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IMPACT OF URBAN DEVELOPMENT ON THE CHEMICAL COMPOSITION OF GROUND WATER IN A FEN-WETLAND COMPLEX

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Abstract: A 15-month-long hydrogeologic investigation of a fen-wetland complex in northeastern Illinois, USA indicated the encroachment of ground-water-borne anthropogenic contaminants into two of three high quality fens. Ground-water flow directions and chemical evidence indicated that plumes of ground water with anomalously large concentrations of Na^- and Cl^- originated from a private septic system and from rock salt spread on an adjacent road. The contamination, in turn, had an adverse effect on fen vegetation; within the plumes, diverse vegetation was replaced by the more salt-tolerant narrow-leaf cattail (*Typha angustifolia*). Ground water of the third fen contained large concentrations of SO_4^{2-} as high as 516 mg/L. The SO_4^{2-} anomaly was observed on a transient and/or seasonal basis in the fen ground water and in an adjacent marsh and pond. Isotopically light $\delta^{34}S$ values in these waters indicated that the addition of SO_4^{2-} resulted from the oxidation of pyrite within underlying peat and/or pyritic gravel. However, the large SO_4^{2-} concentrations had no discernible effect on fen vegetation. The results of this investigation indicate how easily construction of houses with private septic systems and deicing agents from roadway maintenance can contaminate fen ground water with relatively large concentrations of Na^+ and Cl^-, resulting in a significant loss of biodiversity in fens.

Key Words: fen, ground water, water chemistry, hydrology, urban development

INTRODUCTION

Runoff and recharge associated with urban development within the watershed of a wetland may have adverse effects on the chemical composition of ground water. Contaminants from septic systems, lawn chemicals, road salt, vehicular traffic, industrial installations, and waste-disposal facilities within a watershed and in ground-water recharge areas may degrade water quality and, subsequently, negatively impact wetland plant species, particularly those dependent on specific ground-water chemistry (Wilcox 1986 a,b, Grootjans et al. 1988). Grootjans et al. (1988) showed that changes in ground-water types (based on electrical conductance and major cations and anions) and volume reaching fen meadows in The Netherlands had a deleterious effect on fen meadow vegetation. Wilcox (1986 a,b) documented the negative effects of Na^+ and Cl^- on bog vegetation in Indiana, and Scheidt (1988) and Izuno et al. (1991) recorded the changes in wetland vegetation following addition of agriculturally-derived NO_3^- and PO_4^{3-}.

Fens are generally characterized as having herbaceous wetland communities constantly saturated with relatively cold, calcareous ground water (Moran 1981). Fens are dependent on recharge from the watershed, and consequently, changes within the watershed that alter the volume and quality of ground-water recharge can rapidly affect the volume and quality of ground-water received by the fens.

This paper presents the results of an investigation of a fen-wetland complex in northeastern Illinois where rapid expansion of urban development was encroaching on the watershed. Apparent effects on water quality and vegetation from historic construction of a private septic system and roadway deicing agents, in

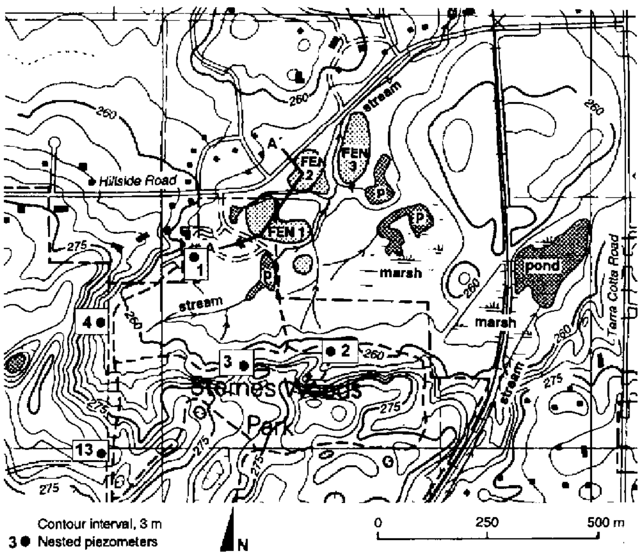

Figure 1. Site map showing major features of the study area, locations of nested-piezometers screened in the sand and gravel aquifers, and line of cross-section A–A'.

the context of the wetlands' hydrogeologic regime, were examined.

SITE CHARACTERISTICS

Geology and Hydrogeology

Sterne's Woods Park is an Illinois State Nature Preserve located within the glaciated central region of the United States about 90 km northwest of Chicago (Figure 1). The wetland complex consists of sedge meadow, wet prairie, and marsh, surrounded on three sides by a large Wisconsinan kamic moraine. Surface drainage within the bowl-shaped complex flows through a narrow gap between two kamic glacial landforms. The bedrock, which consists of Silurian-age dolomite (Woller and Sanderson 1976) is overlain by Wisconsinan-age loam and clay-loam diamicton (10 to 15 m thick) and sand and gravel outwash (15 to 45 m thick). Peat deposits (3 to 6 m thick) have accumulated within the fens and in other low-lying, poorly-drained areas (Curry et al. 1998).

