

# Nitrate in groundwater: a water company perspective

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## Abstract

More than 100 groundwater sources operated by Anglian Water Services are vulnerable to diffuse and point pollution, and 33 of these sources have nitrate concentrations in excess of  $50 \text{ mg l}^{-1}$  as  $\text{NO}_3$ . Most time series nitrate data 'recess' to a long-term rising baseline, upon which seasonal variations and/or data scatter are superimposed. Investigations at boreholes abstracting from the Chalk aquifer show that concentrations decrease with depth below the water table and with time after pump start-up. Abstraction rates do not affect concentrations but the combination of boreholes in use does. A reliable and robust semi-quantitative method for predicting future nitrate concentrations has been developed. Use of this method has allowed a rigorous definition of capital investment requirements under the AMP4 process to maintain compliance with drinking water standards. The method has been used to predict short-term nitrate concentrations for a variety of recharge scenarios.

*Keywords: asset management, baseline trend, capital investment, groundwater, nitrate*

Anglian Water Services (AWS) supplies *c.*  $1250 \text{ Ml day}^{-1}$  of treated water to four million customers in the Anglian region. About half the total is obtained from the 192 groundwater sources that are located throughout the region (Fig. 1). Groundwater is abstracted from three major aquifers (the Chalk (130 sources), Lincolnshire Limestone (28) and Sherwood Sandstone (9)) and five minor aquifers (the Woburn Sands (7), Spilsby Sandstone (11), Sandringham Sands (5), Crag (1) and Sands and Gravels (1)). The supply system also includes 12 groundwater assets operated by the Hartlepool Water Company. The diversity of hydrogeological conditions has resulted in a wide range of borehole depths (6–500 m), borehole yields ( $2\text{--}180 \text{ l s}^{-1}$ ) and asset lives (10 to over 100 years). It has also resulted in a wide range in natural hydrochemistry. Relatively high concentrations of the trace elements mercury, arsenic and nickel occur in a few deeply confined hydrochemical environments. More critically, at least half of the sources are vulnerable to diffuse and point sources of pollution. Of the latter, pollution by fuel additives, solvents and pesticides has occurred at some sources. Of the former, it

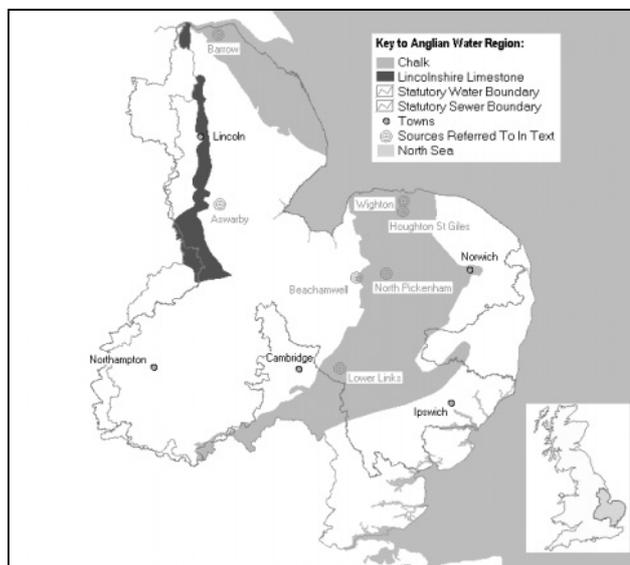


Fig. 1. The Anglian Water supply region.

is nitrate that is of particular concern, with concentrations exceeding the AWS Action Level of  $45 \text{ mg l}^{-1}$  as  $\text{NO}_3$  at 41 sources and the permitted concentration value (PCV) of  $50 \text{ mg l}^{-1}$  as  $\text{NO}_3$  at 33 sources.

Nitrate concentrations increased suddenly and dramatically at some sources during the autumn and winter of 2000–2001 as a result of the very high recharge that occurred at the time. Also, it was recognized that long-term rising trends could raise future concentrations above the AWS Action Level at some sources and could reduce the blending potential at others. AWS wished to understand the key processes that control the trends so that these could be defined and a method developed for predicting future concentrations. Investment requirements to maintain compliance with drinking water standards during Asset Management Planning round 4 (AMP4) and subsequent periods could then be determined.

## Analysis of time series data

Pollution of groundwater by nitrate is a widespread, persistent problem that is well documented (e.g. Foster & Crease 1974; Foster & Young 1980; Wilkinson & Greene 1982). Agricultural and non-agricultural sources of nitrate have been investigated and nitrate variations in the soil zone, the unsaturated zone and the saturated

zone have been quantified and explained (e.g. Foster *et al.* 1986; Chilton *et al.* 1996). Data collected since the 1960s at many groundwater sources show a variable, erratic, but long-term increasing trend in nitrate concentrations, and models have been developed to predict future values (e.g. Carey & Lloyd 1985; University of Birmingham 1993; Chilton *et al.* 1997, 1999). The subject has been thoroughly reviewed by Chilton *et al.* (2003).

