Impacts of Urban Growth on Surface Water and Groundwater Quality (Proceedings of IUGG 99 Symposium HS5, Birmingham, July 1999). IAHS Publ. no. 259, 1999.

Loadings of non-agricultural nitrogen in urban groundwater

DAVID N. LERNER
Groundwater Protection and Restoration Group, Civil and Structural Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK
e-mail: d.n.lerner@shef.ac.uk

YUESUO YANG
Environmental Engineering Centre, Queens University, Belfast BT7 1NN, UK

MIKE H. BARRETT
Robens Centre for Public and Environmental Health, University of Surrey, Guildford, Surrey GU2 5XH, UK

JOHN H. TELLAM
School of Earth Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

Abstract In the groundwater under Nottingham, nitrate concentrations are as high as they are in the surrounding rural groundwater. Fertilizer and agricultural practices are the main sources of rural nitrates, but are insignificant in the city environment. Urban sources of nitrogen in groundwater include leaking sewers, leaking water mains, landfills and industrial chemical spillages. We have recently completed a major field and modelling study of Nottingham to identify and quantify recharge sources and amounts, and loadings of solutes. A novel approach of combining a water balance with multiple solute balances provided the first estimates for a UK city. Sewers contribute about 13% of the nitrogen loading. The size of the nitrogen loading from leaking water mains is more important at about 36% of the total, because they provide over half the recharge in the urban area. The remaining 50% of the N loading includes parks, gardens, landfills and industrial spillages.

INTRODUCTION

Nitrate is often seen as an agricultural pollutant of groundwater, and might be expected to occur at higher concentrations in the groundwaters surrounding a city than in those beneath it. However several studies have shown small differences between rural and urban nitrate concentrations, due to the non-agricultural sources of nitrogen that are concentrated in cities. For example, in Coventry (UK) the ratio of urban to rural concentrations was 1.4 (Nazari *et al.*, 1993), and similar results have been noted elsewhere in the UK (Lerner *et al.*, 1994), North America (Flipse *et al.*, 1984) and Europe (Razack *et al.*, 1988). Urban groundwater is valuable but underused (Lerner, 1996), and a better understanding of the sources and loadings of urban nitrogen will help to make most effective use of this resource. This paper aims to give some estimates and illustrate the significance of non-agricultural sources of nitrogen for groundwater from a case study of Nottingham (UK) (Barrett *et al.*, 1997; Yang *et al.*, in press).