The water table is approximately 20 m beneath the upland areas of the study area and at or near ground surface in the low-lying areas. Ground-water flow is predominantly to the northeast, with a hydraulic gradient of between 0.02 and 0.03. The hydraulic conductivity of the sand and gravel aquifer varies from 1×10^{-3} to 1×10^{-1} cm/s (B.R. Hensel, unpublished data). Springs, which are common along the base of the uplands, flow into small ponds and streams within the wetland complex (Figure 1). Springs and/or seeps also occur near the center of each fen (Hensel et al. 1991).

Modifications of the natural regime prior to 1990 included construction of ponds, drainage channels 2-m-deep, and a house and roads within and immediately adjacent to the fen-wetland complex. Changes after 1990 included construction of numerous houses within the watershed of the complex (K. Reimer, Director, Crystal Lake Park District, personal communications, 1992).

Fen Characteristics

Our investigation focused on three fens totaling 2.5 hectares in areal extent. These fens were characterized by White and Madany (1978) as having high natural quality (i.e., communities with a stable structure and composition showing no effects of disturbance by humans). The fens are underlain by sapric peat soils, saturated with relatively cold, calcareous ground water under flowing artesian conditions. Fen soils support calciphilic plant communities dominated by prairie grasses and/or sedges (Moran 1981, Illinois Department of Conservation 1988). In our study area, the fens provide habitat for 191 plant species, 10 of which are state-listed (six endangered, four threatened). Distribution of two plant species, narrow-leaf cattail (*Typha angustifolia* L.), a wetland generalist, and bulrush (*Scirpus acutus* Muhl.), a fen specialist, was determined in conjunction with this investigation (V.A. Nuzzo, unpublished data).

FIELD AND ANALYTICAL METHODS

One hundred sixty ground-water and 14 surface-water samples were collected throughout the wetland complex from sand and gravel aquifers, peat and marl, and ponds and streams, from February 1991 through May 1992 and analyzed in the field for temperature, pH, Eh, total alkalinity, electrical conductance, and major cations and anions. In conjunction with this work, data on hydraulic heads were collected monthly (over the same time period) in the study area (Hensel et al. 1991). All of these data were used to identify baseline conditions throughout the study area.

Ground-water samples and hydraulic head data from the sand and gravel aquifers were collected from five sets of nested piezometers (Figure 1). These piezometers were screened in the aquifers over 30-cm intervals at depths of 6.0 and 15.0 m. Field variables were monitored while the piezometers were purged ($\geq$ five well volumes), and sampling commenced (using a centrifugal pump) after these variables stabilized. Hydraulic head data from the fens were collected from additional nested piezometers installed at each fen. Samples of interstitial water from peat and marl layers in the fens were collected from specific horizons (0.25 to

0.5 m, 1.5 m, and 3.0 m) intercepted in narrow, hand-dug pits and with point samplers (Panno et al. 1995).

Three transects were established within each fen in the spring of 1992, with three to six sample locations along each transect. The transects were oriented approximately parallel to ground-water-flow directions, and normal to apparent contamination-plume contours. Thirty-two ground-water samples were collected from hand-dug pits near root-zone depths (0.25 to 0.5 m) along transects using mini-bailers, and chemical compositions and field variables were determined for each sample. Density and height of cattail and bulrush were recorded in spring 1992 coincident with the ground-water sample locations (V.A. Nuzzo, unpublished data).

Water samples were filtered in the field through a 0.45-μm filter, stored in polyethylene bottles, and refrigerated at 4° C until analyzed. Samples to be analyzed for cations were acidified with concentrated nitric acid in the field to a pH of less than 2.0. Sample handling and field analyses followed methods described by Wood (1981). Concentrations of cations were determined with a Model 1100 Thermo-Jarrell Ash Inductively Coupled Argon Plasma Spectrometer (ICAP). Anion concentrations were determined using a Dionex 211i ion chromatograph following U.S. EPA Method 300 (O'Dell et al., 1984).

Water-level data, collected with standard methods during the spring of 1992, were used to construct water-table elevation maps of each fen. Vertical hydraulic gradients and ground-water-flow directions in the fens were determined using paired piezometer and observation wells installed in the fens. Paired piezometers consisted of 3-cm OD galvanized steel conduit driven to depths of 1.2 m and to the bottom of the peat and marl (2 to 4 m). Observation wells used to measure ground-water-flow directions consisted of 2-m-long sections of 1.3-cm OD PVC pipe, slotted for about 1 m, and installed in the peat and marl to a depth of 1 m. Ground-water-flow directions in Fen 1 were approximated using shallow piezometers where ground-water flow was predominantly horizontal and using a limited number of observation wells. Locations and elevations of piezometer and observation-well tops were surveyed using standard techniques.

A graphical technique, developed by Sinclair (1974), was used to separate background and anomalous values for ionic concentrations. Originally developed to identify anomalous concentrations for mineral exploration, this method uses a cumulative probability curve to separate often-overlapping, statistically distinct populations of concentrations. Inflection points along the curve were used to separate these populations and are referred to as "thresholds."