The rise in nitrate concentrations in the autumn and winter of 2000–2001 was particularly worrying at five AWS sources that abstract from the Chalk aquifer. The British Geological Survey (BGS) developed flow and transport models for these sources and analysed time series data more generally (reported by Gaus *et al.* 2002; Hughes *et al.* 2002, etc.). The modelling indicated that existing long-term trends are likely to continue for at least the next 15 years irrespective of any recent or future land use changes. The analysis indicated that seasonal variations can be explained by fluctuations in the water table and that dual porosity in the Chalk matrix is a key process controlling nitrate migration. Statistical analysis of the data indicated that, given the often limited amount of data, simple linear regression is the best means of defining trends.

Following on from the BGS study, AWS re-examined all the available time series data, including concentrations recorded in old reports and archives. An example, from Barrow in the Northern Chalk aquifer south of the Humber, is given in Figure 2. Most graphs consist of two distinct components. The first is a background long-term rising trend, and the second is a short-term seasonal variation and/or data scatter that is superimposed above the background trend. The first component is defined by a straight line that is visually fitted as a lower bound to the data (the equation for this line can be generated using Excel or other software applications). This 'baseline' should pass through the minimal concentrations that occur at times of drought. The second component is defined by the maximum concentration above the baseline at any date, and is therefore a 'worst case' with a return period defined by the number of years of record. The slope of the baseline is usually similar to that generated by linear regression, but the more subjective data analysis allows the hydrogeological and hydrochemical processes that control nitrate concentrations to be more fully taken into account.

The background rising trend reflects the slow change in the bulk nitrate concentration of groundwater stored in the aquifer. This slow change is attributed to the historical transfer of nitrate from the soil zone and is controlled by factors such as soil type, the thickness of the unsaturated zone, land use and the application of fertilizer, aquifer hydraulic properties, recharge, and diffusion and exchange processes.

Seasonal variations consist of peaks, which occur in the late autumn and winter, followed by declines in the

late spring and summer. The variations are related to the position of the water table and its interaction with the unsaturated zone in which relatively immobile pore water with enhanced nitrate concentrations is slowly migrating downwards or transferring to mobile water moving in micro- and macro-fissures. Thus, recharge events in the late autumn cause rapid increases in concentrations as the water table rises into the unsaturated zone. Conversely, concentrations decline in the late spring as the water table falls. Bypass flow, which can be important in some areas of the UK, does not appear to influence short-term variations in the AWS region.

The particular pattern of nitrate variation with time is unique to each source, and sometimes to individual boreholes at a source. However, the general pattern at Barrow is typical of groundwater abstracted from the unconfined Chalk aquifer throughout the AWS region: trends have persisted for at least 22 years (the average rate of change is  $1.15 \text{ mg l}^{-1} \text{ a}^{-1}$ ) and seasonal variations are evident. Data from Beachamwell are presented as a second example in Figure 3; the rising trend has persisted since 1976 but seasonal variations are not strong. The pattern is also seen at sources abstracting from the unconfined Sherwood Sandstone, Woburn Sands, and Sands and Gravels aquifers.

An exception is the Lincolnshire Limestone aquifer, in which the pattern of nitrate variation is consistently different. Re-examination of all data from this aquifer indicates that annual minima fall to a baseline that has no trend (the gradient is  $0.0 \text{ mg l}^{-1} \text{ a}^{-1}$ ), and that seasonal variations are large and erratic. The value of the baseline is unique to each source, as is the magnitude of the seasonal variations. Data from Aswarby are shown in Figure 4. In this case, there is an upper and a lower baseline. The latter coincides with times of drought (late 1992, 1996 and 1997); the predicted nitrate concentration during a future drought is therefore  $28.0 \text{ mg l}^{-1}$  as  $\text{NO}_3$ . The causes of this distinctive pattern are poorly understood (it appears to negate the concept of a slow downwards migration of nitrate and implies that nitrate loading during the last 50 years or so has not increased), but the dominance of macro-fissure flow in the aquifer is probably involved.

## Nitrate investigations

Various field investigations were carried out at sources abstracting from the unconfined Chalk aquifer, to examine the processes that control nitrate concentrations and to determine whether or not different operational regimes could significantly affect the quality of the raw water.

