Assessing the effectiveness of Scotland's groundwater nitrate monitoring network

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Abstract

Many countries expend considerable resources collecting and reporting data from national groundwater quality monitoring networks to assess diffuse nitrate contamination, but the reliability of these data depends on the effectiveness of the network. Without a representative monitoring network of reliable monitoring points, there is a risk that groundwater management policies could be developed and implemented based on poor evidence. To help increase confidence in nitrate data, a robust, practical and repeatable methodology was developed to assess the effectiveness of groundwater nitrate monitoring networks, and applied to a network in Scotland. The method combined a rapid site assessment to identify local pollution pressures and the susceptibility of monitoring points to the impacts of these pressures, in order to judge their reliability for monitoring nitrate, with a wider characterisation of the network to identify which land uses and hydrogeological environments are being monitored. The analysis indicates that, with minor exceptions, Scotland's groundwater nitrate monitoring network broadly represents the diversity of conditions expected in Scotland.

Introduction

Effectively monitoring nitrate concentrations in groundwater is fundamental to both the European Nitrate Directive (Council Directive 91/676/EEC 1991) and the Water Framework Directive (Council Directive 2000/60/EC 2000). The principal aim of monitoring nitrate concentrations is the assessment of impacts on groundwater from nitrate derived from agricultural activity.

Most countries expend considerable resources collecting and reporting nitrate data from national groundwater quality monitoring networks. Careful data interpretation, and an awareness by policy makers of the uncertainty inherent in any environmental monitoring, will help to ensure effective policy decisions, but it is vital that the fundamental elements of the system – the individual monitoring points and the networks as a whole – are reliable and effective for the purpose of monitoring nitrate. Most national groundwater monitoring programmes depend heavily on existing groundwater abstraction points, over whose location and construction monitoring authorities have no control (Koreimann et al 1996). A monitoring network must be representative of the environment and pressures it is monitoring (WFD CIS 2007), and careful assessment and selection of monitoring points are needed to ensure a network of reliable groundwater monitoring points that is representative of national conditions. However, time and funding pressures can mean that the individual monitoring points in newly established or expanded monitoring networks are not subject to rigorous assessment to determine their reliability for purpose. In this paper we discuss a robust, practical and repeatable methodology devised to help assess the effectiveness of the Scottish national groundwater quality network for monitoring nitrate, and discuss the issues surrounding nitrate monitoring that are of wider relevance, beyond Scotland. The methodology was developed during a project commissioned by the Scottish Executive to improve confidence in the network, and to establish a baseline before any improvements were made. The work was carried out during the period February to July 2005. There were two parts to the assessment:

1. assessing the condition and status of each individual monitoring point for the purpose of nitrate monitoring; and
2. assessing the overall effectiveness of the Scottish network for monitoring nitrate, in terms of the number, type and distribution of monitoring points.

The Scottish groundwater monitoring network

Evolution of the network

A national groundwater quality monitoring network in Scotland was established in 2000, many years after most other European countries had monitoring systems in places (Fraters et al 2005). The network is maintained by the Scottish Environment Protection Agency (SEPA), and one of its main functions is to monitor nitrate concentrations.

Initially, in 2000, the network consisted of 150 monitoring points: all were pre-existing groundwater abstraction points, and mostly private water supplies. The network was designed to be objective and representative of Scotland's environment, and the monitoring points were spread over 39 biophysical classes based on aquifer permeability, soil leaching potential, and land use (Lilly et al 2003). The specific monitoring points were chosen by SEPA, but at the time the network was initiated, they were not audited to assess their condition (Lilly et al 2003).

