NITRATE POLLUTION OF CHALK GROUNDWATER IN EAST YORKSHIRE—A DECADE ON

By A. R. LAWRENCE, MSc, S. S. D. FOSTER, DSc, MICE, MIGeol, AIL *(Fellow)* and P. W. IZZARD, BSc *(Member)*

SYNOPSIS

AS a sequel to a previous paper, the evolution of the groundwater nitrate problem in the Chalk aquifer of East Yorkshire is described. With the aid of a programme of unsaturated zone research, the fluctuations in nitrate concentration at two major public water-supply sources are explained, and the future outlook for groundwater quality is discussed.

INTRODUCTION

One of the first papers to draw attention to rising nitrate concentrations in British groundwaters and to appraise the probable source and mechanisms of pollution, was published in this *Journal* in 1974[1]. It related to the East Yorkshire Chalk, especially a detailed research area (Fig. 1), north-west of Beverley, containing two public groundwater supply sources. That paper:

(1) suggested the likelihood of the problem resulting, either directly or indirectly, from post-war intensification of arable cropping sustained by increasing applications of inorganic fertilizer,

(2) speculated that much of the nitrate leached from arable soils would migrate only slowly downwards through the thick unsaturated zone and pose an insidious long-term and widespread threat to groundwater quality.

In this sequel, the records of nitrate concentration in the same groundwater sources during the 1970s are presented and interpreted with the aid of a programme of unsaturated zone investigation. This programme involved drilling 11 cored boreholes (in October 1978 and March 1979) to allow the determination of porewater profiles for nitrate, ammonium, sulphate, chloride, calcium, sodium, and tritium, together with the measurement of matrix porosity and hydraulic conductivity. The drilling sites chosen were mainly on long-standing arable land (typical of most of the area) with reliable long-term land use and soil management records. Some sites (Nos. 1 to 5 and 7, Fig. 1.), were underlain by high porosity (0.36-0.42) Chalk and others (Nos. 8-10) by low porosity (0.20-0.25) Chalk, but the detailed areal distribution of these different Chalks is not known. Reference should be made to the original paper[1] for an otherwise comprehensive description of the hydrogeological and agricultural setting of the area.

In East Yorkshire groundwater nitrate concentrations in public-supply sources have, in general, shown steady overall increases during the 1970s. The fortnightly concentration at the Market Weighton (Springwells) source (Fig. 1), and also at North Newbald and Swanland to the south-east exceeded 10 mg NO_3-N/l throughout 1980. The highest concentration for an individual borehole and for a groundwater source (normally comprising a

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Mr Lawrence and Dr Foster are with the Institute of Geological Sciences (Hydrogeology Unit), at Wallingford, Oxon, and Mr Izzard is with the Yorkshire Water Authority (Eastern Division), Kingston-upon-Hull, Yorkshire.

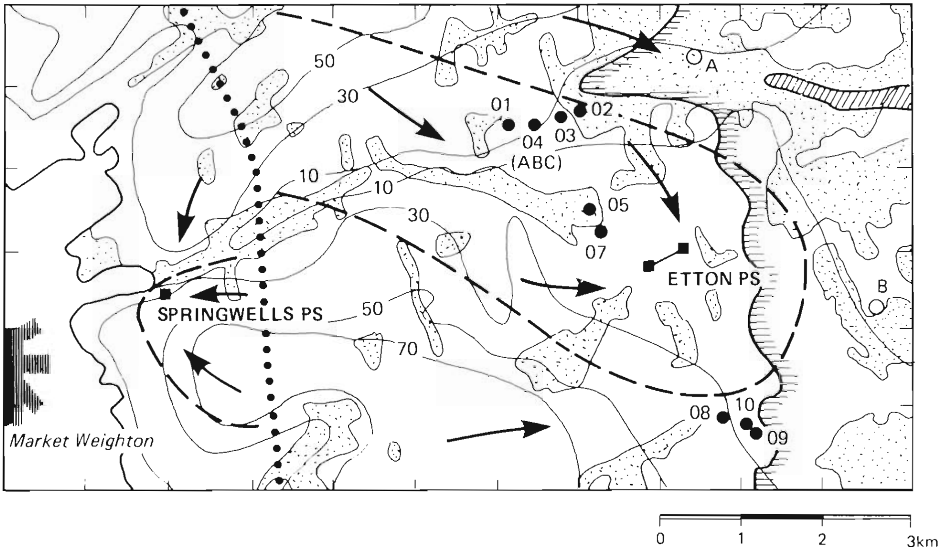

Fig. 1. Hydrogeological sketch map of East Yorkshire research area

mixed supply from more than one borehole) occurred in February 1980 at North Newbald, with values of 14.6 and 11.9 mg NO_3-N/l respectively.