Chemical analyses of water samples yielded errors in ion balance of ≤ 5%. Saturation indices of dissolved minerals for ground-water samples were determined using the USGS geochemical modeling program WATEQF (Ball et al., 1987). The sulfur isotopic composition of high-SO_4^{2-} water samples was determined using techniques described by Veda and Krouse (1986). National Bureau of Standards and in-house, Illinois State Geological Survey standards were used to determine $\delta^{34}S$, and data were referenced to Canyon Diablo Troilite.

RESULTS AND DISCUSSION

The results presented here are primarily from data and ground-water samples collected in the spring of 1992. Data on ground-water quality, vegetation, and water-levels collected during 1991, 1992, and subsequent years (Panno et al. 1998) indicate that the data and samples collected during the spring of 1992 are representative of long-term conditions (S.V. Panno, unpublished data).

Fen Hydrogeology

The water table was typically at or within a few cm of the surface of each fen throughout most seasons. The horizontal hydraulic gradients within the fens ranged from 0.01 to 0.07, similar in magnitude to those in the rest of the wetland complex. Vertical hydraulic gradients, as great as 0.34 (upward) were found at seeps near the centers of Fens 1 and 2, and as great as 0.95 (downward) were found adjacent to the man-made trenches that border the fens.

Chemical Composition of Ground Water

The sand and gravel aquifers of Sterne's Woods Park contain a Ca^{2+}-HCO^{3-}-type ground water typical of glacial deposits in North America and of ground water from calcareous fens (e.g., Komor, 1994). Most water samples were at or near saturation with respect to calcite, dolomite, and quartz. Saturation indices were consistent with ground water at or near equilibrium with the minerals that commonly make up basal outwash deposits of northeastern Illinois (Masters and Evans, 1987).

The chemical composition of fen ground water (Table 1) revealed a broad range for selected ions attributable to anthropogenic (Na^+ and Cl^-) and natural sources (Ca^{2+} and SO_4^{2-}). The spatial distribution of these ions in ground water of the fens and aquifers indicates the presence of chemically-distinct plumes; the shapes and locations of the plumes were consistent with ground-water-flow directions. Threshold concentrations for these variables were used to identify the

Table 1. Range and medians of chemical variables of all fen ground-water samples. Uncontaminated and contaminated ground-water samples for Fen 1 are presented and were separated on the basis of the threshold concentration for Cl^-. Samples were collected seasonally from February 1991 through May 1992. Concentrations are in mg/L unless indicated. NC = not calculated. The median and range of the chemical data are used because they are a resistant measure of water quality data and their extreme values (Helsel and Hirsch 1997).

Variable	Fen 1 Uncontaminated (n = 21) Range		Fen 1 Uncontaminated (n = 21) Median	Fen 1 Contaminated (n = 25) Range		Fen 1 Contaminated (n = 25) Median	Fen 2 (n = 34) Range		Fen 2 (n = 34) Median	Fen 3 (n = 23) Range		Fen 3 (n = 23) Median	Threshold Concentrations
Temperature (°C)	5.3	18.0	10.0	5.1	18.0	9.0	6.9	19.0	12.0	6.2	16.0	11.0	NC
pH	6.1	7.8	7.4	6.9	7.8	7.4	6.5	8.2	7.5	6.6	7.7	7.2	NC
Eh (mV)	−468	+423	−238	−262	+558	+276	−309	+368	+129	−176	+373	+264	NC
E.C. (mS/cm)	0.73	1.24	0.83	0.85	1.73	0.94	0.88	1.41	1.09	0.63	1.17	0.82	NC
Alk. (as $CaCO_3$)	348	416	368	364	444	384	368	452	408	136	390	310	NC
Na^+	1.41	17.1	6.27	3.10	153	16.6	3.60	93.2	39.0	<1.34	10.4	3.49	10
K^+	<0.63	3.60	2.08	<0.63	9.10	2.91	<0.63	7.5	3.6	<0.63	4.3	1.36	4.0
Ca^{2+}	92.7	140	111	102	183	114	101	161	118	70.4	152	104	180
Mg^{2+}	34.8	64.0	46.3	42.3	77.2	51.6	48.2	66.1	57.4	34.8	67.0	45.6	NC
Sr^{2+}	0.08	0.21	0.10	0.20	0.09	0.11	0.10	0.32	0.14	0.09	0.24	0.16	NC
Si	7.46	9.80	8.86	6.53	10.7	9.33	7.98	10.3	9.57	6.11	9.85	11.5	NC
NO_3^-	0.04	0.65	0.17	<0.01	1.20	0.33	0.08	2.00	0.26	0.07	0.89	0.23	1.0
SO_4^{2-}	49.7	163	72.3	53.3	246	72.0	43.5	123	72.5	38.6	516	93.4	110
PO_4^{3-}	<0.01	0.30	<0.01	<0.01	0.53	<0.01	<0.01	0.43	<0.01	<0.01	0.73	<0.01	NC
Cl^-	17.0	44.3	38.3	46.0	339	57.7	31.4	283	112	8.80	44.2	29.2	45
Fe	<0.01	0.16	<0.01	<0.01	0.30	0.05	<0.01	0.24	<0.01	<0.01	0.12	<0.01	NC
Mn	<0.01	0.20	0.02	<0.01	0.70	0.02	<0.01	0.33	0.03	<0.01	0.11	0.04	NC
TDS	497	840	620	456	1297	715	640	1400	817	498	1143	625	1000

