Field and modelling studies to assess the risk to UK groundwater from earth-based stores for livestock manure

D C Gooddy[1*], A G Hughes[1], A T Williams[1], A C Armstrong[2*], R J Nicholson[3] and J R Williams[3]

[1]*British Geological Survey, Wallingford, Oxfordshire, OX10 8BB*

[2]*ADAS Gleadthrope, Meden Vale, Mansfield, Nottinghamshire, NG20 9PF*

[3]*ADAS Boxworth, Battlegate Road, Boxworth, Cambridge, CB3 8NN*

[*]*Corresponding authors*

e-mail *dcg@bgs.ac.uk* *fax 01491 692345*

e-mail *adrian.armstrong@adas.co.uk* *fax 01623 844 472*

Abstract. Boreholes have been constructed at eight sites on the Permo-Triassic Sandstone and Chalk aquifers to assess the extent of chemical and microbiological contamination emanating from unlined farm manure stores. Slurry along fracture faces in the Chalk was found on cores taken from beneath two stores. Porewaters from the Chalk sites and one of the Sandstone sites were discoloured and showed high concentrations of nitrate, ammonium and organic carbon to depths in excess of 10 m. Although *Cryptosporidia* and *E.coli* O157 were found in many of the cattle slurry lagoons, neither were found in the aquifer material beneath. The self-sealing of unlined slurry stores is seen as a crucial step in minimising leakage. A simple mass balance shows farm boreholes near to contaminant sources are at greater risk than public supply wells. Contaminant modelling shows discontinuing use of an unlined farm manure store will lead to little difference in solute concentrations over the short to medium term. Groundwater is most at risk where the water table is shallow since direct hydraulic connection between the lagoon base and the water table considerably increases the rate of vertical migration. This is of greatest significance for pathogens that are thought to be relatively short lived in the subsurface. Under the majority of situations minimal threat is posed to potable groundwater drinking supplies.

Keywords: cattle slurry, aquifers, porewaters, groundwater, pathogens, contaminant modelling

INTRODUCTION

Groundwater provides over 30% of all water abstracted in England and Wales and accounts for more than 80% of the total public supply in south-east England. Both industry and agriculture rely on groundwater in many areas and it is the predominant source for private water supplies. The total abstraction of groundwater in the UK, including that used by industry and agriculture, is some 2400 million m^3 yr^{-1}, with the majority of this coming from England. About 85% is pumped from two major aquifers, the Chalk and the Permo-Triassic Sandstone, which provide 60% and 25% of groundwater needs respectively.

Although storage of livestock manure can present a serious potential risk of surface water pollution, there has not been the same concern about potential pollution to groundwater possibly because of the greater dilution and less immediate impact expected in groundwater systems. The majority of livestock slurry storage structures generally only pose a risk of water pollution because of structural or operator failure. Only in the case of unlined earth-based slurry lagoons, which were unregulated before 1991, and field heaps of solid manure, is there a potential risk where they have been built on relatively permeable sites and leakage of pollutants through the base and walls may occur and cause pollution of groundwater (Withers *et al*. 1998). Recent observations have suggested that unlined earth-banked farm slurry stores have the potential to pose a threat to groundwater. There are an estimated 11,000 slurry lagoons in England and Wales (Nicholson & Brewer 1997) many of which could be overlying aquifers. Data from a single site indicated that the slurry and its constituents might in some circumstances leach from the bottom of these stores (Gooddy *et al*. 1998). This study aims to investigate the extent of leaching under a wider sample of unlined earth-based slurry stores situated over aquifers and to assess the risk posed to potable water supplies at the catchment scale by using hydrological models.

METHODS

Sites

Since all stores constructed after 1991 should have an impermeable base, field studies focussed on unlined earth-based stores on permeable soils. Field sites were selected after extensive surveying in which some 68 potential sites were considered for a full study. In all, 3 Chalk and 5 Sandstone sites were eventually investigated. Details of the sites are shown in Table 1. At each of these, a borehole was constructed adjacent to manure stores with the intention of sampling the interstitial porewaters and so identify any pollution from the store. As all of the slurry stores were still in use, it was necessary to also construct an inclined borehole (generally at an angle of 45°) at each site so as to obtain material from directly underneath the lagoon. For all but one of the sites, continuous cores were obtained through the unsaturated zone by rotary coring using air as the lubricating fluid. At Chalk site 3 where turkey litter was stored above ground on the bare surface of the Chalk, core was obtained through a percussion drilling process where no lubricant was required. These boreholes were constructed vertically just after the annual site clearance.