PORE-WATER PROFILES IN THE UNSATURATED ZONE

TRITIUM

The profiles are reasonably consistent between sites and show a single large tritium peak between 9-15 m depth, with a decline in concentration below (Fig. 2); the peak concentrations, which can be assumed to represent 1963-64 infiltration, occur at 11.5 and 15.0 m for the sites with high and low porosity Chalk, respectively. The interpretation of such profiles has been discussed elsewhere[2]. At the high porosity sites, the volume of water held in the profile down to the peak agrees quite closely with the total infiltration since October 1961 (Table I). This is not so for low porosity sites where the profile water content is substantially less, suggesting that a significant by-pass flow occurs.

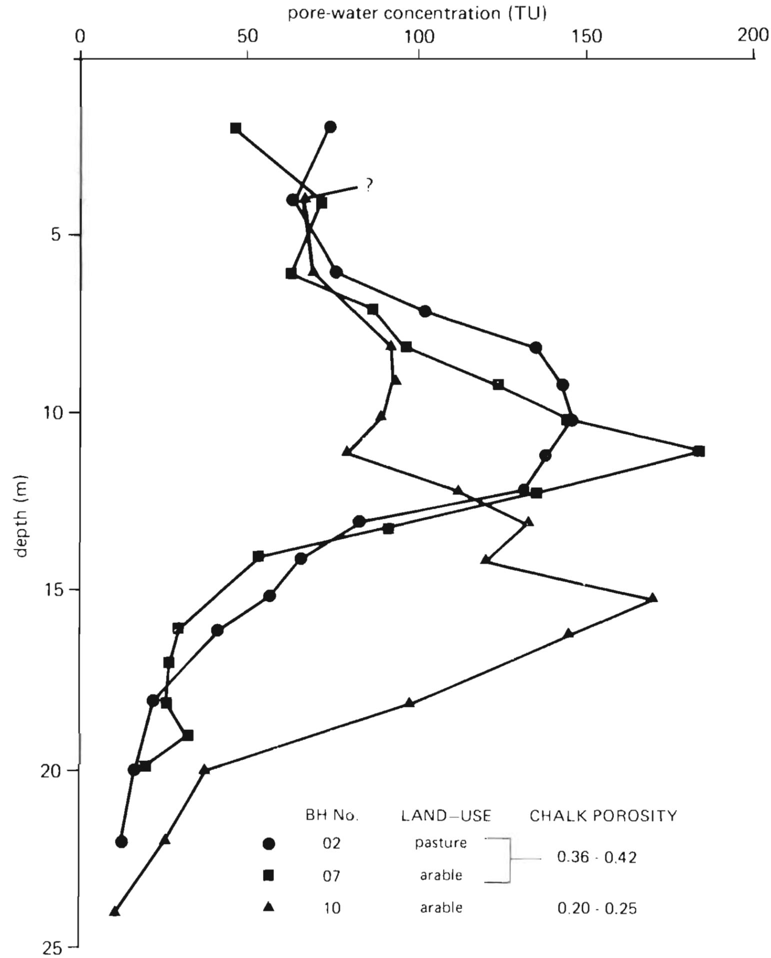

Fig. 2. Tritium profiles from Chalk unsaturated zone in East Yorkshire (October 1978)

The tritium content of the profile down to the peak concentrations is similar for both high and low porosity, and about 20 per cent more than the tritium input from infiltration which was determined using the average monthly concentration of tritium in U.K. rain and a root constant and field capacity of 25 mm and 250 mm respectively. However, this mass balance is rather sensitive to numerous factors[2]. Attempts to simulate the tritium profiles by a simple piston flow model, produced much higher peak concentrations than those observed, even when a field capacity of 2000 mm was used in the soil mixing model, and significant dispersion of tritium within the profile must thus occur.

