

Evidence for sewage contamination of the Sherwood Sandstone aquifer beneath Liverpool, UK

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Abstract Urbanization of the Liverpool area in northwest England began in 1207 and the area was prosperous by the 1700s. As an area with a long history of urbanization, the objective of this study was to map the water quality of the underlying major Sherwood Sandstone aquifer with special attention to whether leaking sewers are contaminating the groundwater. The sewerage system in Liverpool has been extensive since the late nineteenth century, expanding along with the city. Twelve samples were collected from sites in Liverpool and analysed for several markers of sewage contamination, including the nitrogen isotope composition of dissolved nitrate, microbiological indicators, boron and major ions such as nitrate and potassium. The results showed saline intrusion and widespread contamination of the aquifer. The sewage “fingerprint” was positively identified and provides the first conclusive evidence for sewer-derived contamination of Liverpool’s groundwater.

INTRODUCTION

Urban areas are served by a dense network of underground pipelines including water mains and sewers from which leakage can occur (Lerner & Barrett, 1996; Hoffman & Lerner, 1993; Rauch & Stegner, 1994). Exfiltration from sewers is of particular interest as it adversely affects groundwater quality (e.g. Hoffman & Lerner, 1993). Sewage contains a wide range of substances, both human and industrial wastes. Constituents of human waste include organic matter and pathogenic micro-organisms, while industrial discharges may comprise diverse organic and inorganic contaminants (Misstear & Bishop, 1997). Nitrate, potassium and boron are amongst the substances indicative of contamination by sewage (e.g. Hoffman & Lerner, 1993). Elevated concentrations of nitrate and potassium have been found in the groundwater of Liverpool compared with surrounding rural areas (Tellam, 1996; Brennan, 1997) and have been attributed to leaking sewers (Ion, 1996; Brennan, 1997). However, there are various potential sources of nitrate and previous evidence for leakage of sewers beneath Liverpool is inconclusive. In this study, a multiple marker method (Barrett *et al.*, 1997) was adopted to determine whether leaking sewers are a cause of the poor quality of the groundwater beneath Liverpool. In particular, the nitrogen isotope composition of dissolved nitrate in conjunction with microbiological indicators were used to “fingerprint” sewage contamination.

THE LIVERPOOL STUDY AREA

Population and infrastructure

Liverpool, with a population of around 470 000, is located in northwest England, adjacent to the Mersey estuary (Fig. 1). The area is gently undulating rising from sea-level to about 60 m a.m.s.l. Urbanization began in 1207 and by the 1700s the town was prosperous due to thriving commerce and industry (Harley, 1970), becoming an important port and industrial centre from the time of the Industrial Revolution. In recent times, industry has declined and the city centre is now mostly occupied by business and commerce.

Local groundwater resources met Liverpoolian demands for water until the mid-nineteenth century after which surface reservoirs were constructed in neighbouring upland areas (Harvey, 1970). Industrial usage of the groundwater beneath Liverpool has continued, albeit at dwindling rates. The sewerage system in Liverpool has been extensive since the late nineteenth century (Marriner, 1953). The sewer network has expanded with the city such that, in general, the oldest sewers are found in the centre of Liverpool (Ion, 1996). The sewers are primarily egg-shaped brick sewers or smaller diameter clay pipes, mostly about 100 years old, although some have been replaced by modern concrete sewers (Misstear *et al.*, 1996).

Geology and hydrogeology

A geological map of Merseyside is shown in Fig. 2. The oldest rocks exposed in the district are the Upper Carboniferous Coal Measures which are unconformably overlain by Permo-Triassic sandstone and mudstone formations. Liverpool is located almost

