, When Accumulation Was at 0.13 cm h^{-1}.

Parameter	Inlet	Outlet
Flow Rate (L min^{-1})	207.6	227.4
pH (S.U.)	6.3	6.5
Dissolved Fe (mg L^{-1})	9.9	9.6
Dissolved Mn (mg L^{-1})	7.0	7.4

DISCUSSION

Normal metal treatment processes may be relatively unaffected, adversely affected, or even interrupted at mine drainage wetlands during heavy rains. At the smaller wetland, the heavy spring rain interrupted both iron and manganese retention. During dry periods, this wetland lowered iron concentrations to compliance levels. However, during the heavy spring rain, treatment efficiency was reduced to zero. Because flow rates during rainstorms were greater than twice the normal, this depressed treatment efficiency translated into a significant export of otherwise retained iron.

Prior to the storm, this wetland was exporting approximately 6.1 g Fe $hour^{-1}$. However, during the rainstorm, total iron was exported at a rate of 131.0 g Fe $hour^{-1}$. Clearly, the combination of higher spring base flows, local precipitation, and the interruption of iron retention processes that occur during a significant rainstorm resulted in a sizeable mass of iron released into stream waters. However, the higher base flow in receiving waters during spring served to mitigate (by dilution) the temporary increase in effluent iron concentration.

Manganese retention during dry periods followed a similar, though less effective, treatment pattern. Normally, approximately half of the manganese was retained by the (smaller) Hartzfeld wetland. However, during the heavy spring rain, outlet manganese concentrations equaled or surpassed inlet manganese concentrations. This pattern for manganese is thus similar to that of iron during storm events. However, manganese retention at the Hartzfeld wetland appeared to be a function of successful iron treatment. For a given wetland cell, whenever the iron concentration at the cell outfall exceeded 3.0 mg L^{-1}, manganese retention did not occur (Brooks *et al.*, 1990). These observations are consistent with those in other constructed and natural wetlands receiving iron and manganese in mine water (e.g., Hedin and Nairn, 1993). During a significant storm event, iron concentrations at the wetland outlet may be elevated above 3.0 mg L^{-1}, which interfered with the normal retention of manganese by the wetland. Thus, the interruption of iron retention at Hartzfeld may underlie the export of manganese during storm events (as opposed to a direct effect of local rainfall).

During a heavy rain, outflow rates may greatly exceed inflow rates, depending on the wetland area and the amount of rainfall. At the larger of the two wetlands (Simco), rain events of > 3 cm resulted in significant increases in outflow rate: outflow rate exceeded inflow rate by a factor of up to 3.5. Lighter rainstorms, however, had a negligible effect on flow rates. The outlet pH at Simco was not significantly correlated to rainfall. However, outlet pH rose slightly during a rain and then reverted to the pre-rain pH when the storm subsided.

While the smaller Hartzfeld wetland was less subject to wide variations in outflow rate during a heavy rainstorm, metal retention processes were disrupted to a greater degree than in the larger Simco wetland. Outlet iron concentrations at Simco remained within daily compliance (< 7.0 mg L^{-1}), even during the heaviest of rains (nearly 13 cm in 3 days). Some elevation in outlet total iron was observed during and following precipitation events, but it was usually less than 1 mg L^{-1}. Findings at the Simco wetland for iron and pH were similar to those reported by Taylor et al. (1993) for two Tennessee wetlands treating mine water. At the Tennessee wetlands, effluent total iron was elevated from a baseline level of about 1 mg L^{-1} to about 3.5 mg L^{-1} during both dry (summer-fall) and wet (winter-spring) seasons, and it never exceeded compliance levels. In addition, effluent pH was elevated during rainstorms. With respect to total suspended solids (T.S.S.), Taylor *et al.* (1993) reported significant exports of T.S.S. from wetlands during storms, indicating that this is worthy of future study.

Rainfall was positively correlated to outflow rates but neutral with respect to inflow rates. This pattern was also observed in wetlands studied in Tennessee (Taylor *et al.*, 1993). In the present study, localized rainfall immediately elevated outflow rates (i.e., on the same day) but had no immediate effect on inflow rates. When outflow rates rose in response to a storm, outlet iron concentrations also increased. Despite the strong correlation between inflow and outflow rates, no correlation existed between inflow rate and outlet iron concentration. Furthermore, no correlation existed between precipitation and outlet iron concentration. Since precipitation had an immediate effect on outflow rates, and outflow rates and iron concentration were fairly strong positive correlates, it was not obvious why precipitation and outlet iron concentration were not also positive correlates. However, if outflow rates reflected not only inflow rates (which responded in a delayed fashion to rain events) but also local precipitation events, outflow rate may be a better predictor of outlet iron concentration than either inflow rate or precipitation.

While Taylor *et al.* (1993) attributed differences in effluent water quality between the two wetlands as related to vegetative cover, the differences between the two wetlands in the present study (which have similar plant cover) may stem from their different configurations. The Simco wetland included a series of wetland cells followed by a series of three ponds, which doubtless assisted in the settling of solid particles, including any iron resuspended during a rain event. However, the Hartzfeld wetland was not configured with ponds; the wetland effluent flowed directly into a watershed. Future studies should address the effect, if any, on the water quality during storm events at the immediate outlet from a wetland versus that which is allowed to flow through a series of ponds. In addition, we suggest that sizing criteria for constructed wetland design may have to be reassessed to take storm events into consideration.

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