During short constant rate tests concentrations declined from when the first sample was taken (after 15 min of pump start-up) to a stable value within

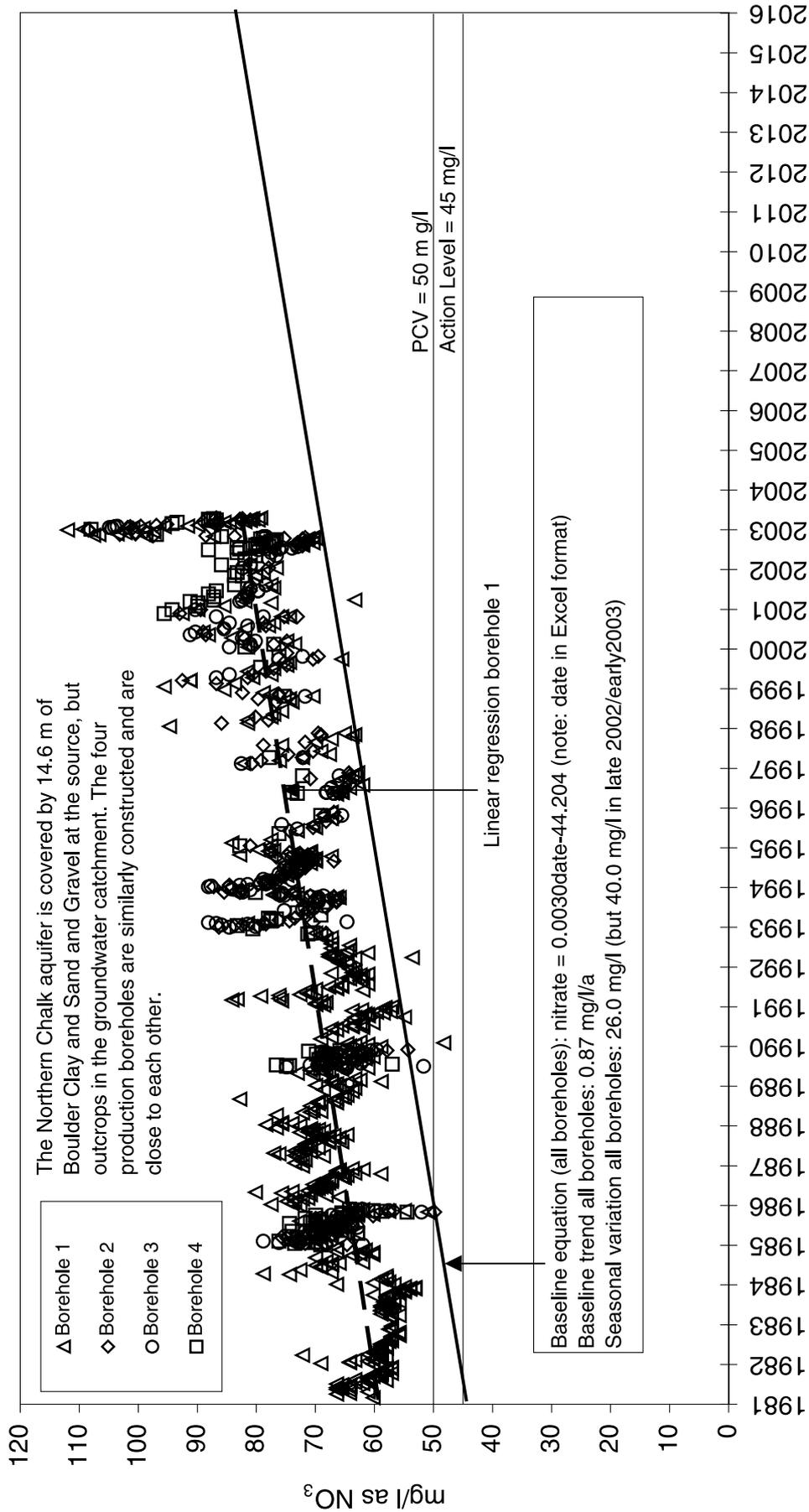


Fig. 2. Nitrate concentrations at Barrow (Northern Chalk).