Sample extraction and analysis

At each borehole, core material was extracted, and examined visually for evidence of pollution by slurry. The sample was then split into sections 1m long, porewater extracted for analysis as soon as possible and samples taken for microbiological examination.

Porewater was extracted by using the high speed centrifuge ‘drainage’ method (Edmunds & Bath, 1976) and split into three fractions; one filtered and acidified for cations; one filtered and but not acidified for anions; the other unfiltered and not acidified for dissolved organic carbon. All analyses of porewater samples were carried out in the BGS laboratories at Wallingford. Filtered acidified porewaters were analysed using an ARL 34000C Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES). Nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N), molybdate-reactive phosphorus (MRP) and Cl were determined using standard Auto Analyser II colorimetric methods (Kinniburgh & Miles 1983) on the filtered, non acidified water fraction.

Core material from the boreholes was sampled at approximately 5 m vertical intervals, comminuted and suspensions were prepared using a wrist action shaker for 15 minutes. The suspensions were examined for a wide range of micro-organisms including *Cryptosprodium* oocysts and *E.coli* O157:H7. Standard techniques were used and are detailed in Gooddy *et al.* (2000a).

Gas samplers were installed in two locations (Chalk site 2 and Sandstone site 1) at depths of 2 m increments to the base of the borehole. These were made from short lengths of plastic waste pipe perforated with 10 mm diameter holes at 30-40 mm centres and packed with glass wool to prevent ingress of the sand screening material. After installation at the required depth, they were surrounded with coarse sand, and isolated from neighbouring samplers using a thick bentonite seal (Kinniburgh *et al.* 1999).

Modelling studies

A model was developed to examine the balance of water in a slurry lagoon subject to both downward seepage, and time varying inputs. This model predicts the water level in a slurry store as a function of the mass balance. Using a daily time step, the amount of fluid in the store accumulates due to the addition of more material from the farm, supplemented by daily rainfall. Water is removed by evaporation and seepage. The seepage through the bottom of the store was calculated using the Richards' equation (Marshall & Homes 1988) for saturated/unsaturated flow. This model predicts the fluxes through the bottom of the store and through the base of the soil profile, over a period of years. It was used with a variety of soil profile descriptions to identify the importance of the surface sealing layer, and to estimate the fluxes of water that would travel to the groundwater.

Assuming leakage from a slurry store, further models were used to estimate the maximum concentration of contaminant arriving at an abstraction well due to pollution from the slurry store. Three solutions were developed:

1. A simple mass balance calculation based on recharge rate, abstraction rate and of the capture zone area.
2. A groundwater flow model with particle tracking employed to define the position of the capture zone area.
3. An analytical transport model.

The mass balance equation was used to provide an initial model-independent estimate of the total concentration reaching a well, which could later be used to check/verify the transport model results. The analytical model simulates flow and transport along a series of streamtubes, from the ground surface through to output features where concentration predictions are required, in this case, from slurry stores to abstraction wells. The particle tracking facility within the flow modelling package was used to identify streamtubes and their connection to surface zones. Further consideration of the models is provided in the section 'Modelling Contaminant Movement'.

RESULTS: FIELD SITES

Typical uncontaminated values of groundwater chemistry in the Chalk and Sandstone can be found in Table 2. *Cryptosporidium* oocysts were found in slurry at Chalk sites 1 and 2, and Sandstone sites 2, 3 and 5. Slurry from the lagoon at Sandstone site 5 was also found to contain *E.coli* O157.

Chalk sites

Observation of the core from Chalk site 1 showed visible slurry along fractures within the Chalk matrix, which is reflected in the chemical results. These demonstrated gross porewater contamination throughout the depth of the two profiles with highest concentrations occurring below 10 m. Bicarbonate was roughly 10 times baseline concentrations and potassium nearly 2 orders of magnitude greater than baseline (Table 3). Calcium concentrations were very low relative to baseline, nearly a factor of 10 lower for the deeper porewaters from both boreholes. DOC and ammonium concentrations were both very high, 2 and 3 orders of magnitude above typical baseline values. Microbiological data showed high total clostridia counts which demonstrate faecal contamination at 15 metres below ground level (mbgl) but the absence of *E.coli* and faecal enterococci suggests that this occurred some considerable time before sampling. The concentrations of clostridia were fairly similar between the two boreholes with the vertical borehole showing greatest contamination. Other pathogens such as *E.coli* O157, salmonella and *Cryptosporidium parvum* were absent.