The monitoring network has been subject to a number of alterations since its inception. In 2001, a review of twelve of the monitoring points led to six of these being identified as subject to local contamination and removed from the network (Ball and MacDonald 2001a). Further network development was done in tandem with the process of designating nitrate vulnerable zones (NVZs) in 2002. Areas delineated as NVZs are those associated with waters where nitrate concentrations exceed, or are likely to exceed, the level of 50 mg l^{-1} nitrate that is set in the Nitrate Directive (Council Directive 91/676/EEC 1991, Statutory Instrument 1996 No. 1564 (S.137) 1996.). During this process, 70 groundwater quality monitoring points were added to the network, all located in those agricultural areas where nitrate loading and leaching is high and where aquifers are typically vulnerable (Ball and MacDonald 2002). A further ten boreholes were drilled in 2003 specifically for use as monitoring points and located in areas assessed as being at risk of nitrate contamination, but where there were no pre-existing groundwater abstraction points that could be used as monitoring points. In 2004, monitoring points in the Nithsdale NVZ in southwest Scotland were reviewed and several additional points added to the network (MacDonald and Abesser 2004). In addition to these changes, some of the monitoring points have been removed from the network for reasons including changes in ownership, breakdown of equipment, or drying up of sources.

Data from the monitoring network was used to assist the delineation of NVZs in 2002. Approximately 14 % of Scotland's land area was designated as a NVZ, based on an assessment of groundwater vulnerability and the risk of nitrate contamination, as well as on existing data on groundwater nitrate concentrations, including data from the newly established monitoring network (Lilly et al 2001; Ball and MacDonald 2001b, Ball et al 2005).