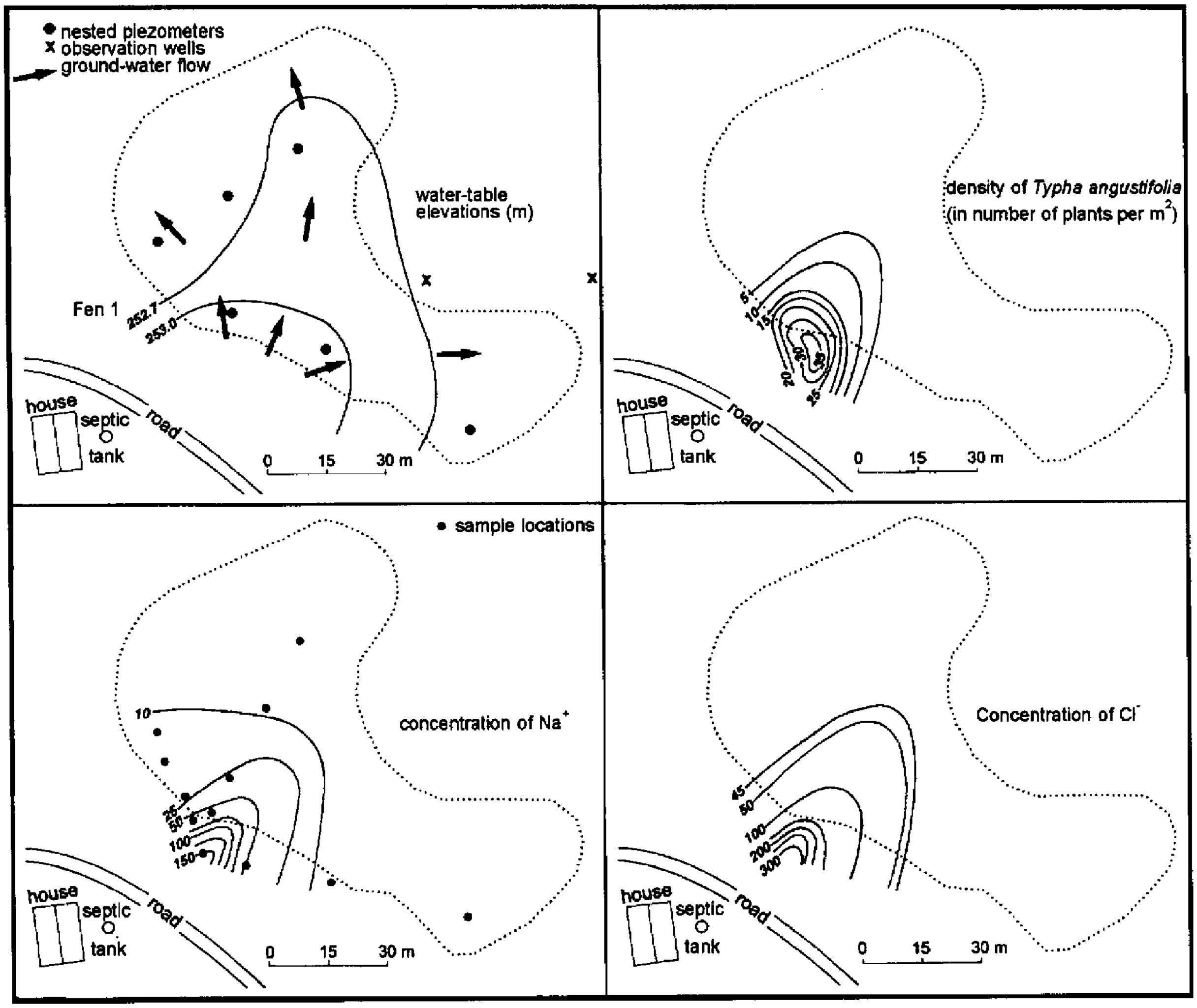

Figure 2. Water-table elevation, *Typha* density (V.A. Nuzzo, unpublished data), and areal distribution of Na^+ and Cl^- in Fen 1 (spring 1992). The dotted line marks the edge of fen vegetation.

geographic extent of their movement in the study area and were calculated for selected ions from water quality data (Table 1). Threshold concentrations for ions indicate values that separate background concentrations from anomalous concentrations (or separate, statistically-distinct populations) derived by graphical techniques (Sinclair, 1974). For example, those ground-water samples with concentrations of Cl^- that exceed the calculated threshold value are part of a population with anomalously high Cl^- concentrations that probably resulted from ground-water contamination.