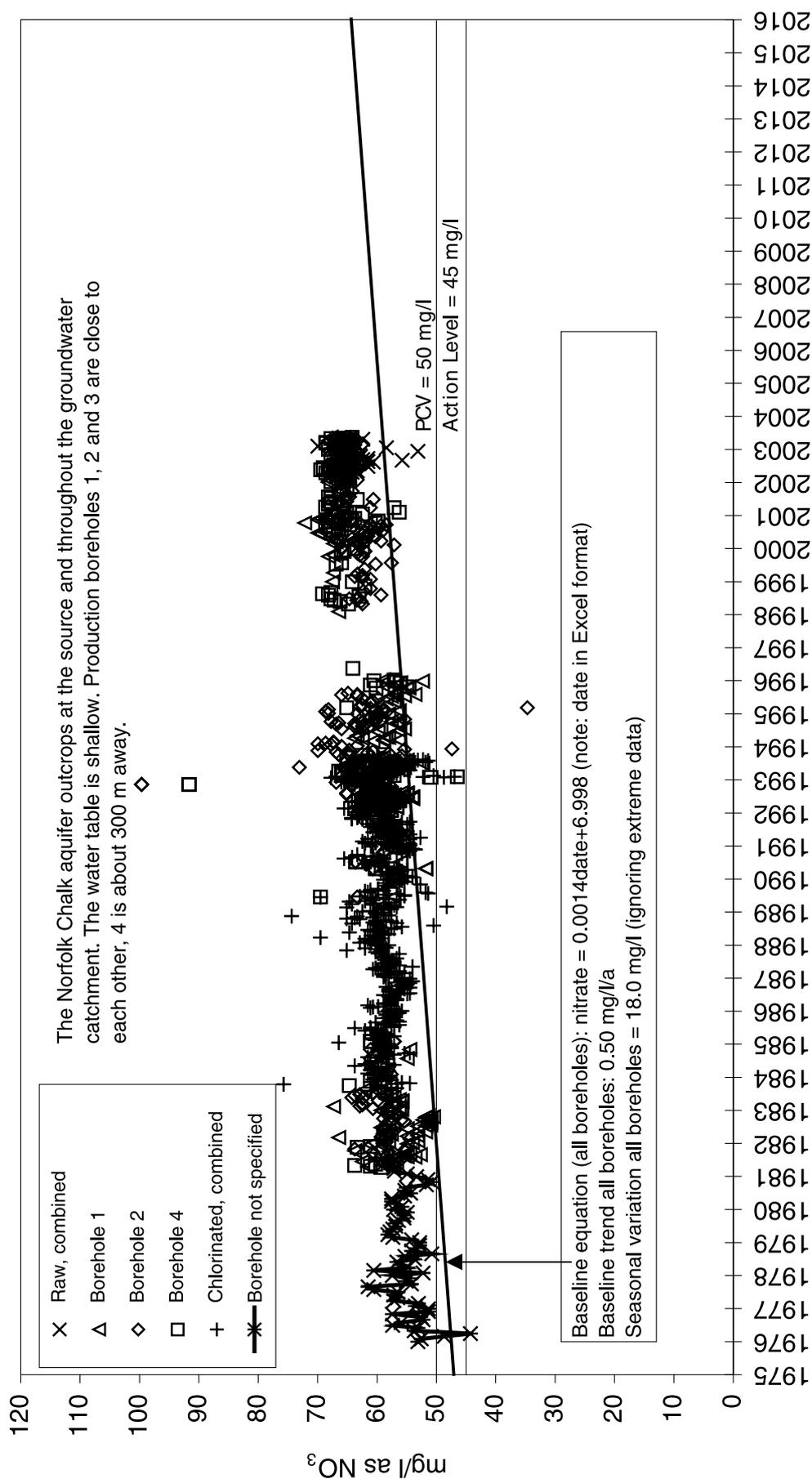


Fig. 3. Nitrate concentrations at Beachamwell (Middle Chalk, Norfolk).