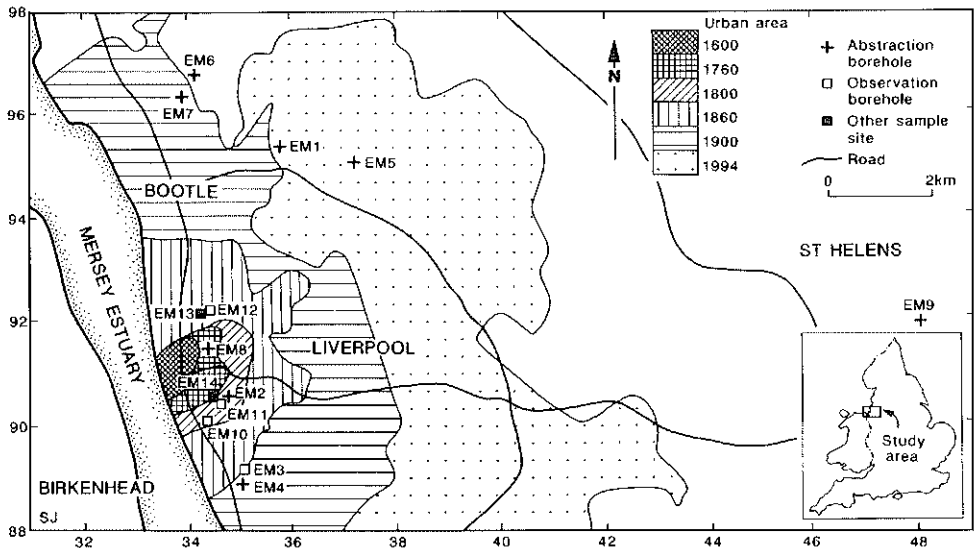


Fig. 1 Map of the study area showing the growth of the Liverpool conurbation since 1600 (after Ion, 1996) and the location of sample sites EM1–EM14.

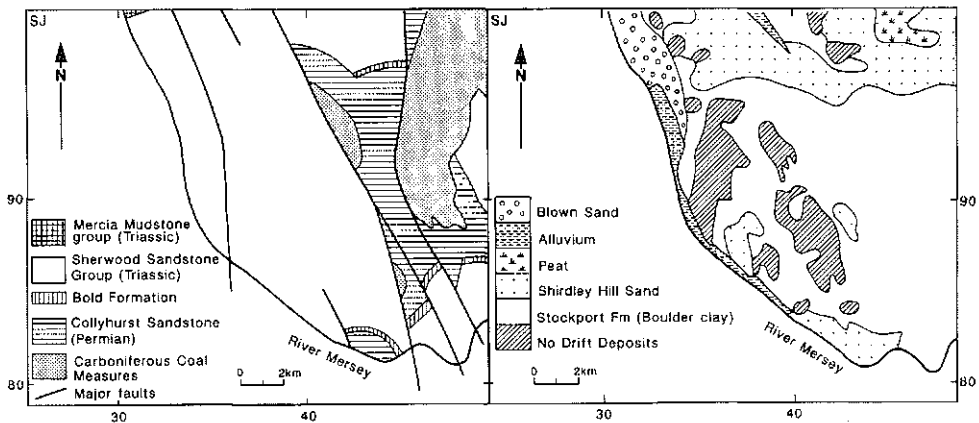


Fig. 2 Maps of the pre-Quaternary (solid) geology and Quaternary deposits of Merseyside (after Tellam, 1996).

entirely upon the Sherwood Sandstone Group, which comprises three distinct rock units with a dip to the south of about 5° . The older rocks are draped with Quaternary deposits, including glacial tills (boulder clay) and sands, which vary greatly in thickness and composition. Given the presence of an urban surface, the ground in Liverpool will have been disturbed, and “made ground” is likely to be commonplace. The geological structure of the area is dominated by several north-northwest trending normal faults, which commonly offset strata by over 100 m (Anon, 1984). The Sherwood Sandstone group is fractured, with the frequency of open fractures decreasing with depth due to the load of overlying rocks (Allen, 1969).

The Permo-Triassic sandstones form a regionally important aquifer. Typical values for transmissivity range from $140\text{--}780\text{ m}^2\text{ day}^{-1}$, for total porosity are 20–30% and specific yield is 0.14 (Allen, 1969; Anon, 1984). The large range of values for transmissivity reflects the heterogeneous and anisotropic nature of the aquifer, which results from the lithological diversity (Rushton *et al.*, 1988). Fissures greatly enhance overall porosity and permeability. To the north of the study area the aquifer is confined by the overlying Mercia Mudstone Group. The Quaternary deposits (glacial till) used to confine extensive areas of aquifer but past exploitation of groundwater has lowered groundwater levels such that unconfined conditions have become widespread (Tellam, 1994). However, groundwater levels are now rising at rates of up to 0.3 m year^{-1} ; this is mainly attributed to declining abstraction rates and, according to Ion (1996), leakage of water from mains and sewer pipelines.

Hydrochemistry

The chemistry of groundwater beneath Liverpool can be classified on the basis of their salinity with freshwaters having a chloride concentration below 300 mg l^{-1} (Tellam, 1996). It is widely reported that nitrate levels peak in the city centre, typically in excess of 30 mg l^{-1} (Tellam, 1996), and decrease towards less developed areas. An analysis of historic data by Ion (1996) showed that this spatial trend has persisted over time, while concentrations of nitrate have risen.