Cores from Chalk site 2 also contained visible slurry along fracture planes, although to a lesser extent than Chalk site 1. This is reflected in the lower solute concentrations in the porewaters (Table 3). Clostridia were present throughout both boreholes but at lower levels than Chalk site 1 and again the pathogens *E.coli* O157 and *Cryptosporidium parvum* were absent.

Porewater concentrations for the borehole constructed through the centre of the turkey litter store, Chalk site 3, showed very high solute concentrations in the top part of the profile (Table 3). These are up to 50 times the baseline groundwater concentration for chloride (3000 mg l^{-1}) and even higher for ammonium (500 mg l^{-1}), potassium (10,000 mg l^{-1}) and dissolved organic carbon (3000 mg l^{-1}). However, concentrations declined rapidly with depth and were at baseline level at about 15 m. The top 8 porewater samples were highly coloured, ranging from a ‘crude oil’ black in the top 50 cm, through ‘whisky’ brown and a ‘pale straw’ yellow by about 5 m. Solute concentrations peaked at 3.5 m which may reflect the very slow movement of a contaminant front, travelling less than 5 metres in 20 years, due to the relatively impermeable nature of the turkey litter to recharging rainwater. Porewaters for the borehole constructed through the edge of the litter showed more variable solute concentrations suggesting the loading of litter at this point had been less consistent. Consequently nitrate-N and ammonium-N concentrations were much lower than in the other borehole (maxima of 70 mg l^{-1} and 25 mg l^{-1} respectively). Moisture contents were generally 5-10% higher than borehole 1 and may explain the large peak in nitrate concentration around 10 m. Contamination can move more rapidly through the unsaturated zone in the areas not always covered by a thick matting of litter. With the exception of the top 50 cm, where low levels of clostridia were isolated, none of the test micro-organisms was detected, supporting the chemical analysis by indicating very slow movement of the contaminant front.

Sandstone sites

During the drilling in the Permo-Triassic Sandstone a number of difficulties were encountered in the recovery of core material and also the subsequent extraction of interstitial waters. Sandstones are highly variable by their nature and the problems encountered included the material containing too much clay; the material being too soft; the material being too dry; and the material being interspersed with layers of gravel. Results of the porewater extractions that could be carried out are shown in Table 4.

Sandstone site 1 is predominantly mudstone and water yields were correspondingly low, typically around 2-

3% ranging from 0.3 to 7%. Due to the low recovered volumes, only a few samples have a complete elemental analysis. Both inclined and vertical profiles followed a similar trend with highest concentrations of chloride beneath the solid manure store. Nitrate concentrations were similar beneath both stores. Water from the farm borehole had a conductivity of 555 µS cm^{-1}, chloride concentration 38 mg l^{-1} and nitrate-N concentration 8.2 mg l^{-1}. Nitrate concentrations in the store boreholes were therefore roughly half those in the farm borehole. Limited ammonium data showed concentrations averaging 0.03 mg l^{-1} and 0.01 mg l^{-1} beneath the solid and liquid stores. No microbial contamination was found in any of the extracted cores. The inference of similar concentrations in each pair of boreholes is that leakage was occurring from the bottom and sides of both stores. The higher conductivity values in the vertical hole than in the inclined hole suggests leakage was occurring at a slightly greater rate from the sides of the solid manure store. This may have been due to some sealing of the store bottom, which has not occurred at the sides.

For the 'whole' profile of Sandstone site 2, concentrations of chloride and nitrate-N were roughly 3 times higher than the baseline chemical composition although concentrations in the profile below 10 m are lower. This implies that the lagoon has an influence over the chemistry of the immediate unsaturated zone although this is likely to be small at the catchment scale. It is likely that the comparatively small solids content of the liquid slurry store has not been able to form a very effective seal at the base of the lagoon. The lack of any ammonium suggested that the environment is strongly oxidising. Concentrations of chloride and nitrate-N in the porewaters obtained from beneath the solid slurry store are significantly lower than beneath the solid store and close to baseline suggesting little or no movement of slurry components from the store through the aquifer. Dissolved organic carbon concentrations are surprisingly high but may reflect the organic content of the underlying carboniferous rocks. Microbiological samples from cores taken beneath both stores on this site showed no evidence of any microbial contamination.