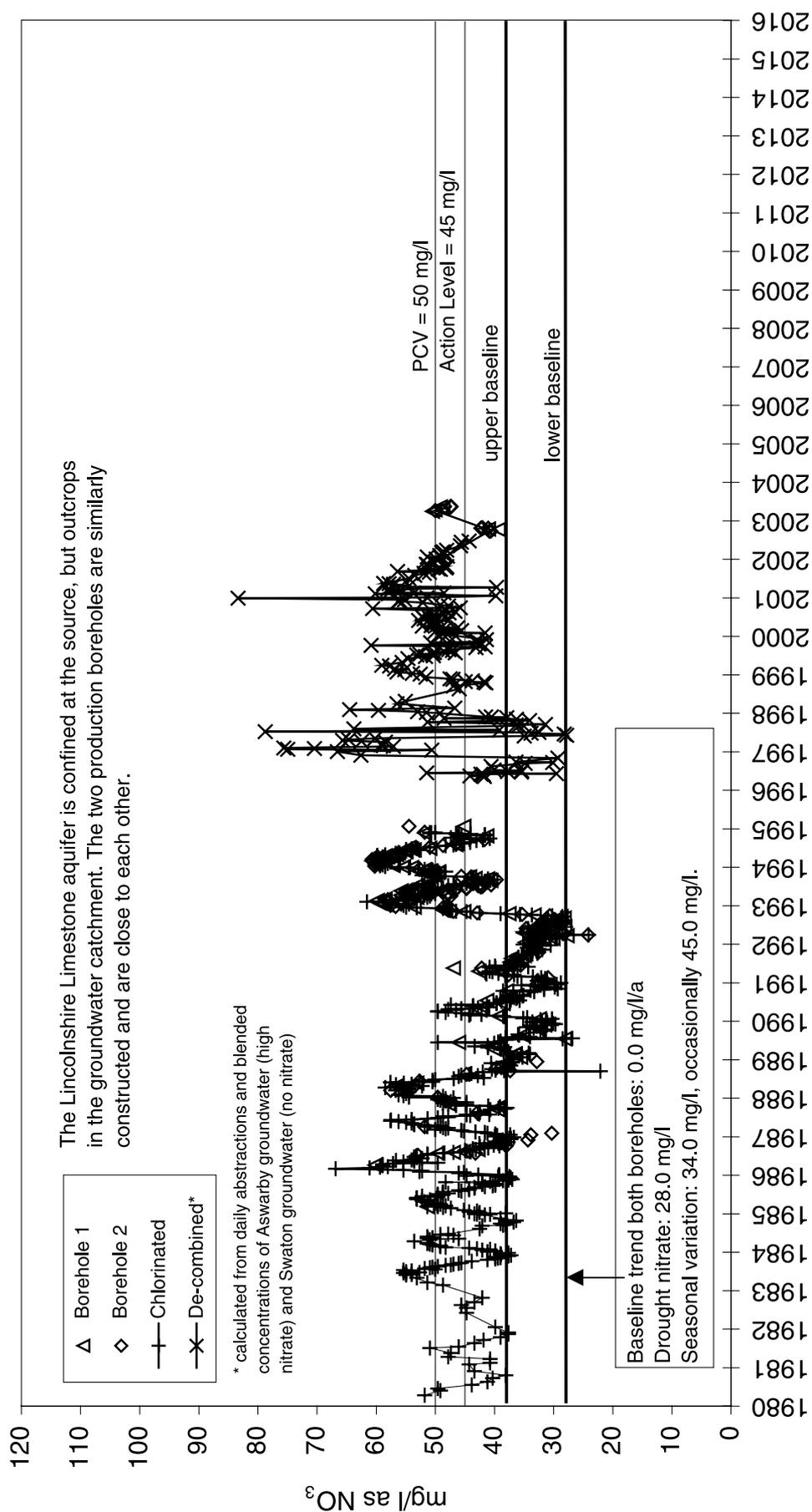


Fig. 4. Nitrate concentrations at Aswarby (Lincolnshire Limestone).