TABLE I. Analysis of Pore water from Chalk Unsaturated Zone Profiles Beneath Long-standing Arable Land in East Yorkshire

	Volume of water held in profile,	Total infiltration since October 1961	Chloride in profile	Chloride input	Nitrate in profile	Nitrate input	Tritium in profile	Tritium input
	mm	mm	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
High porosity sites (12.5 m)	4 730	4 777[1]	1 740[2] (BH04)	1 285 (BH04)	400[2] (BH04)	1 053 (BH04)		
			1 595[2] (BH07)	1 135 (BH07)	1 311[2] (BH07)	1 291 (BH07)	445 (BH07)	413[3]
Low porosity sites (18.5 m)	4 190	4 777[1]	2 034[4] (BH10)	1 943 (BH10)	768[4] (BH10)	2 135 (BH10)	439 (BH10)	413[3]
			2 138[4] (BH08)	1 897 (BH08)	870[4] (BH08)	2 175 (BH08)		

[1]root constant of 25 mm used
[2]based on average porosity of 39 per cent
[3]root constant of 25 mm used with a soil field capacity of 250 mm
[4]based on average porosity of 23 per cent

Chloride

The chloride profiles are also generally consistent between sites with a subdued peak occurring between 3-7 m depth. Peak concentrations are typically in the range 40-70 mg/l. The chloride content of the profile down to 12.5 m at the high porosity sites (the assumed depth of the 1961-62 infiltration input) generally exceeds the estimated input (Table I), even ignoring any plant uptake which may be significant for certain crops, such as sugar beet. However, at the low porosity sites where more chloride is likely to be transported by rapid by-pass flow, the corresponding profile chloride content (down to 18.5 m) is similar to the input. Porewater chloride concentrations, within the zone of maximum groundwater level fluctuation, are in the range 20-25 mg/l.

Nitrogen Species

The nitrate profiles are similar to those of chloride, with a peak occurring between 3 and 5m, with peak concentrations in the range 20-40 mg NO_3-N/l. Concentrations decline gradually below the peak and within the zone of maximum water level fluctuations are usually in the range 12-15 mg NO_3-N/l and 5-12 mg NO_3-N/l for the low and high porosity sites respectively (Fig. 3). Assuming a similar rate of downward migration of nitrate to tritium, an amount of nitrate, equivalent to 30-40 per cent of the applied fertilizer nitrogen in the period 1963-79, is held in the unsaturated zone profiles (Table I) and this represents, at minimum, a leaching rate of 30 kg N/ha/a.

The ammonium profiles from all the sites are similar and show a uniform concentration with depth mostly in the range 0.02-0.06 mg NH_3-N/l.

Sulphate

The sulphate profiles generally show a subdued peak from 1-7 m, with a fairly uniform decline below to about 25 m, but exceptions to this are the profiles from sites 9 and 10. Sulphate concentrations within the zone of maximum water level fluctuation are usually in the range 40-80 mg/l.