Sodium and Chloride Contamination

The discrete plumes of Na^+ and Cl^- and ground-water-flow directions in Fens 1 and 2 indicate the presence and likely sources of anthropogenic contamination (Figures 2 and 3). Fen 1 is located just east of a house and a leach-field type septic system that were constructed in 1947 (K. Reimer, personal communication, 1992) (Figure 2). Leach fields consist of perforated pipes that extend away from a settling tank; they allow overflow to seep into the soil (Patterson et al. 1971). A sample of the effluent, collected as it overflowed from the settling tank, revealed a Na^+-HCO_3^--type water with relatively high concentrations of Na^+ (393 mg/L), HCO_3^- (575 mg/L), NO_3^--N (130 mg/L), Cl^- (324 mg/L), PO_4^{3-} (34.5 mg/L), and TDS (1243 mg/L). These values are consistent (although somewhat higher for Na^+ and Cl^-) with those reported by previous studies of private septic systems (e.g., Harman et al. 1996). These constituents are consistent with domestic sewage and the ingredients of laundry detergents, chlorine bleach, dishwashing compounds, and water-softener salts.

Ground-water flow within the fen was predominantly toward the north and northeast, away from the area occupied by the house and septic system. The

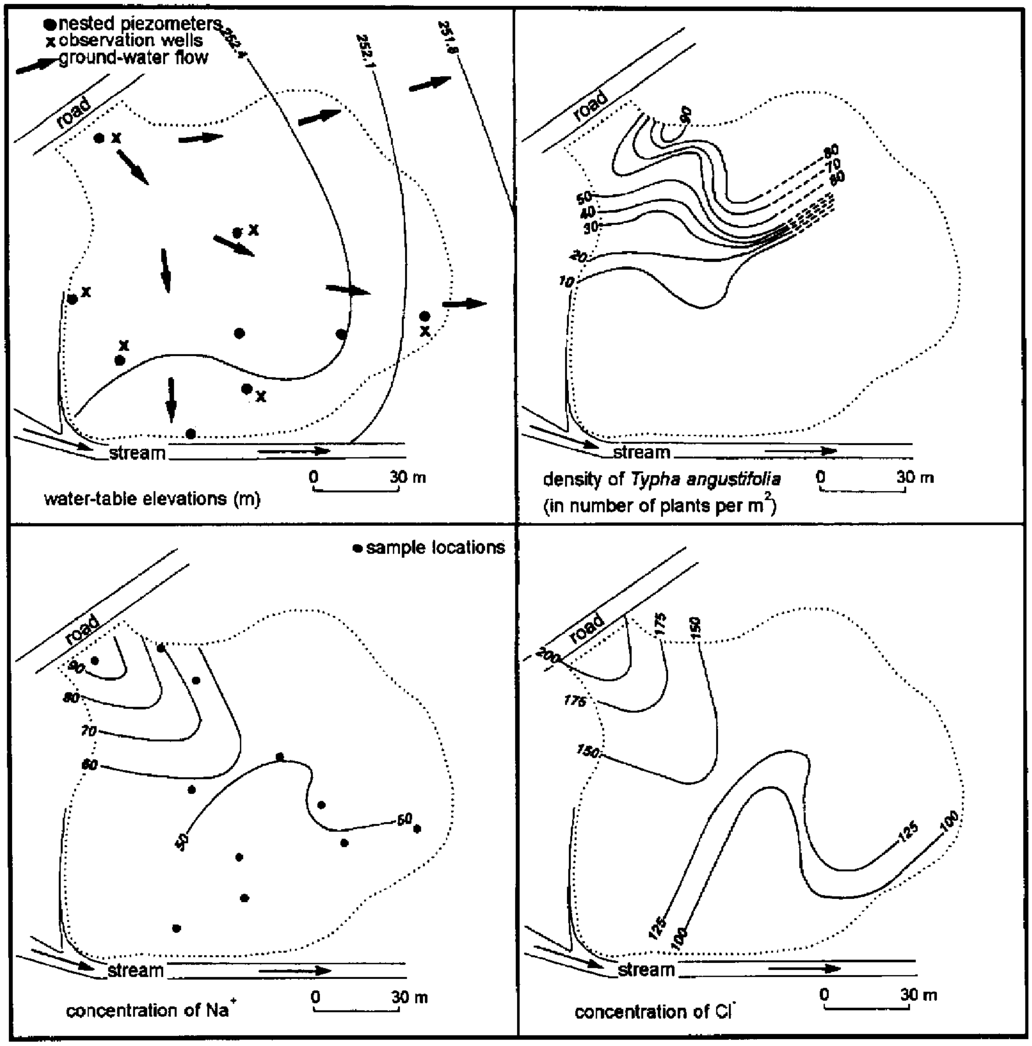

Figure 3. Water-table elevation, *Typha* density (V.A. Nuzzo, unpublished data), and areal distribution of Na^+ and Cl^- in Fen 2 (spring 1992). The dotted line marks the edge of fen vegetation.