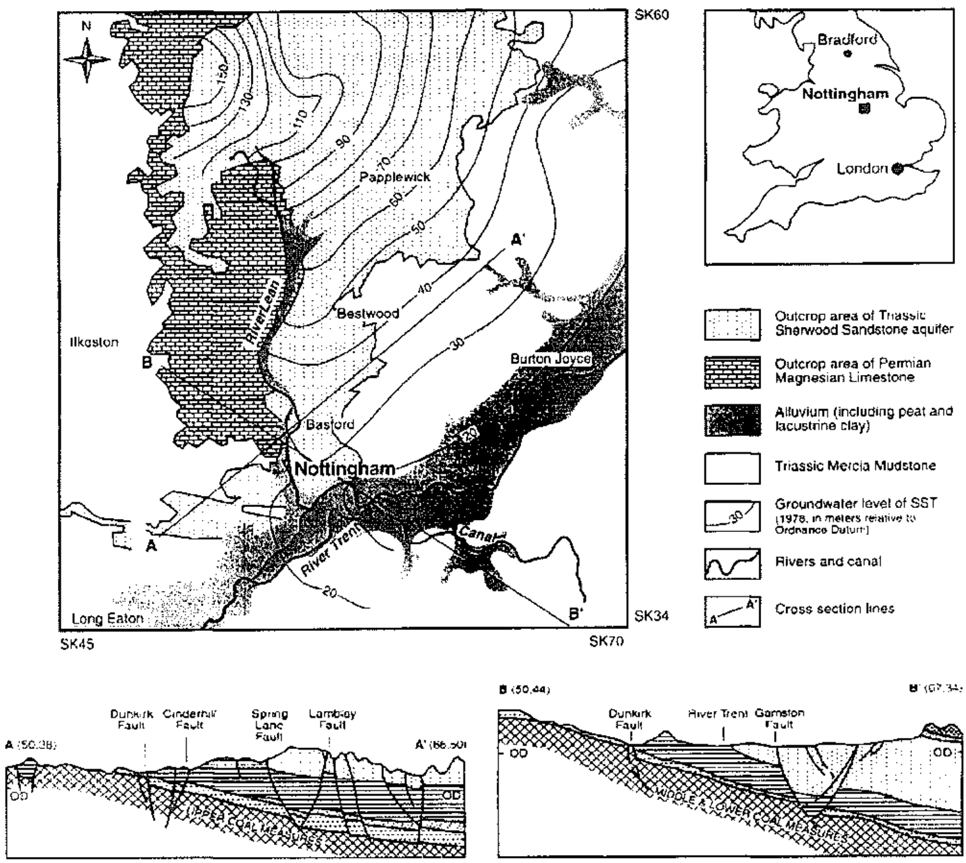

Fig. 1 Geology and groundwater of the Nottingham area (after BGS, 1981; Charlsey *et al.*, 1990).

GEOLOGY AND HYDROGEOLOGY

Nottingham was chosen for the study, offering contrasts and similarities with previous work in Birmingham and Coventry (Rivett *et al.*, 1990; Burston *et al.*, 1993; Ford & Tellam, 1994). It has no significant superficial cover to complicate interpretation, and has rural areas nearby for comparison.

Groundwater is principally found in the Triassic Sherwood Sandstone Group (Fig. 1). This is a fluviatile red-bed sequence which varies in thickness from zero in the west to over 150 m in the north. A typical regional hydraulic conductivity is a few metres per day. Matrix porosity is about 25–35%, specific yield about 10–15%, and there is some fracturing. It is confined to the east and south by the Mercia Mudstone Group, and overlain in the valleys of the rivers Leen and Trent by alluvium.

Regional groundwater flow is to the south and east, discharging into boreholes with high pumping rates and the two rivers (Fig. 1). Pumping for public supply started in the late 19th century, and is continued by a network of one urban and six rural pumping stations, supplemented by surface water from the River Derwent (Edwards, 1966; Severn Trent Water information).

METHODS

The overall approach to the study had three components:

- regular sampling of expected recharge sources (precipitation, rivers, water mains, sewers) and groundwaters (rural and urban, deep and shallow boreholes);
- use of groundwater flow and solute transport models for Cl, SO_4 and total-N to quantify recharges from sewers, mains and precipitation;
- interpretation of the chemistry and quantities of recharge to estimate solute loads from the various sources.

NITROGEN CONTENT OF RECHARGE AND GROUNDWATER

The inorganic quality, as expressed by concentrations of major ions, is poorer in the urban than rural area. None of the concentrations are high enough to be of concern, except for nitrate (Table 1). This is the only major ion to have similar concentrations in urban and rural areas and exceeds the drinking water limit of 50 mg l^{-1} in many locations. Ammonium was observed sporadically, most often in shallow, urban samples.

The results of analyses for nitrate, ammonium and total-N in Nottingham's precipitation, river water, mains water and sewage are summarized in Table 1. In the river and mains water samples, nitrate is the dominant species (as would be expected given the oxic conditions). The precipitation samples contained a greater content of ammonium (generally of the range 2–10 mg l^{-1}) and lesser content of nitrate (7–10 mg l^{-1}). It should be noted that the total nitrogen concentration of the precipitation samples is not so different to the mains water due to the high proportion of nitrogen contained in ammonium. Not surprisingly, the raw sewage samples analysed contained negligible nitrate concentrations, but high ammonium (28–52 mg l^{-1}). On two occasions, total nitrogen was measured in the sewage samples. Comparing ammonium and the higher total nitrogen concentrations suggests that 32–38% of the nitrogen was as organic nitrogen. Thus sewage provides a large potential source of nitrogen.