Sandstone site 3 is a short term store which is scraped clear every 2-3 days. Porewaters obtained from this site were a straw yellow colour with a strong odour. The degree of contamination increased throughout the drilled length of the borehole partly as a result of drilling at an angle of just 8° due to local obstructions, so the middle of the store was not crossed until the borehole was 12 m deep. For operational reasons, the borehole was not constructed beyond 18 m so the extent to which contamination had penetrated was hard to estimate. Below 10 m, chloride and ammonium concentrations were similar to levels found beneath the heavily contaminated Chalk sites 1 and 2. Conductivity and chloride concentration were an order of magnitude higher than baseline. The near-absence of nitrate suggests highly reducing conditions beneath and around the store and the dissolved organic carbon concentrations were considerably higher than at the other sites. Acidic conditions (pH <6) were present in contrast to the contaminated Chalk sites which were all basic (pH >8). Also in contrast to the Chalk sites concentrations of both iron and especially manganese were very high. In addition, concentrations of arsenic were found up to 1 mg l^{-1}. Surprisingly microbial examination of the core material revealed little by way of microorganisms. Faecal enterococci were found in the first sample (down to a depth of 2.5 m) and clostridia were found in limited numbers down to about 7 m, suggesting unsaturated Sandstone is acting as a very efficient filter.

Due to the very poor core recovery from Sandstone site 4 only a few samples could be taken and there was insufficient sample for any microbiological examination. The water table was reached at about 18 m and it is significant that porewaters had lower solute concentrations below this depth. The high concentrations of ammonium raise some concerns, although the concomitant lack of DOC suggests this may not be due to slurry infiltration.

Porewater profiles for Sandstone site 5 showed solute concentrations which are slightly elevated compared to baseline but not to any significant degree, especially for farmland. Microbial examination of the core material however, only revealed a very small number of clostridia present in the top 12 m with the indicator pathogens absent.

Gas samplers

A previous study under agricultural grassland (Kinniburgh *et al.* 1999) has shown that gas samplers can take up to 12 months to re-equilibrate with the unsaturated zone environment following installation. Data for Sandstone site 1 however showed little seasonal variation. Oxygen concentrations were consistently 9% lower than baseline data (Darling *et al.*1997) although carbon dioxide concentrations were roughly the same. Nitrous oxide (N_2O) concentrations were about an order of magnitude higher than baseline, and coupled with the elevated nitrogen to argon ratio (average of 84.46 (0.52) data suggest some biological activity and limited denitrification.

Chalk site 2 exhibited a radically different gas chemistry relative to baseline. The act of borehole construction and the inevitable introduction of atmospheric air had a significant impact on both oxygen and methane concentrations. However, carbon dioxide concentrations remained remarkably similar from one sampling to the next with a peak concentration of 23% at 17 mbgl. Concentrations of oxygen fell from 10% at 15 mbgl to <1% from the first (176 days after installation) to last sampling (569 days after installation). Concentrations of methane at depth increased by five orders of magnitude from the first sampling to the second (>10% methane), with the concentration of methane found at 17 mbgl of the same order of magnitude as that found in landfill sites. By the third round of sampling, the methane concentration had fallen to below 1%. High concentration of methane at depth indicate that considerable microbial activity was still on-going. Significantly, the ?^{13}C-CO_2 ratio did not change during the large change in methane concentrations. The high microbial activity is reflected in a high nitrogen/argon ratio which, for samplers deeper than 7 mbgl sampled after 428 and 569 days, averaged 90.5 (4.9. The maximum N_2O concentration occurred around 10 mbgl, although the peak in the nitrogen/argon ratio occurred around 15 mbgl, concurrent with a minimum of N_2O. At this point a large enrichment of the ^{15}N isotope is also found (Figure 1).