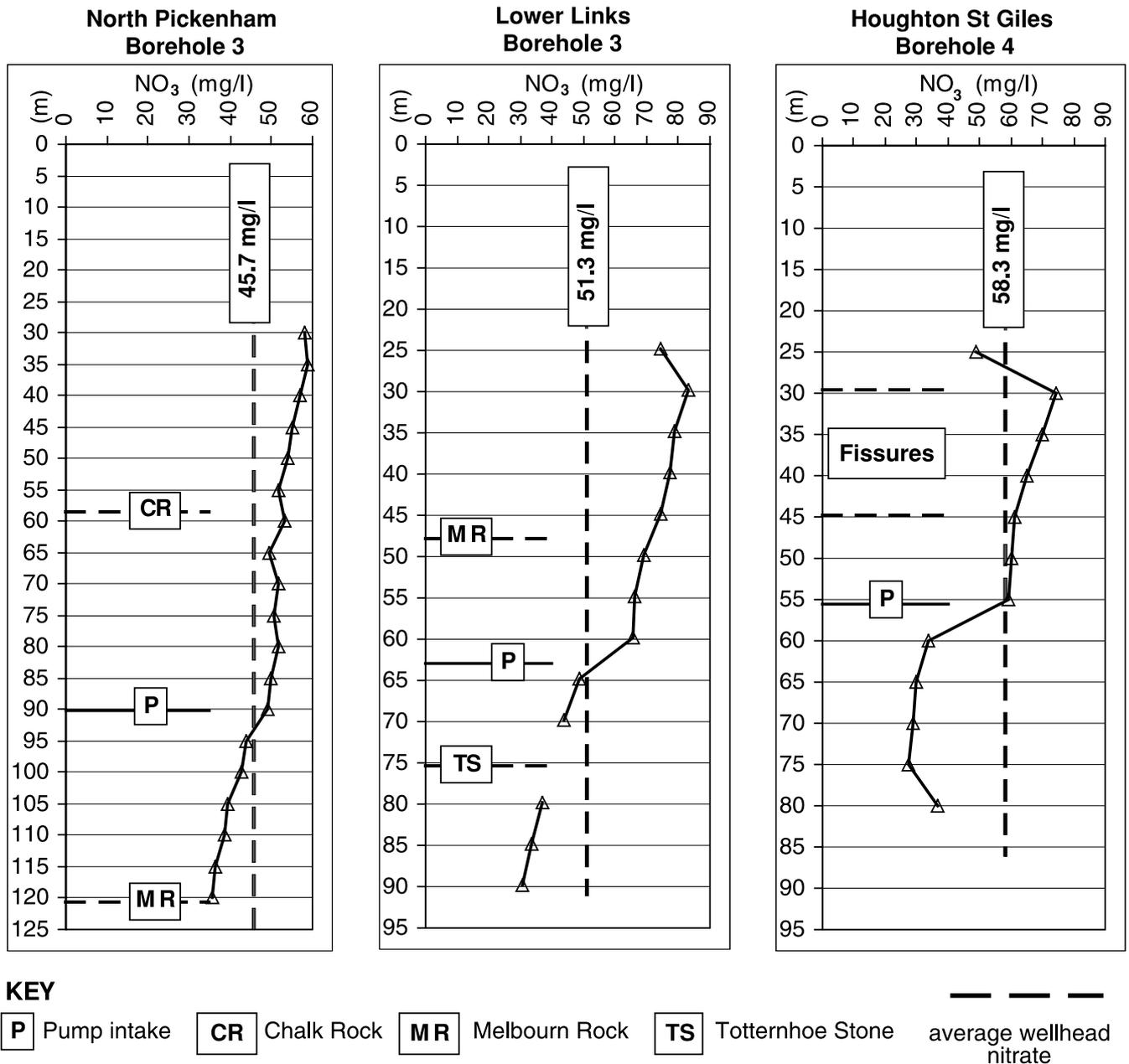


Fig. 5. Depth profiles.

120 min. The decline was a maximum of about  $4.5 \text{ mg l}^{-1}$  as  $\text{NO}_3$  and is attributed to dewatering of the uppermost flow horizons as the tests proceeded.

Concentrations were not affected by the pumping rate during short duration step tests.

Multiple testing consisted of pumping the boreholes at a multiple source in different combinations. Concentrations at one borehole were affected by pumping from another, but not by more than about  $4.5 \text{ mg l}^{-1}$  as  $\text{NO}_3$ . The effect is attributed to 'competition', with one borehole being more able to abstract from higher horizons than another.

The procedure for depth profiling consisted of setting the pump in the borehole at such a depth that the contributory flow horizons were 'split' above and below

it. The pump was run continuously as depth samples were collected at 5 m intervals down the borehole. Samples of groundwater at the wellhead were taken at the same time as the sampler was activated. The average concentration at the wellhead was then compared with the concentrations at different depths. Concentrations decreased with depth, as shown for three sources in Figure 5. Interpretation of the results suggested that there is some groundwater with relatively low nitrate (about  $35 \text{ mg l}^{-1}$  as  $\text{NO}_3$ ) at North Pickenham and Lower Links, but there is none at Houghton St Giles below 45 m.

Scavenger well testing, in which two pumps set at different depths in a single borehole were run simultaneously, proved that groundwater with distinctly