The range of concentrations seen in the shallow urban groundwaters is not significantly different from that of the deep groundwaters. The rural shallow boreholes

Table 1 Summary of average nitrogen concentrations in Nottingham waters during 1995–1996 (mg l^{-1}).

Possible recharge waters	Mains	Sewage	Rainfall	River Lean	River Trent
No. sites sampled	21	1	9	5	6
NO_3	17.3	<1.3	8.7	16.8	18.2
NH_4	bd (<0.05)	38.1	5.5	0.49	0.88
Organic N	nm	19.1	nm	nm	nm
Groundwaters	**Caves**	**Shallow urban**	**Shallow rural**	**Deep urban**	**Deep rural***
No. sites sampled	6	11	4	20	5
NO_3	43	44	73	51	54
NH_4	0.67	0.11	0.1	0.07	0.35
Organic N	nm	nm	nm	nm	nm

bd = below detection nm = not measured

*Unconfined only.

have consistently higher concentrations than the rural deep boreholes, which suggests there may be a future upward trend in rural nitrates.

Conditions in the aquifer are generally oxic, so nitrogen is generally as nitrate, but it can be organic or ammonium in the recharges, before oxidation in the aquifer. Similarly sulphur is normally as sulphate.

QUANTIFYING RECHARGES

The hydrology of a city is too complex to be able to quantify recharges directly. There are three recharges to estimate for Nottingham (precipitation, mains and sewers) and each is expected to vary in space and time. Our approach has been to simultaneously calibrate four flux balance models, thereby maximizing the information used and minimizing uncertainty in the outcome. The fluxes were groundwater and the three conservative chemical species, chloride, sulphate and total nitrogen. A groundwater flow model and three solute transport models were constructed and calibrated against groundwater level hydrographs and all available measurements of solute concentrations, including a few measurements from the nineteenth century. The area was divided into six zones, and the study period of 1850–1995 was divided into six different recharge and solute periods, based on analysis of the growth of the urban area. Time was further subdivided into 13 periods to include variations in pumping. The models used much smaller discretizations to solve the governing equations, with grid sizes down to 250 m and time steps of one year.

Full details of the methods and results are given by Yang *et al.* (in press). Averaging their estimates over the urban area for the most recent period gives the following estimated recharge rates:

Total recharge	211 mm $year^{-1}$
Recharge from mains leakage	138 mm $year^{-1}$
Recharge from sewer leakage	9 mm $year^{-1}$

SOURCES OF NON-AGRICULTURAL NITROGEN

Table 2 summarizes the sources of nitrogen for urban groundwater. Some root zone leaching will occur, as in agricultural areas. An urban feature of soil processes will be the disturbance due to housing developments. This will be equivalent to ploughing up permanent pasture which is known to be a major input of nitrogen in agricultural areas. Leakage from sewers and water mains are mainly urban sources, as are the various forms of contaminated land.

The modelling exercize has enabled us to quantify the average concentrations of total-N in urban and rural recharges for Nottingham, as shown in Fig. 2. This shows that urban and rural loadings have approximately kept in step with each other. The last task is to quantify the contribution of each of the sources to these overall inputs. The modelling study estimated the inputs from sewers as equivalent to a recharge of 10 mm $year^{-1}$ of sewage with an average concentration of 30 mg N l^{-1}. The modelling also quantified the contribution from leaking mains as 138 mm $year^{-1}$ at an average concentration of 5.6 mg N l^{-1}.

Table 2 Sources of nitrogen in urban groundwater.

Category	Origin of nitrogen	Form reaching groundwater
Root zone leaching	Atmospheric inputs	NO_3
	Urban fertilizer use	NO_3
	House-building	NO_3
Sewage infiltration	Leaking sewers	NH_4 and
	Septic tanks	organic-N
Water supply leakage	Drinking water	NO_3
Contaminated land	Leaking landfills	NH_4
	Gas works	NH_4
	Industrial spillages	Various chemicals
Miscellaneous	Urea de-icing of airports and bridges	Urea