Saline water from the Mersey estuary has intruded the Permo-Triassic sandstone aquifer as a result of groundwater abstraction (Tellam, 1996), although the encroachment of saline water has been retarded by the existence of low-permeability faults and the generally high storage capacity and moderate transmissivity of the aquifer (Barker *et al.*, 1998; Howard, 1987). The aquifer also contains saline water at depth which is believed to have an origin in the dissolution of evaporite deposits contained within the Mercia Mudstone Group (Tellam, 1996).

METHODS AND RESULTS

Fieldwork was conducted in Liverpool during June 1998 and of the 14 samples collected, four were pumped from Environment Agency observation boreholes, eight from water supply boreholes, one from a tap in the city centre and one from a surface water canal. The observation boreholes were pumped for at least 15 min prior to sampling with a Grundfos MP1 pump positioned 5 m below the water level. Abstraction boreholes were either sampled from a tap on the rising main or from storage tanks. At the observation borehole sites, the well head parameters pH, redox potential (Eh), electrical conductivity (EC) and temperature were measured during pumping, either in a flow cell or in flowing water. Except for temperature, the evaluation of these parameters in the other samples was delayed until return to the laboratory, although the Eh readings are unlikely to be accurate. Alkalinity was determined in the laboratory on all samples by the standard titration procedure shortly after return from the field.

Microbiological analyses, including tests for total coliforms, *Escherichia coli* and faecal streptococci were performed by the North-West Water company. Biological samples were only taken from those sites where freshly abstracted groundwater could be obtained. Sample taps were sterilized by squirting household bleach inside and outside the tap, with the taps thoroughly rinsed prior to collecting the sample in 500 ml sterile bottles. The samples were returned to the laboratory on their day of collection and membrane filtration methods used to isolate the organisms of interest. The organisms form distinctively coloured colonies when incubated under controlled conditions and the analyses are routinely used as a sensitive means of identifying faecal contamination of water (D. Taylor, personal communication).

The concentrations of the major anions (nitrate, sulphate and chloride) were determined by ion chromatography and the cations calcium, sodium, magnesium and potassium, by flame atomic absorption spectrophotometry. The minor ions of ammonium and boron were determined, respectively, by colorimetry and ICP-OES. Samples containing sufficient nitrate were prepared for nitrogen isotope analysis using the distillation method described by Feast & Dennis (1996). Following distillation, the collected ammonium sulphate solution was evaporated and dried before the powder was combusted in an evacuated tube to convert the nitrogen present to nitrogen gas. The nitrogen gas was cryogenically purified to remove residual carbon dioxide and water, and analysed by isotope ratio mass spectrometry at the University of East Anglia. The nitrogen isotope ratios are reported relative to a nitrogen reference gas (purified air) standard and reported using the δ -notation to

Table 1 Results of sample analyses of selected major and minor ions, microbiological parameters and nitrogen isotope composition for Liverpool groundwaters and other environmental waters. Location of sample sites is shown in Fig. 1.

Sample	Type ^a	K (mg l ⁻¹)	NO ₃ (mg l ⁻¹)	NH ₄ (mg l ⁻¹)	Cl (mg l ⁻¹)	B (mg l ⁻¹)	Total coliforms ^b	<i>E. coli</i> ^b	F. strep. ^b	δ ¹⁵ N _{NO₃} (‰)
EM1	ABH	2	22	n.d.	41	0.18	0	0	0	+13.2
EM2	U	10	98	n.d.	99	0.18	0	0	1	+12.3
EM3	OBH	8	15	0.03	115	0.28	0	0	1	
EM4	ST	19	90	0.05	119	0.32				
EM5	ABH	4	9	n.d.	161	0.17	0	0	0	-11.8
EM6	ST	4	12	n.d.	76	0.16				+10.8
EM7	ABH	4	14	n.d.	54	0.20	0	0	0	+10.9
EM8	ABH	13	103	n.d.	397	0.20				+11.4
EM9	ABH	6	23	n.d.	44	8.16	3	0	1	+8.4
EM10	OBH	98	<0.3	n.d.	2264	1.58	0	0	1	
EM11	OBH	32	38	n.d.	72	0.55	0	0	0	+11.8
EM12	OBH	6	<0.3	n.d.	793	0.32	0	0	1	
EM13	LLC	5	<0.3	n.d.	58	0.29	74	31	116	
EM14	MW	2	7	n.d.	20	0.18				-6.9

^a Sample types: ST – storage tank; U – unknown; OBH – observation borehole; ABH – tap or flow from abstraction borehole main; LLC – Leeds & Liverpool Canal; MW – mains water from tap adjacent to site of EM11.