chemical composition of fen ground water near the house was distinctly different from that of the Ca^{2+}-HCO_3^--type ground water in the rest of the fen (Table 1). Specifically, concentrations of Na^+ and Cl^- within the plume were as much as 15 and 7.5 times greater, respectively, than threshold concentrations. Nitrate was enriched in fen ground water near the septic system by 2 to 4 times its threshold concentration. However, even though concentrations of NO_3^- and PO_4^{3-} in the effluent sample were 130 mg/L and 34.5 mg/L, respectively, their concentrations in fen ground water did not exceed 2.0 mg/L and 0.73 mg/L, respectively. The fen vegetation near the septic system leachfield was dominated by a dense, fan-shaped stand of narrow-leaf cattail, coincident with the plume of mixed-cation-HCO_3^--type shallow ground water enriched in Na^+ and Cl^- (Figures 2 and 4).

Fen 2 is located northeast of Fen 1 (Figure 3) and is bounded on the north by a paved road built prior to 1900. Ground-water flow extends from the road toward a seep at the approximate geographic center of the fen and then southeast toward a stream south and east of the fen (Figure 3). Ground water in this fen is a mixed-cation-HCO_3^--type water that contained anomalously high concentrations of Na^+ and Cl^- and high TDS and alkalinity (Table 1). Both lateral and vertical differences in concentrations of selected constituents were observed in the fen (Figures 3 and 4). Specifically, the greatest concentrations of Na^+ and Cl^- were found near the road, although most of the fen contained Na^+ and Cl^- concentrations that were well above threshold concentrations (Table 1). The distribution of these ions, as represented by Cl^- (Figure 4), was consistent with lateral ground-water flow originating from the direction of the road and is most probably attributable to road salt. Narrow-leaf cattail dominated the area immediately adjacent to the road (Figure 4).

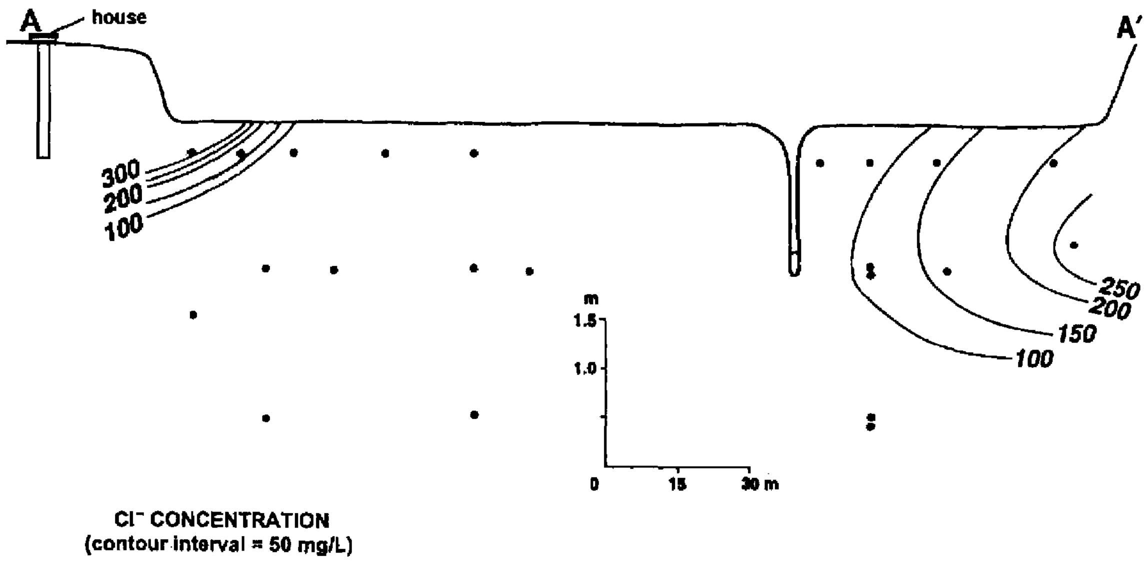

Figure 4. Cross section (A–A') across Fens 1 and 2 showing vertical distribution of Cl^- (spring 1992). Points indicate locations of ground-water samples, and the buried feature near the house represents the depth of the septic system. The fens are separated by a man-made drainage channel.

Fen 3, located near the northeastern boundary of the complex, contains both Ca^{2+}-HCO_3^- and Ca^{2+}-SO_4^{2-}-type ground water (Figure 5). Unlike Fens 1 and 2, ground water in Fen 3 did not have Na^+ and Cl^- concentrations that exceeded threshold values (Table 1) nor were there areas of the fen dominated by cattails.