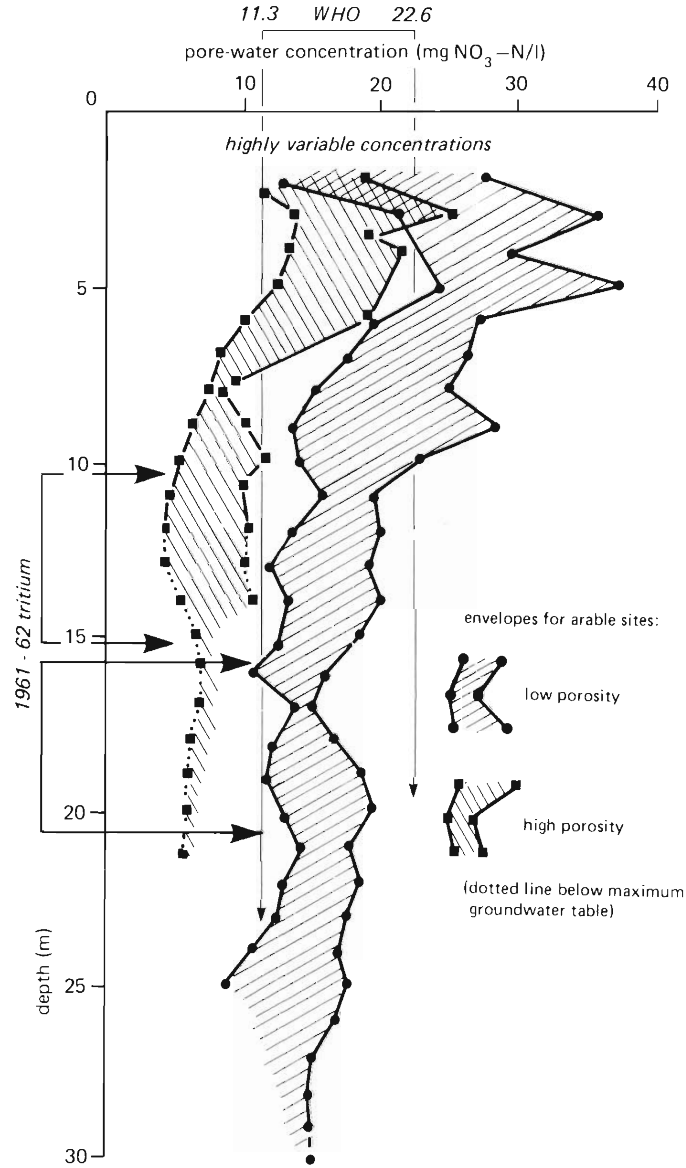

Fig. 3. Nitrate profiles in Chalk unsaturated zone beneath long-standing arable land in East Yorkshire (October 1978 and March 1979)

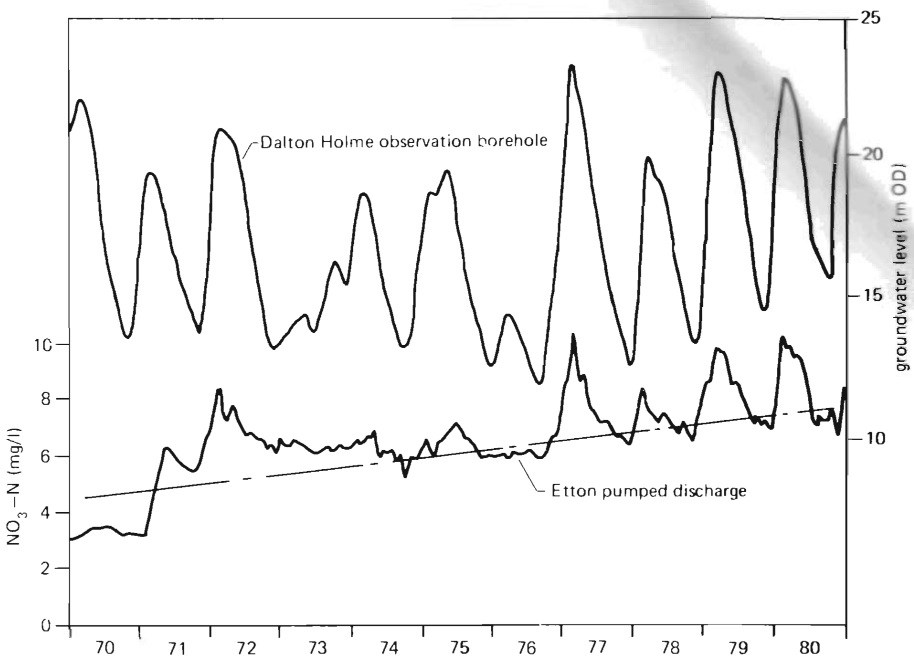

Fig. 4. Correlation between nitrate concentration in groundwater supply and regional groundwater table fluctuations during 1970-80.

Calcium and Sodium

The calcium profiles are somewhat similar to those of sulphate, and show a subdued peak from 1-7 m with a fairly uniform decline below. Calcium concentrations within the zone of maximum water level fluctuation are mostly in the range 70-90 mg/l.

The sodium profiles are uniform with no apparent variation in concentration with depth. Concentrations are in the range 12-18 mg/l.

Summary

(a) Nitrate and other solutes (sulphate, chloride, and calcium) are present in the Chalk pore-water above the groundwater table at concentrations several times greater than in the saturated zone. Similar profiles have been observed in other areas[3, 4].

(b) The chloride content held in the profiles containing post-1961 tritium is at least equal to, and generally greater than, the estimated input from fertilizers and rainfall in the corresponding period. This suggests that solutes may be moving through the unsaturated zone at a somewhat slower rate than tritium on overall balance. The question of solute transport through fissured porous rock is discussed elsewhere[5].

(c) More rapid by-pass flow probably occurs in those sites where the porosity of the unsaturated zone is low.