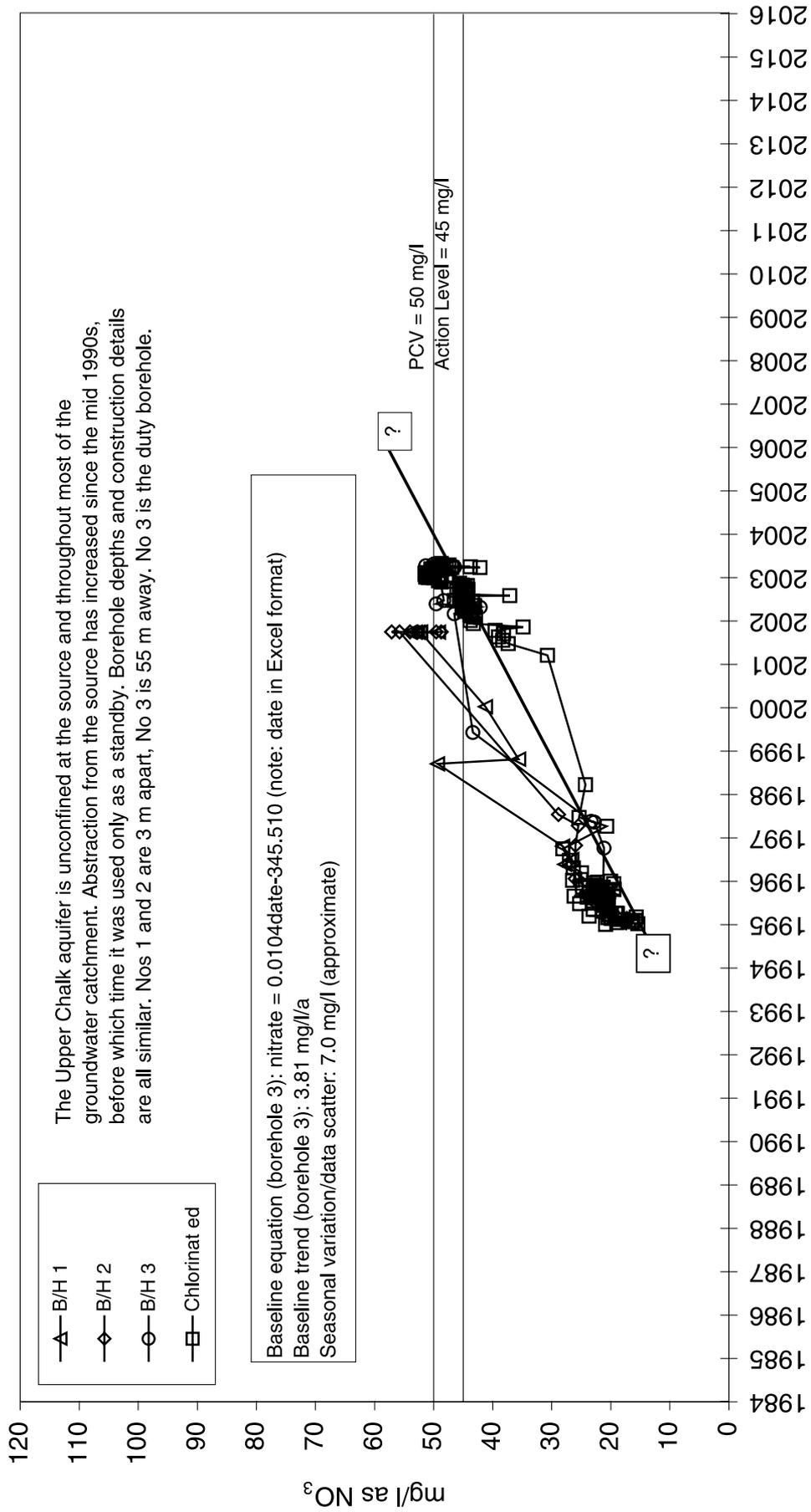


Fig. 6. Nitrate concentrations at Riddlesworth (Upper Chalk, Norfolk).