Implications of field site results

The self-sealing of unlined slurry and manure stores by solids present in the slurry is seen as a crucial step in minimising leakage and consequent groundwater contamination. It is important for unlined facilities that good practice is carried out during emptying so that any seal, once formed, is not broken. Where a seal has formed early on in the lifetime of a slurry store, limited leakage occurs and there is sufficient oxygen present in the unsaturated zone of the aquifer to allow the oxidation of ammonium to nitrate and the efficient oxidation of organic carbon to carbon dioxide. Where a store fails to seal or the seal is poor, the ammonium remains unoxidised and migrates in this form. Field data tend to suggest that stores do not form such good seals on the side walls and some seepage is able to occur through this route.

At Chalk site 2, although a good seal is believed to have occurred, subsurface environmental conditions are sufficiently reducing for denitrification to occur with the subsequent removal of a large component of the nitrate. The nitrate loading to groundwater is therefore considerably decreased although further detailed study would be required to more accurately determine denitrification rates. Where no seal or a poor seal has formed, such as Chalk site 1 and Sandstone site 3, conditions become more reducing, with high concentrations of organic carbon and ammonium persisting. Indeed, there is evidence to suggest that sulphate reduction is taking place at Chalk site 1 (Gooddy *et al.* 2000b). In the Chalk sites, the geochemical reactions taking place can often be buffered by the calcium carbonate based Chalk matrix. However, in Permo-Triassic Sandstones little calcium carbonate is present which can lead to a fall in pH as ammonium is oxidised to nitrate. This combined with a reducing environment can lead to the mobilisation of metals present in the Sandstone matrix.

The detection of clostridia in many of the microbiological results confirm the presence of reducing conditions beneath the slurry stores. At all sites the movement of contamination appears to be slow, which suggests that the risks of any pathogens present in the store manure entering the groundwater through matrix flow are small. However, the presence of fractures and the observation of slurry on fracture faces suggests a rapid route for otherwise short lived pathogens to reach groundwater, especially in the in the early years of lagoon operation or after refilling following emptying.

MODELLING CONTAMINANT MOVEMENT

Unsaturated zone modelling: estimates of fluxes through a slurry store

Fluxes through the unsaturated zone were estimated using the Richards' equation coupled to a water balance model to define both depth of water in the store and the flow through the bottom of the store. It was assumed that the store was designed to hold 6 months production of slurry at a daily rate of addition of 0.01 m d^{-1} and was therefore set to be 2 m deep.

The hydraulic properties were based on the description of the unmodified geological material given by Allen *et al.* (1997). Median values for the Permo-Triassic Sandstone were used, with a hydraulic conductivity of 0.56 m d^{-1} and a porosity of 26%. Values for the Chalk are more difficult to estimate, because of the observation that hydraulic conductivity measured in boreholes is at least an order of magnitude greater than that measured in the matrix. The median conductivity of the Chalk matrix is 6.3×10^{-4} m d^{-1}, so a value an order of magnitude greater (6.3×10^{-3} m d^{-1}) was used for the fracture system.

The hydraulic conductivity of the contaminated layers at the base of the store were more difficult to estimate. Studies by Owens (no date) and other workers (Barrington *et al.* 1987) demonstrated a reduction of hydraulic conductivity of the order of 94-98%.

In order to investigate the effect of sealing, four layered soil scenarios were created and are summarised in Table 5. One, two or three layers were used to represent the sealed layer. Their conductivities were one, two or three orders of magnitude smaller than that of the unsealed geological material. In addition, the model was used to estimate the possible magnitude of the macropore flow component in the Chalk (scenarios M1-M4)

The results showed that, for each of these scenarios, an equilibrium flux was established within 2 years. It was also clear that the major component of the flux was the daily addition of water to the store in the form of slurry, and any impact of rainfall and evaporation was secondary.

The model demonstrates the importance of the sealed layer. In the Permo-Triassic Sandstone:

1. Without the sealed layer (scenario P4) or with only a thin sealing layer (P3) the slurry store acts as a soak-away.
2. A sealing layer with a conductivity of 1% of the initial value decreases fluxes to no more than about 2-3 times the natural recharge (i.e. 450 mm yr^{-1} as opposed to about 200 mm yr^{-1}).
3. Only with a thin surface layer having a conductivity 3 orders of magnitude lower than the unsealed material (P1) did the flux become less than the natural recharge.

The pattern within the Chalk (scenarios C1 to C4) is very similar to that in the Sandstone, although numerically smaller. Without a sealing layer (Scenario C4), the movement across the store surface could even be in both directions, as summer evaporation induces upwards movement of water.