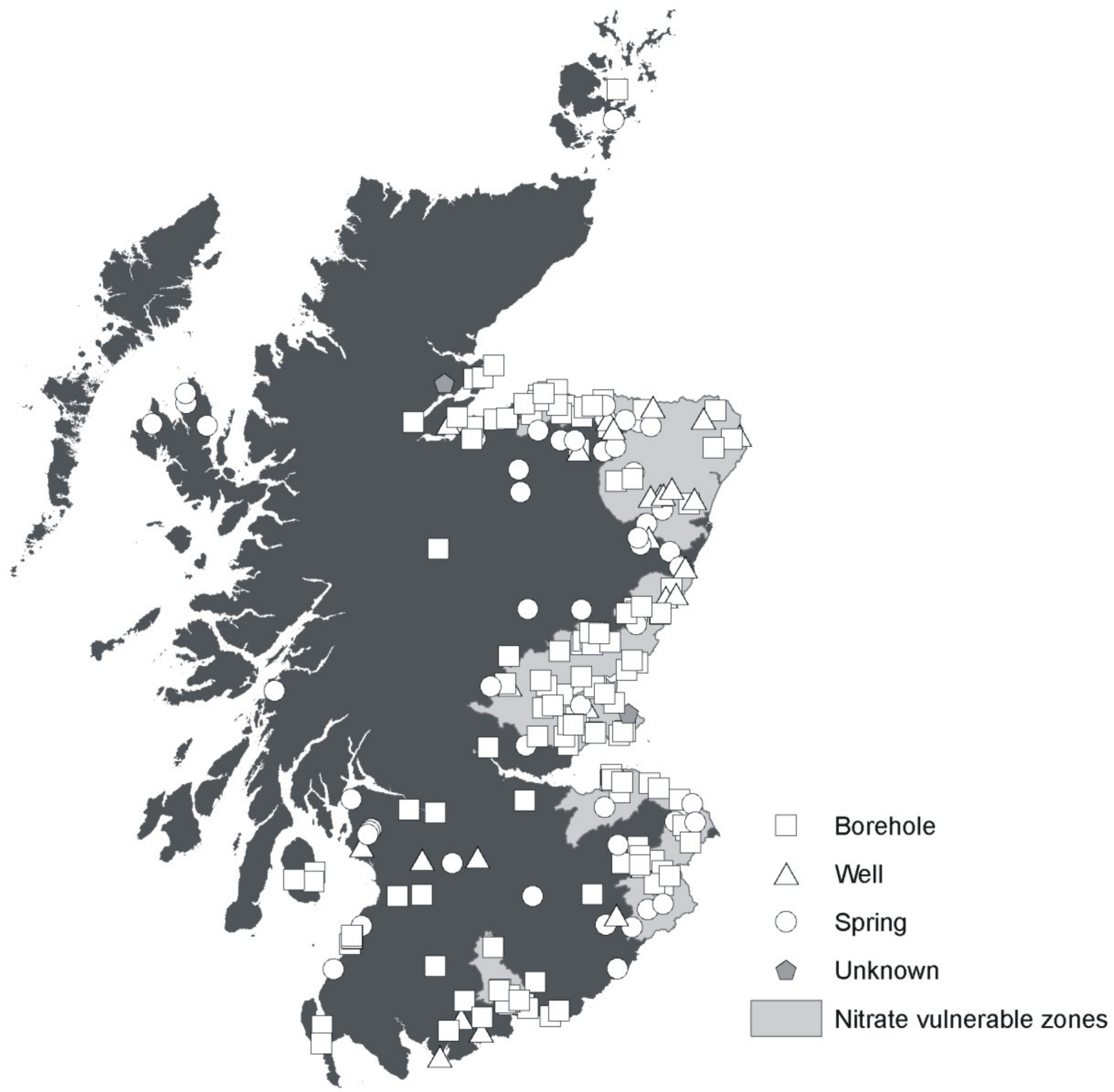
The current network

In 2005, the Scottish groundwater nitrate monitoring network comprised 219 monitoring points (Figure 1). This is a subset of a network of approximately 300 groundwater monitoring points used to monitor other parameters, such as sheep dip pesticide residues. The nitrate monitoring network was deliberately skewed towards the east of the country to reflect this area's higher population density, greater proportion of intensive agricultural land use, and greater usage of groundwater (Lilly et al, 2003), with 67% of the monitoring points in agricultural areas.

There are three types of groundwater abstraction points in the nitrate monitoring network (Figure 1). The majority of the 219 monitoring points (64%) are boreholes; 24% are springs; and

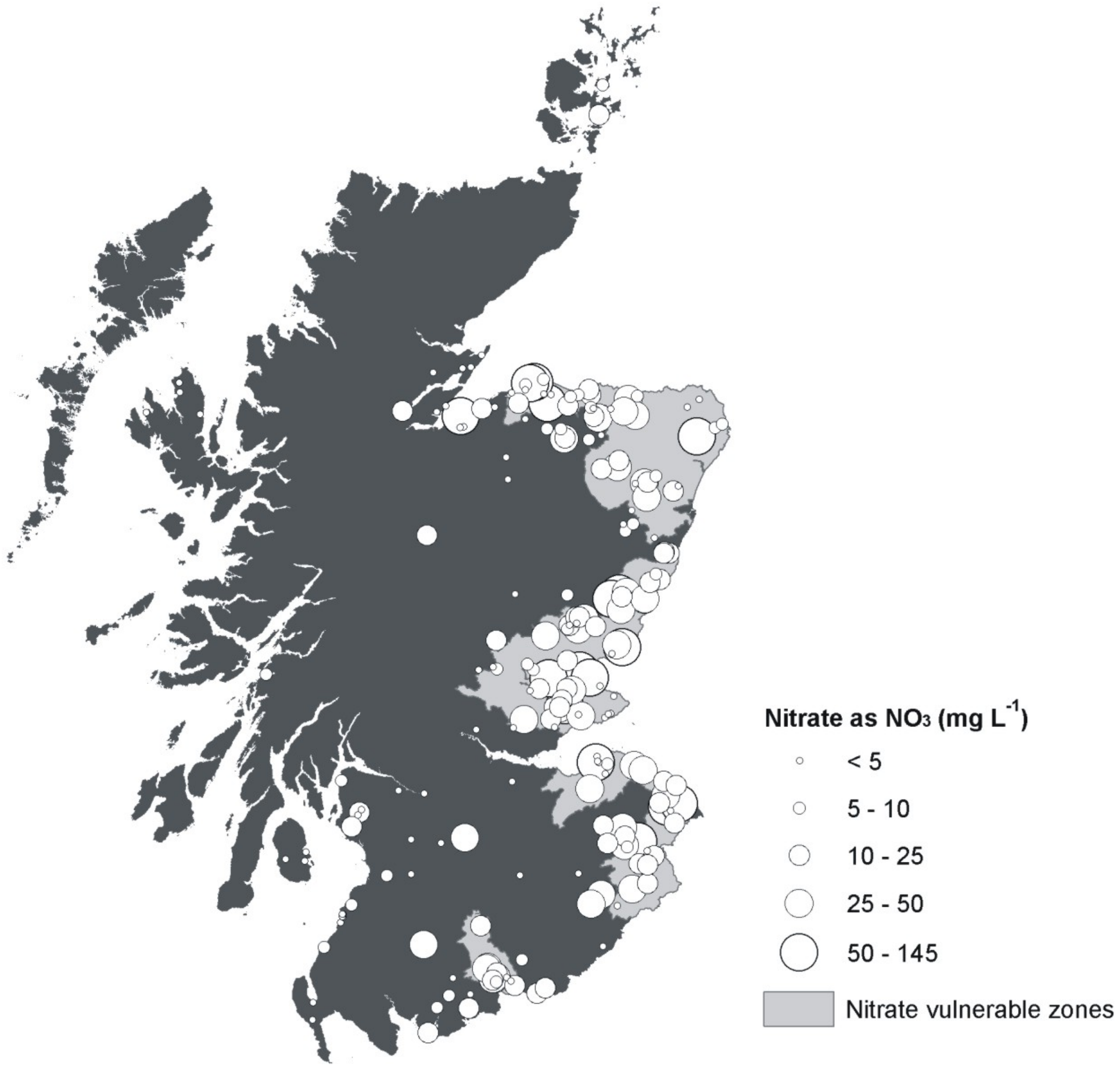
12% are wells. The monitoring points are sampled quarterly. Apart from the 70 sites added to the network in 2002, most of the monitoring points had not undergone a formal risk assessment prior to 2005, and detailed information for the points was not available.