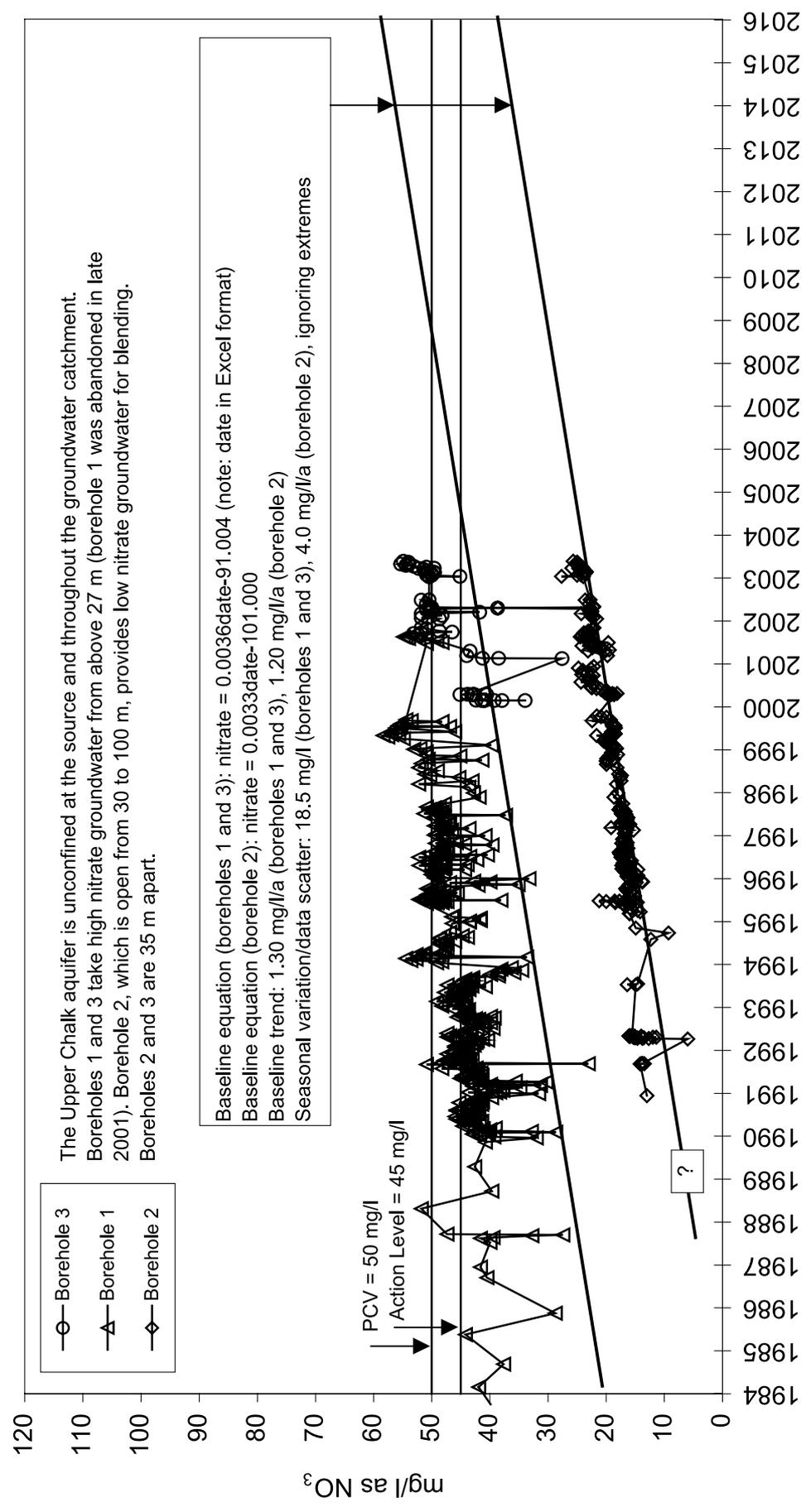


Fig. 7. Nitrate concentrations at Wighton (Upper Chalk, Norfolk).

different concentrations can be effectively partitioned between the high nitrate from the shallow pump and low nitrate from the deep pump. Stable concentrations occurred within about 120 min of pump start-up. The difference between the shallow and deep concentrations was changed by changing the proportion of the total flow from each pump.

The results of the various field investigations support the concept of slow downwards migration of high-nitrate water. This is made more complex at the five Chalk sources where, although flow does occur through the body of the Chalk, it also occurs along discrete flow horizons; low nitrate at depth partially reflects the greater lateral distance that nitrate in deep horizons travels compared with that in shallow horizons. The field investigations have also shown that little can be done operationally to reduce nitrate concentrations significantly. Also, although low-nitrate groundwater is present at some of the sources, the lower flow horizons are poorly developed in terms of secondary permeability and so the groundwater is of too small a quantity to be useful for blending.

All the investigations, apart from the scavenger well tests, were of a relatively short duration, and pumping for much longer periods of time could give somewhat different results. Data from several new sources suggest that baseline trends are relatively steep for at least the first 5 years of abstraction. This is probably because the most permeable, shallow flow horizons are developing and expanding their influence during the early years of production. An example of this phenomenon is given in Figure 6.

### Maintenance of water quality standards

To comply with the Water Supply (Water Quality) Regulations (DWI 1989, 2000) AWS currently treats high-nitrate groundwater by blending at 27 sources, ion exchange at 13, and reverse osmosis at one source.

Low-nitrate water for blending is obtained from deep on-site boreholes in the same aquifer, from on-site and off-site boreholes in a different aquifer, from off-site boreholes in the same aquifer but where conditions are reduced, and from surface water. Time series data for Wighton, where shallow high-nitrate groundwater is blended with deeper low-nitrate groundwater from an on-site borehole, are shown in Figure 7. The boreholes abstract from the unconfined Upper Chalk aquifer in Norfolk. The rising trend at the deeper borehole is such that its blend potential will gradually reduce, although the groundwater will remain suitable for blending until at least 2015.

Time series graphs were prepared in October 2002 for all groundwater sources affected by diffuse source nitrate where non-compliance with respect to the Regulations

may become an issue during AMP4 and subsequent AMP periods. Future concentrations were predicted using the analytical method described above: baselines were fitted to the data; equations for the baselines were calculated and used to define 'baseline' concentrations at the ends of 2005, 2010 and 2015; and seasonal variations were added to these. Maximum variations were applied, as these give 'worst case' predictions. The method assumes that the background trends will remain the same for at least the next 10 years, that the variability in recharge will be the same in this period as in the previous 20 years, and that no new mechanisms will influence future concentrations until at least 2015. It is accepted that these assumptions may not apply in every case, particularly if the effects of climate change become more pronounced. The extreme seasonal variation in late 2002–early 2003 at Barrow (Figure 2) may be an example of this.

More than 20 sources have been identified where there is no existing treatment or where existing blend and/or treatment capacities will be insufficient to reduce future nitrate concentrations to the AWS Action Level of  $45 \text{ mg l}^{-1}$  as  $\text{NO}_3$ . Capital investment requirements have been defined for these sources, based upon the most appropriate treatment option for each source.

The analytical method has also been used to predict concentrations for a variety of recharge scenarios. A chosen seasonal variation is assumed for a particular scenario (maximum variation for high recharge, minimum variation for low recharge) and this is added to the predicted baseline concentration at any future date. This is of particular relevance to conditions in 2004. A continued drought throughout late 2003 and early 2004 will result in low nitrate concentrations during 2004, but a change to high recharge could cause concentrations to rise excessively at some sources.

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