Mass balance model

The results from the mass balance model are summarised in Table 6. If the abstraction rate is large (>1000 m^3 d^{-1}), then the mass flow rate of a water soluble pollutant such as nitrate from the slurry store is a small proportion of that derived from rainfall recharge. Dilution is therefore high and the impact of the slurry store on the concentration at the well is negligible. However, the contribution of pollutant mass from the slurry store to the concentration at the well becomes more significant when the abstraction rate is small. If the proportion of volumetric flow from the slurry store is large with respect to rainfall recharge then dilution of the contaminants is low. This analysis suggested that the danger from contamination by soluble pollutants is only of concern at a small abstraction supply near the slurry store, such as a farm borehole, and this danger is exacerbated by low rates of rainfall recharge. However, it must be emphasised that this analysis is for a dissolved (non-particulate) contaminant that travels with the recharge water. Additionally, this analysis gives no measure of travel times and so cannot be used as a relevant indicator of bacterial contamination. Naturally, if the contaminant is highly toxic and has a low maximum admissible concentration in groundwater, even the small increases in concentration for the larger abstractions shown in Table 6 might be significant.

Numerical modelling

Following the mass balance work, some simple models were developed using a finite difference numerical groundwater flow model, MODFLOW (McDonald & Harbaugh 1988), to investigate the likelihood that a slurry store would be within the catchment area of a farm borehole. Using Chalk site 2 as an example, the model was set-up to produce groundwater gradients similar to those on the regional hydrogeological map. This was done by using values of recharge rate, hydraulic conductivity and river leakage within a typical range for a Chalk aquifer (Table 7). Once satisfactory gradients were obtained, an abstraction well was introduced to the model, and the capture zone of the well was determined using MODPATH (Pollock 1989). The capture zone for a well likely to be used for farm supply (10 m^3 d^{-1}) was shown to be very narrow, having a width of less than 10 m. As it would be very unlikely that a slurry store would be positioned within this 10 m wide zone it appears that the risk of groundwater contaminated by slurry reaching such a well is low.

This conclusion is based on modelling at one site. In regions with lower hydraulic gradients or lower transmissivities the width of the capture zone will be greater, thus increasing the possibility that the slurry store will be in the capture zone of the borehole. Thus it is important that such supplies are tested periodically if they are used for human consumption.

Travel times

The travel time of pollution from a slurry store to an abstraction point is important if pathogens are considered. The site based MODFLOW model can be used to give an indication of travel times within the aquifer if an effective porosity is known. The time of travel from a farm manure store to a nearby borehole is summarised in Table 8.

The assumptions used for these estimates are

1. Solute travels through the unsaturated zone at the rate of 1 m yr^{-1} (based on an average value for unsaturated flow in the Chalk of southern England, Wellings 1984).
2. Saturated flow in Chalk can be represented by a porous medium with a porosity of 1%.

These results clearly demonstrate that, for the likely distance from a livestock manure store to a farm supply borehole (<1 km), the time for the contaminants to pass through the unsaturated zone is far greater than the travel time in the saturated zone. This demonstrates the importance of characterising unsaturated zone processes for determining the impact of agricultural pollution on groundwater quality. Also, these calculations of the time taken to travel through the unsaturated/saturated zones means that, even if the use of existing unlined farm manure stores is discontinued, then there is a significant time (~10s years) before this affects water quality at nearby abstractions. Where a very shallow unsaturated zone exists the potential risk to groundwater is greater than a deep unsaturated zone since direct hydraulic connectivity between the base of the lagoon and the water table is more likely to be made. For pathogens that might have relatively short lifespans in the subsurface this could be of great significance, since transit times from store to well would be greatly reduced.

Impact on large abstractions of removing unlined slurry stores

Both Sandstone and Chalk public water supply abstractions show large short-term variations in measured nitrate concentrations (Chilton *et al.* 1999). These have proved to be very difficult to model. However, a regional numerical model combined with analytical transport modelling has been used to identify the long term trends and so predict the effects of management changes (Chilton *et al.* 1999). As an example, the effects of discontinuing the use of manure stores in the year 2000 for a Sandstone and a Chalk site are shown in Figures 2 and 3. These figures do not represent likely long term changes in groundwater nitrate concentrations on a national basis, but demonstrate trends for an abstraction borehole in the same catchment as a leaking slurry store. The results show concentrations still rise with the removal of slurry stores as residual contamination in the aquifer remains. There is a negligible effect on predicted nitrate concentrations (less than 0.1 mg l^{-1} after 20 years) due to the large dilution effects involved and in the case of the Chalk (Figure 3) the effect of discontinuing use is even smaller as a result of the dual porosity nature of the saturated Chalk aquifer.