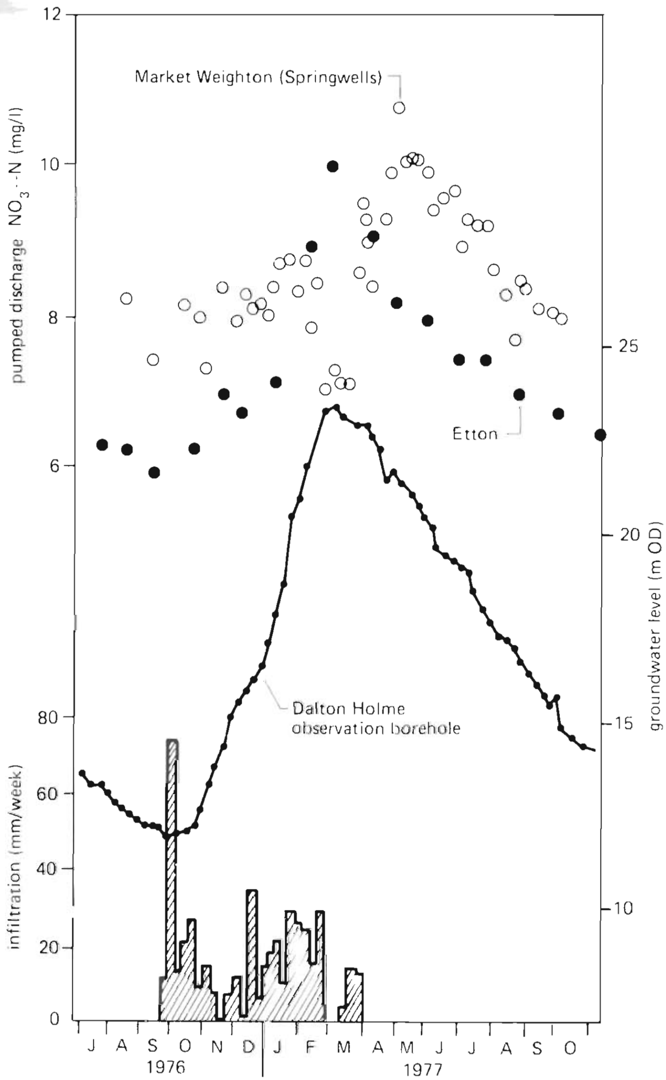

Fig. 5. Detailed fluctuation of nitrate concentration in groundwater supplies during July 1976-October 1977

GROUNDWATER QUALITY MONITORING RECORD

Etton

The nitrate concentration of groundwater pumped from the Etton area showed substantial increases during the early 1970s[1], and has continued to rise slowly during the rest of the decade. Superimposed upon this gradual rise is a marked seasonal variation in groundwater quality, which shows a strong correlation with groundwater levels, as measured at Cherry Burton and Dalton Holme (Fig. 1). A number of features can be observed from the monitoring record (Figs. 4 and 5):

(i) the rise of nitrate (and chloride) concentration in the pumped groundwater coincides with the rise of groundwater level during the early part of winter;
(ii) peak groundwater level and maximum nitrate concentrations, coincide, to within a few days;
(iii) maximum nitrate concentrations appear to correlate with the height of peak groundwater levels; thus, those years with a greater than average recharge show a higher maximum nitrate concentration.

The increase in the nitrate content of groundwater with rising groundwater-table might be attributed to: (1) rapid recharge directly from agricultural soils, or (2) elution of pore-water solutes from within the zone of groundwater level fluctuation. No correlation between intense rainfall events and high nitrate concentrations exists, and the mechanism of rapid recharge does not adequately explain the clear coincidence of peak groundwater level with maximum nitrate concentrations observed over a number of years (Fig. 4). When the groundwater table rises, diffusion exchange between pore water, within the previously unsaturated zone, and mobile fissure water can occur. If equilibrium conditions are attained, the nitrate and chloride concentrations of the mobile fissure water can currently be expected to reach 8-15 mg NO_3-N/l and 20-25 mg/l, the respective concentrations at the base of the porewater profiles. Such a process can explain all the observed phenomena since the profile concentration increases with height above the groundwater table.