There is a clear difference between nitrate concentrations measured in groundwater in the areas designated as NVZs and those that are not. Based on measurements made in summer 2003 (Figure 2), the mean nitrate (as NO_3) concentration in groundwaters within the NVZs is 25 mg-NO_3 l^{-1} and the median 17 mg-NO_3 l^{-1}; the mean concentration outside the NVZs is 9 mg-NO_3 l^{-1} and the median 4.4 mg-NO_3 l^{-1}.



Nitrate vulnerable zones as defined by the Scottish Executive (http://www.scotland.gov.uk/Topics/Agriculture/Environment/NVZintro/NVZmap1. Accessed 2 July 2007)

Figure 1 The Scottish groundwater nitrate monitoring network in 2005, showing monitoring point type and the extent of nitrate vulnerable zones



Nitrate vulnerable zones as defined by the Scottish Executive (http://www.scotland.gov.uk/Topics/Agriculture/Environment/NVZintro/NVZmap1. Accessed 2 July 2007)

Figure 2 Groundwater nitrate concentrations in summer 2003.

Assessing the reliability of individual monitoring points

Criteria for assessment

International criteria for assessing the suitability and reliability of individual groundwater monitoring points are only now being established (WFD CIS 2007). During the period when most European groundwater monitoring networks, including Scotland's, were being set up, no such agreed criteria existed, partly because a monitoring point can serve many different functions, depending on what is being measured. One of the main aims of the Scottish groundwater nitrate monitoring network is to measure nitrate from *diffuse* agricultural sources. Any assessment criteria must reflect this, and be able to identify sources that are at risk from direct contamination from surface water, or are dominated by indirect point source contamination, such as leakage from a slurry pit, both of which can mask the effects of diffuse contamination (Figure 3).