Effects of Ground-Water Contamination on Fen Vegetation

Contaminant plumes are coincident with the occurrence and proliferation of *Typha angustifolia* (Figures 2 and 3), and the absence of *Scirpus acutus* within Fens 1 and 2 (Nuzzo et al. 1993). That is, portions of both Fens 1 and 2 contained dense growths of *Typha angustifolia* coincident with no *Scirpus acutus* whereas Fen 3 did not. Both species are emergent aquatics, but *Typha angustifolia* is a salt-tolerant herb (McMillan 1959) known to invade following salt contamination (Wilcox 1986a) and physical disturbance of a wetland (Grace and Harrison 1986). It is common in marshes and along expressways and only occurs in fens that have been disturbed (Swink and Wilhelm 1994).

Because NO_3^- and PO_4^{3-} were found to provide nutrients responsible for rapid growth of cattails in wetlands at the expense of more diverse vegetation (Scheidt 1988, Izuno et al. 1991), we initially thought that these nutrients might be responsible for the apparent changes in vegetation within the fens. However, the very low concentrations of NO_3^- and PO_4^{3-} found in fen ground water (Table 1) during all seasons, strongly suggested that Na^+ and Cl^- were responsible for the dense growth of *Typha angustifolia* observed in the study area (Nuzzo et al. 1993). Further, the occurrence of *Typha angustifolia* does not seem to be related to the elevation of the water table; seeps within Fen 1 and 2 have standing water at the surface throughout the year and are well away from their cattail-rich areas. The high density of narrow-leaf cattail in areas of high Na^+ and Cl^- concentrations in Fens 1 and 2 mirrored findings of Wilcox (1986 a,b), who documented cattail invasion of a road-salt-impacted bog in Indiana.

Sulfate Enrichment

The median concentration of SO_4^{2-} in ground-water samples from all fens was 75.4 mg/L. Sulfate concentrations in fens commonly increase with depth, probably due to microbial reduction in the peat (Mitsch and Gosselink 1986), and an upward hydraulic gradient. Ground water from parts of Fen 3, and its adjacent pond and marsh (Figure 1) contained concentrations of Ca^{2+} and SO_4^{2-} as great as 353 and 897 mg/L, respectively, in the fall of 1991. Continued work in the area suggests that the anomalously high concentrations of Ca^{2+} and SO_4^{2-} in water samples from Fen 3 were seasonal. For example, the largest SO_4^{2-} concentrations in a ground-water samples from northern part of Fen 3 was 516 mg/L in the spring of 1992, but only 103 mg/L in the summer of 1994. The configurations of the SO_4^{2-} plumes in Fen 3 indicated that they originated as seepage from the pond just east of the fen (Figure 5). In spite of its high concentrations in ground water in parts of Fen 3, SO_4^{2-} had no apparent effect on the fen vegetation (V.A. Nuzzo, unpublished data).