The thickness of the unsaturated zone, in the zone of influence of Etton pumping, varies from 10 m to more than 30 m. It is necessary to determine whether the amount of nitrate that can be released from the porewater is sufficient to account for that contained in the pumped discharge. The Etton source comprises four production wells of slightly different construction and at any one time the supply is obtained by mixing the waters. As a result there may be a slight variation in water quality depending upon which boreholes are in use. This, however, is not significant when compared with the seasonal changes already described. During periods of low groundwater table, the bulk of the water pumped is derived from a lower highly permeable horizon some 7 m thick at about -20 m OD[6], when the nitrate content is typically 6 mg NO_3-N/l (Fig. 5).

A second major producing horizon is present within the lower part of the zone of seasonal fluctuations, which accounts for nearly 50 per cent of the pumped water at times of high groundwater table[6]. Clearly, for peak nitrate concentrations of the pumped water to reach 10 mg NO_3-N/l, as in February 1977, the groundwater inflow from the upper producing horizon must contain 14 mg NO_3-N/l. However, the porewater concentrations at this horizon are generally somewhat less, suggesting that the amount of groundwater derived from the upper producing horizon, at times of exceptionally high groundwater table, exceeds 50 per cent of the total pumped. This is feasible, as the groundwater levels in 1977 were higher than at the time the hydraulic conductivity distribution of the aquifer was determined.

During February 1977, springs started to flow near the Etton source, reportedly for the first time in 30 years. Analyses of these spring discharges showed 10.2-10.9 mg NO_3-N/l, and this supports the hypothesis of chemical stratification of the aquifer with a nitrate-rich layer within the zone of groundwater level fluctuation.

Similar groundwater quality stratification within the Chalk aquifer has been observed in West Norfolk, where nitrate concentrations of 14 mg NO_3-N/l were determined for a major water-supply pumping station, while concentrations as high as 20 mg NO_3-N/l were simultaneously recorded from samples within the zone of groundwater level fluctuation[7].

For groundwater levels and nitrate concentrations in the pumped discharge to peak at the same time, there must be very rapid flow (of the order of days) through most of the zone influenced by pumping. Earlier work[6] suggested rates of flow of up to 200 m/d, based on an hydraulic conductivity of 200 m/d, an hydraulic gradient of 1/200, and a specific yield of 0.005.

Other dip-slope groundwater sources in East Yorkshire show similar behaviours to those of Etton, although slight differences can be explained by variations in catchment land use, unsaturated zone thickness, and borehole construction. However, there is a substantially different response in the case of the escarpment sources, such as Market Weighton (Springwells).

Market Weighton (Springwells)

It is of relevance, therefore, to discuss the example of Market Weighton (Springwells) further. In comparison with Etton this shows:

(a) generally higher nitrate, sulphate, and chloride concentrations throughout the year;
(b) less clearly defined peak concentrations;
(c) much more variable concentrations throughout the groundwater level recession;
(d) peak concentrations generally later in the year (April/May) and not coincident with peak groundwater levels (apparently attributable to direct leaching of fertilizer nitrate applied to the fields at this time, with significant rapid groundwater flow in the unsaturated zone);
(e) no obvious correlation of groundwater nitrate concentrations and rainfall intensity;
(f) frequent records of low nitrate concentrations during January/February, perhaps due to the diluting effect of infiltration once the autumn solute "build-up" in the soil has been leached.

The different groundwater quality regime here and along the escarpment generally, is probably due to:

(i) the greater importance of rapid by-pass flow through the unsaturated zone: the higher tritium content of the groundwater found at Springwells (25-32 TU) compared with that of Etton (1-4 TU)[1] supports this view since, because of the steepness of the escarpment, the unsaturated zone is generally thicker around Springwells than Etton.
(ii) in the small area where the unsaturated zone is thin, on the steep slopes themselves, the land is mostly used as pasture and so the input of nitrate can be expected to be low;
(iii) the restricted aquifer thickness, at Springwells, about 20 m, precludes the possibility of significant groundwater quality stratification.

GROUNDWATER QUALITY OUTLOOK

Since nitrate concentrations in the porewater above the groundwater table beneath arable land are currently 2 to 4 times higher than in the groundwater supplies, the long-term quality trend of the groundwater sources must be towards substantially higher levels of nitrate.

A regression line (Fig. 4) for nitrate concentrations during the groundwater recession at Etton, which is broadly typical of other dip slope sources, can be drawn for the period 1972-81. If this trend were to continue the nitrate concentration would exceed 11.3 mg NO_3-N/l in the early 1990s.