Implications of modelling study

The results of these studies show that travel times within the aquifer system, from store to the groundwater table and then to an abstraction point are relatively long. Where a seal has been formed, transport from the store to the water table is at a maximum velocity of around 1 m yr^{-1}, which gives travel times of many years at most sites. Without the sealed layer, the slurry store can act as a soak-away as hydraulic connectivity is reached between the base of the store and the water table. This may also occur where the unsaturated zone is very shallow. Within the aquifer itself the travel times from the water table to an abstraction point obviously depend on the distance, but are generally measured in years rather than days. It is therefore important to characterise the thickness of the unsaturated zone and likely travel times of pollutants from a slurry store to the water table.

Consideration of the nitrate concentrations in the leachate from the stores leads to the conclusion that this poses little additional risk to the quality of abstracted water, unless the abstraction is small and is in the immediate vicinity of the store. However, the work has concentrated on consideration of nitrate, which is also present in the environment from many other agricultural sources. Other possible pollutants which behave in a different way, in particular micro-organisms such as *Cryptosporidium* parvum, have not been modelled. Such pollutants travel in different pathways to dissolved pollutants as they are often too large to access all the pore space. From the modelling work reported here it was not possible to identify their rates of movement without additional laboratory and field studies.

CONCLUSIONS

The field studies showed contamination of the unsaturated zone at two of the Chalk sites and provided evidence for slurry movement along fractures in the Chalk. Dark staining along fracture faces was observed to depths of at least 15 m below ground level. The age of the slurry on these fractures was not determined and so it is unclear as to whether or not this is an relict of a lagoons' initial filling after which the fractures became effectively sealed, or represents a continual source of raw slurry throughout the unsaturated zone and beyond. Little movement of solutes was observed in the Sandstone sites except for site 3 where the base of the store was regularly scraped clear. There is strong evidence for microbial reduction of organic carbon at the most contaminated Chalk sites.

Although some micro-organisms were detected in the unsaturated zone beneath many of the stores investigated, none of these were pathogens, even though pathogens were found to be present in the slurry lagoons themselves. This is an encouraging finding although it should be taken in the context of a small subsample of the total number of unlined slurry lagoons.

The results from both field studies and contaminant modelling suggest that in the majority of situations, unlined earth-based slurry stores pose little threat to potable groundwater drinking supplies. The store represents a relatively small point source of contamination in the very large water body of a groundwater catchment, hence there is a high potential for dilution. However, the potential for contamination of a farm borehole is much greater than that of a public drinking supply although risk of interception of pollution is lower. The siting of wells for drinking and other agricultural purposes should be up groundwater gradient from the lagoon source. Contaminant modelling has also shown that discontinuing use of an unlined farm manure store will make little difference to the increase in concentration of nitrate in a catchment over the short to medium term and may not palliate the relatively small pollution threat.

The travel time for a contaminant between the farm manure store and abstraction is likely to be controlled by the unsaturated zone. Where there is direct hydraulic connection between the lagoon base and the water table, contaminant travel times to reach groundwater and potential potable water supplies would be considerably reduced. This is of greatest significance for pathogens that are thought to be relatively short lived in the subsurface. It is therefore deduced that the highest risk category for an unlined farm manure store would be in an area where the aquifer has no drift cover and the water table is shallow. The Chalk is particularly vulnerable due to its fractured nature allowing rapid vertical flow.

This study has focused on the impacts of earth-banked slurry stores which are unlined and overlying the two principal aquifers in England and Wales, the Chalk and Permo-Triassic Sandstone. Stores thus situated are generally accepted as the farm manure facilities most likely to pose a threat to groundwater quality. Few resources have been directed at solid manure heaps and these are not governed by regulations in the same way as unlined slurry lagoons. It is felt that the risk to groundwater from solid heaps is minimal due to the relatively impermeable and high dry matter content of the manure, but further work is needed on this issue.

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