^b Results of microbiological analyses are given as number of organisms per 500 ml sample. n.d. Sample concentration below the detection limit of method used.

within $\pm 0.3\%$. No results are available for two samples (EM3 and EM4) due to the loss of sample gas at the measurement stage.

Table 1 presents selected analytical results for all samples collected in this study. The microbiological data show that the canal water (EM13) contains significantly higher numbers of the indicator micro-organisms than any of the groundwater samples. Only four groundwater samples contain indicator bacteria; EM3, EM10 and EM12 have 1 faecal streptococci and sample EM9, the most contaminated of the groundwaters, has 3 total coliforms and 1 faecal streptococci in the 500 ml sample. None of the groundwaters analysed contains *E. coli*.

The major ion analyses show that the groundwaters contain between 2–98 mg l⁻¹ potassium (median = 7 mg l⁻¹). Sample EM1 has the lowest concentration and EM10 the highest and these two same sites also contain the lowest and highest chloride concentrations of 41 and 2264 mg l⁻¹, respectively. Nitrate is undetected in two groundwater samples, while three sites (EM2, EM4 and EM8) have values in excess of 90 mg l⁻¹. The distribution of nitrate concentrations remains as described by Ion (1996) and Brennan (1997), with the highest concentrations in the city centre groundwaters. Ammonium was only detected in two boreholes at low concentrations of <0.05 mg l⁻¹. The boron concentration in the majority of samples (groundwater and non-groundwater) ranged between 0.16 and 0.55 mg l⁻¹ boron, with samples EM9 and EM10 containing significantly elevated concentrations of 8.16 and 1.58 mg l⁻¹, respectively.

Except for sample EM9, the nitrogen isotope composition of all the groundwater samples is in excess of +10‰ and is indicative of a source of nitrate that has originated from human or animal waste. However, high δ¹⁵N values may also result from

denitrification although the few available Eh data (typically greater than 120 mV) and the absence of the expected trend of increasing $\delta^{15}\text{N}$ values for decreasing nitrate concentration would suggest that denitrification is not a significant process in explaining the nitrogen isotope data. The mains water sample (EM14) has a significantly different $\delta^{15}\text{N}$ value of -6.9% .

EVIDENCE FOR SEWAGE CONTAMINATION

The presence of indicator micro-organisms in four of the nine Liverpool groundwater samples demonstrates the presence of sewage contamination, as the only other possible source of faecal contamination in this urban area is manure spreading in parks and gardens. Importantly, the microbiological data prove that sewer leakage is occurring at present, and is not purely an historic problem as suggested elsewhere (e.g. Misstear *et al.*, 1996).

The Liverpool groundwater samples show elevated concentrations of major ions, and are probably derived from a combination of saline intrusion, industrial contamination and sewer leakage. The nature of this multiple source input is such that there is no obvious correlation between those major ions associated with sewage, such as nitrate and potassium. The boron concentration of all the groundwater samples exceeded 0.16 mg l^{-1} which is greater than the concentrations reported for rural groundwaters in the Permo-Triassic sandstone aquifer (Tellam, 1994). It is possible that these high boron concentrations have resulted from industrial contamination, although since industrial activity in Liverpool has been focussed around the docks and in the northern suburbs, such pervasive contamination is more likely to have originated from leaking sewers.

The nitrogen isotope composition of water leaking from sewers would be expected to have a similar value to that of tap water since sewers carry a mixture of mains and other waters (e.g. precipitation). The mains water sample (EM14) gave a distinctive $\delta^{15}\text{N}$ value of -6.9% in accord with its rural surface water origin. It might therefore be expected that sewer exfiltration would cause a decrease in the $\delta^{15}\text{N}$ composition of the groundwater. However, the relatively low nitrate concentration of the mains water probably means that this effect is not significant.

The degree of corroboration of sewage marker species will be affected by the many factors controlling the chemical and biological composition of the groundwater at an individual location. Although the groundwaters analysed in this study show no correlation between nitrate and boron concentrations, or between microbiological contamination and major ions, the microbiological data give high confidence that sewers are indeed leaking into the groundwater beneath Liverpool. In the absence of evidence for significant denitrification, such leaks are the most probable cause of the enriched nitrogen isotope compositions of the dissolved nitrate. Overall, the chemical and biological data demonstrate that sewer leakage is occurring at present and is having a detrimental impact on the groundwater quality in the sandstone aquifer.

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