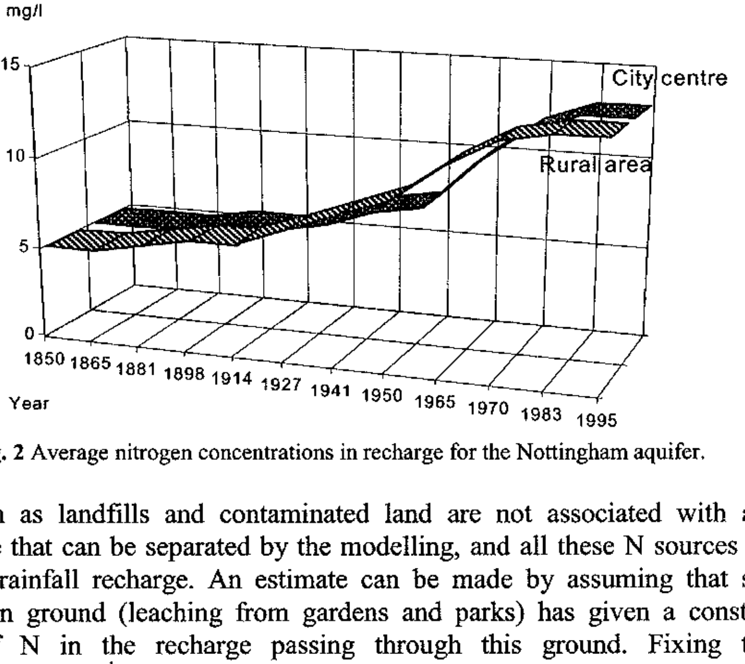

Fig. 2 Average nitrogen concentrations in recharge for the Nottingham aquifer.

Sources such as landfills and contaminated land are not associated with any regional recharge that can be separated by the modelling, and all these N sources are lumped in with rainfall recharge. An estimate can be made by assuming that soil processes in open ground (leaching from gardens and parks) has given a constant concentration of N in the recharge passing through this ground. Fixing this concentration at 3 mg N l^{-1}, which is the value from the earliest period of the model, gives a soil-N loading equivalent to 6.6 kg ha^{-1} $year^{-1}$ over the limited open area. The loads from contaminated land and house-building have been estimated by difference, and all the estimates are shown in Fig. 3. These are average loads for the unconfined aquifer in the current urban area. They are averages over the three zones which are now urban, and so include their temporal transition from rural to urban status.

The estimates in Fig. 3 give a total-N loading in the urban area of 21 kg ha^{-1} $year^{-1}$ in the recent period. This is divided between the various sources in the ratios:

Leaking mains	37%
Leaking sewers	13%
Soil leaching	9%
Others (contaminated land, industry, etc.)	41%

Sewage is likely to make its greatest impact on groundwater in a city such as Nottingham due to permeable soils and a deep water table. At less than 15% of the

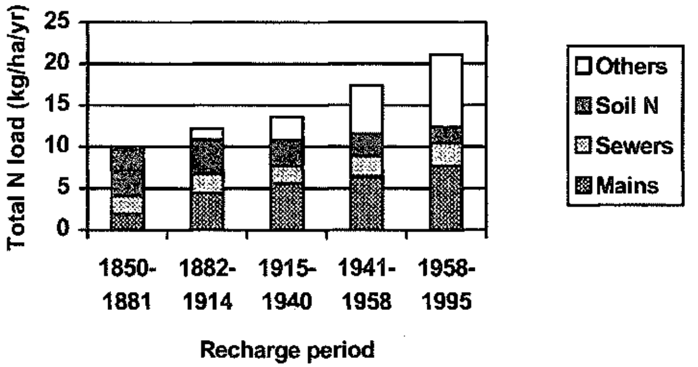

Fig. 3 Average nitrogen loadings for the urban area of Nottingham. "Others" includes contaminated land, industrial spills, house-building.

total nitrogen loading, this impact is not severe. Leaking water mains make a major contribution to N loads in Nottingham. They may be the easiest of the various sources to control by changing the quality of drinking water; reducing leakage may have the counter effect of increasing N concentrations in groundwater by reducing dilution of the stronger recharges. Our experience of urban pollution studies suggests that it is probable that the contributions from industrial spillages and contaminated land will reduce rather than grow in the future. House-building will continue to disturb soils and release N in urban and suburban areas in the UK.