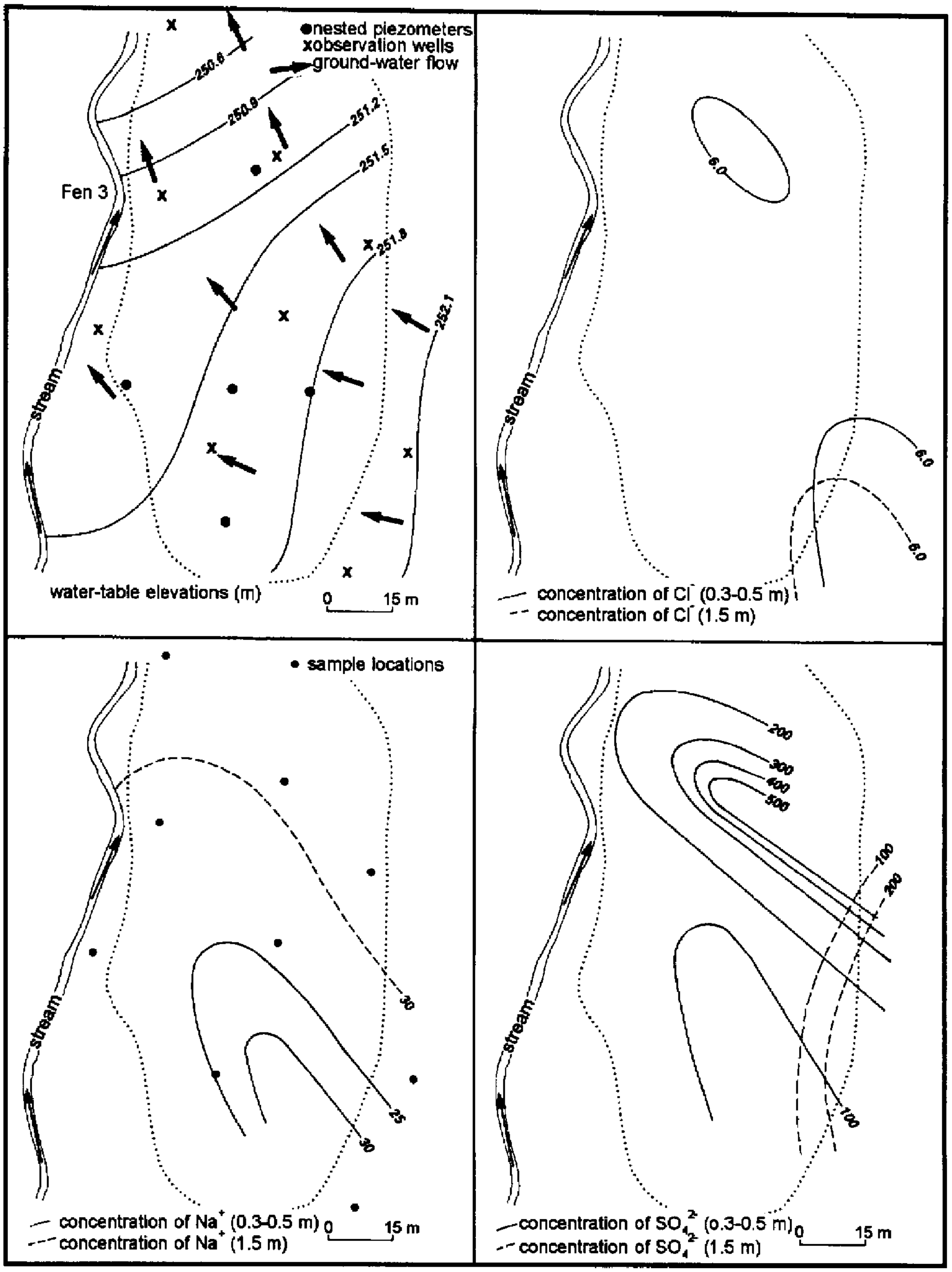

Figure 5. Water-table elevation and areal distribution of Na^-, Cl^-, and SO_4^{2-} in Fen 3 (spring 1992). The dotted line marks the edge of fen vegetation.

Analysis of Ca^{2+}-SO_4^{2-}-type water from the pond and marsh yielded isotopically light $\delta^{34}S$ values of -6 parts per thousand (ppt) for the SO_4^{-2}. Because the $\delta^{34}S$ values were isotopically light (at or below -1 ppt), it is likely that the SO_4^{2-} originated from the oxidation of a reduced sulfur source such as pyrite. Evaporite SO_4^{2-} is not a reasonable alternative source because its lower limit for $\delta^{34}S$ is $+10$ ppt (Dowuona et al. 1993). Isotopically light values also preclude the possibility of atmospheric sources; Jackson and Gough (1989) report on studies showing $\delta^{34}S$ values for rainfall in the Chicago area that range seasonally from $+2$ to $+10$ ppt.

Pyritic dolomite is a component of outwash deposits of the study area (Masters and Evans, 1987), and oxidation of that pyrite could serve as a source of SO_4^{2-}. Seasonally low water in the pond and complete drying of the marsh just southeast of Fen 3, both of which contain a meter or so of peat, could have resulted in exposure of the base of the peat and the top of the underlying gravel to oxygenated water resulting in the oxidation of any pyrite present. We suggest that the oxidation of pyrite associated with sand and gravel and/or peat in the marsh and pond (i.e., due to wet-dry cycling) and concomitant dissolution of carbonate minerals resulted in the transient formation of Ca^{2+}- and SO_4^{2-}-enriched ground and surface waters. The presence of such natural plumes, although not detrimental to fen vegetation, could lead to confusion by yielding high electrical conductance values that often are used as an indication of water quality.

CONCLUSIONS

The chemical composition of most of the ground-water samples from the Sterne's Woods Park fen-wetland complex was typical of that in glacial deposits in North America. That is, most ground water was classified as Ca^{2+}- to mixed cation-HCO_3^- type waters. However, ground-water samples collected from fens and aquifers that were adjacent to a county road and a domestic septic system showed the presence of contaminant plumes. Ground-water compositions within these plumes approach those of Na^+-Cl^--type ground water. Within the fens, these Na^+-Cl^- plumes were coincident with dense stands of *Typha angustifolia*. Such relationships had been previously observed in bogs (Wilcox 1986 a,b) and in wetlands where nutrients such as NO_3^- and PO_4^{3-} were available from agricultural activities (Scheidt 1988, Izuno et al. 1991).

Areas underlain by peat that contained standing water (a marsh and ponds) generated transient and/or seasonal plumes of Ca^{2+}-SO_4^{2-}-type ground water that seeped into one of the fens. Sulfur isotopes and the seasonal nature of Ca^{2+}-SO_4^{2-} plumes suggest that oxidation of pyrite in peat and/or underlying sand and gravel was responsible. In spite of SO_4^{2-} concentrations in the fen as high as 516 mg/L, no effect on fen vegetation was observed.

The results of this investigation demonstrate the ease by which ground-water quality within the drainage basin of a wetland may be degraded by development within a watershed and how sensitive the native vegetation is to such changes. It is likely that further urbanization of watersheds in this and other wetland areas of Illinois and states of the midwestern United States will result in degradation of water quality and wetland vegetation. Possible methods for mitigating the effects of urbanization within the watershed of a fen or other ecologically-sensitive areas include restricted land use, reduced use of road salt as a deicing agent, the use of septic systems that do not discharge effluent, and replacement of septic systems with a regional sewer system.

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