Future groundwater nitrate concentrations at Etton can also be estimated by considering the rate of solute movement through the unsaturated zone. The average thickness of the unsaturated zone of the high porosity Chalk in the Etton catchment is 15 m. Assuming non-dispersive flow and a rate of solute movement similar to that of tritium (0.7 m/year) the concentration of nitrate at the groundwater table would reach 10-20 mg NO_3-N/l (the present concentration at 6 m) by the early 1990s and produce, after mixing with water derived from the lower producing horizon, a concentration of about 8-13 mg NO_3-N/l during periods of high groundwater level. The boundary between high and low porosity Chalk is not clearly defined, although the area of this catchment underlain by low porosity Chalk is probably small. The nitrate concentration at the groundwater table, in the low porosity Chalk where the groundwater table is deeper (at least 30 m), will probably also reach 12-20 mg NO_3-N/l by the early 1990s as the nitrate concentration, in the unsaturated zone, and the rate of movement (1.0 m/year) are both higher.

It is uncertain whether the nitrate concentration at Etton will exceed 22.6 mg NO_3-N/l, even in the distant future, since the present maximum concentration in the high porosity Chalk only just reaches 22 mg NO_3-N/l. Whether the pumped water will approach 22.6 mg NO_3-N/l will depend on (1) the relative proportion of high and low porosity Chalk within the catchment; and (2) the extent of dilution with water derived from woodland and permanent pasture.

CONCLUSIONS

(a) There is a rising trend of nitrate concentrations in most public groundwater supply sources abstracting from East Yorkshire Chalk.

(b) The current fluctuations in concentration at a dip-slope source, such as Etton, are primarily a function of the proportion of arable land use in the groundwater catchment, the average unsaturated zone thickness and the borehole construction.

(c) The regime of groundwater quality fluctuations at an escarpment source, such as Market Weighton (Springwells), is different, reflecting the greater importance of rapid unsaturated zone by-pass flow and saturated zone mixing.

(d) The rate and mode of downward migration of higher concentrations through the unsaturated zone will be of importance in the precise prediction of future groundwater quality.

(e) Nevertheless, concentrations in groundwater sources used for public supply are likely to exceed 11.3 mg NO_3-N/l in the early 1990s on a widespread basis.

(f) The groundwater nitrate problem in East Yorkshire does not appear as severe as that in some of the drier areas of the Chalk outcrop, primarily, it would seem as a consequence of higher infiltration rates resulting in greater dilution of soil nitrate excess to crop requirements during the winter months, and secondarily of the somewhat higher proportion of non-arable land.

(g) The high nitrate concentrations recorded in the unsaturated zone pore-water profiles suggest recent soil leaching losses in the range 30-50 kg N/ha/a or more, with a manufactured value equivalent to £10-15/ha/a.

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COMMUNICATION ON "VIBRATION OF HYDRAULIC GATES"*

Mr M. J. Kenn (Imperial College, London) wrote that the paper provided a cogent reminder of some of the hydraulic problems which must be either avoided or resolved in gate designs. The designer must indeed pay meticulous attention to the complex fluctuating flow patterns generated within his structures in order either to avoid or to control the associated engineering problems.

The need for simple hydraulic model studies had been stressed in order, for example, to obtain reliable data on hydrodynamic downpull at various gate openings. These loads could be substantial and must be considered in the design of the hoisting gear (or of any ballast to ensure closure). A hydrodynamic downpull of 150 tons was, for example, originally anticipated (at part opening) for each of the gates in the diversion ports of the Long Sault dam on the St. Lawrence Power Project. Hydraulic models, however, demonstrated that, with small changes of design, the hydraulic downpull for each gate could be reduced to a mere 50 tons[1]. Downpull forces of similar magnitude were also determined for the emergency gates of the Massena Intake[1].

Categorization of flow-induced gate vibrations had been avoided in the paper. This was perhaps wise, because flow-induced vibrations might often be interlinked and their individual origins consequently difficult to identify. At the El Chocon Hydro-Power scheme, for example, eddies generated from an intake pier were shown by studies at Imperial College to have been the *indirect* cause of resonant gate vibrations (in the fully-open condition) but *transmitted* by induced resonant water-hammer surges which served also to amplify the resonant gate vibrations[2].

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*Paper by Lewin, J. 1983 *Journ. I. W.E.S.*, 37, 165.