CONCLUSIONS

The groundwater under Nottingham is of poorer quality than in nearby rural areas. Nitrate concentrations are similar in urban and rural areas, and frequently exceed the drinking water limits. There is evidence of pollution by leaking sewers. Although total recharge in the city is similar to that in the urban area, the components are very different. Mains leakage is the major recharge source in the city, and leaking sewers contribute about 10 mm $year^{-1}$.

Nitrogen loads are similar for the rural and urban aquifers, but from very different sources. Sewers contribute <15% of the nitrogen load to the urban aquifer, and the major contributors are leaking water mains and general urban pollution from contaminated land and industry; house-building may also be significant.

Acknowledgements The research was supported by the Engineering and Physical Sciences Research Council (EPSRC), Seven Trent Water plc, the Environment Agency, Stanton plc and the Ministry of Agriculture Fisheries and Food. The results do not necessarily reflect the funders' views.

REFERENCES

Barrett, M. H., Hiscock, K. M., Pedley, S., Lerner, D. N. & Tellam, J. H. (1997) The use of marker species to establish the impact of the city of Nottingham (UK) on the quantity and quality of its underlying groundwater. In: *Groundwater in* *the Urban Environment*, vol. 1: *Problems, Processes and Management* (ed. by J. Chilton *et al.*), 85–90. Balkema, Rotterdam, The Netherlands.

BGS (British Geological Survey) (1981) *Hydrogeological Map of the Northern East Midlands, Scale 1:100 000.* Institute of Geological Sciences, Natural Environment Research Council, London, UK.

Burston, M. W., Nazari, M. M., Bishop, P. K. & Lerner, D. N. (1993) Pollution of groundwater in the Coventry region (UK) by chlorinated hydrocarbon solvents. *J. Hydrol.* **149**, 137–161.

Charlsey, T. J., Rathbone, P. A. & Lowe, D. J. (1990) Nottingham: A geological background for planning and development. *BGS Technical Report WA/90/1, British Geological Survey, UK.*

Edwards, K. C. (1966) Water supply. In: *Nottingham and Its Region*, 165–174. Prepared for the meeting of the British Association for the Advancement of Science, Nottingham, 1966.

Flipse, W. I., Katz, B. G., Lindner, J. B. & Markel, R. (1984) Sources of nitrate in ground water in a sewered housing development, Central Long Island, New York. *Ground Wat.* **22**, 418–426.

Ford, M. & Tellam, J. H. (1994) Source, type and extent of inorganic contamination within the Birmingham urban aquifer system, UK. *J. Hydrol.* **156**, 101–135.

Lerner, D. N. (1996) Urban groundwater – an asset for the sustainable city? *Europ. Wat. Pollut. Control* **6**(5), 43–51.

Lerner, D. N., Halliday, D. & Hoffman, J. M. (1994) The impact of sewers on groundwater quality. In: *Groundwater Problems in Urban Areas* (ed. by W. B. Wilkinson) (Proc. Conf. Inst. of Civil Engineers, June 1993), 64–75, discussion 197–211.

Nazari, M. M., Burston, M. W., Bishop. P. K. & Lerner, D. N. (1993) Urban groundwater pollution: a case study from Coventry, United Kingdom. *Ground Wat.* **31**(3), 417–424.

Razack, M., Drogue, C. & Baitelem, M. (1988) Impact of the urban area on the hydrochemistry of a shallow groundwater, town of Narbonne, France. In: *Hydrological Processes and Water Management in Urban Areas* (Proc. Symp. at Duisburg, 24–28 April 1988), 487–494.

Rivett, M. O., Lerner, D. N., Lloyd, J. W. & Clark, L. (1990) Organic contamination of the Birmingham aquifer. *J. Hydrol.* **113**, 307–323.

Yang, Y., Lerner, D. N., Barrett, M. H. & Tellam, J. H. (in press) Quantification of groundwater recharge in the city of Nottingham, UK. *Environ. Geol.*