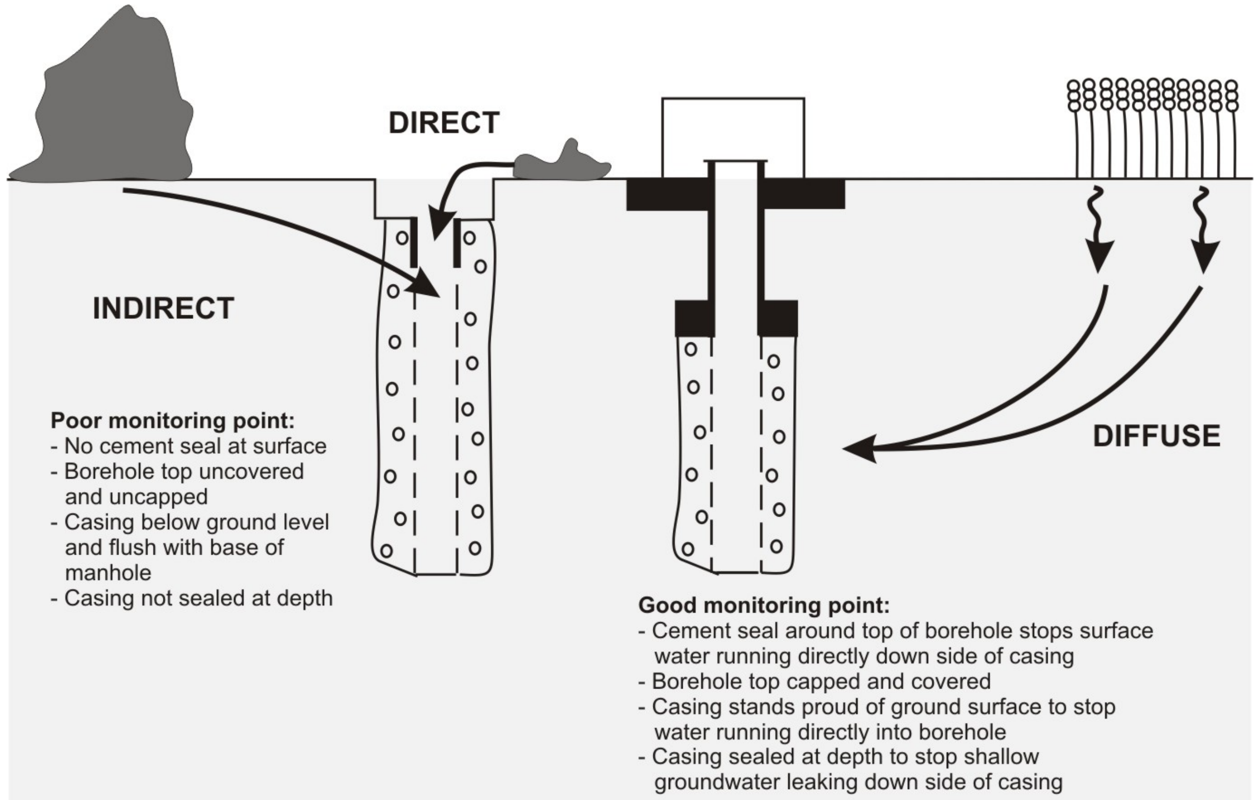


Figure 3 Illustration showing potential routes and sources of direct, indirect and diffuse contamination of boreholes.

Sources impacted by direct or indirect local contamination are not effective monitoring points in a network designed to identify the impacts of diffuse contamination. The criteria developed during this study were based around three key issues:

The condition of the monitoring point:

Is the monitoring point (borehole, spring or well) inadequately constructed or protected, so that it is vulnerable to:

- Direct contamination of groundwater, for example down the side of borehole casing?
- Indirect local contamination, for example, could shallow groundwater with a short flow path enter the source, contaminating the deeper groundwater that has a longer flow path?

Hazards around the monitoring point

- Are there any pollution hazards within 10 m of the monitoring point?
- Are there any pollution hazards between 10 and 50 m of the monitoring point or further upstream within its zone of influence?

Sampling procedure

- Is the existing sampling procedure adequate: for example, can a purged sample be easily and safely taken, or could the water chemistry change between groundwater source and sample point?
- Are arrangements with owners adequate: for example, is it particularly difficult to arrange to take a sample?

Figure 4 illustrates how these questions were used to judge the quality of individual monitoring points. The questions listed here guided the assessment of each monitoring point and ensured consistency across the network, but were not used rigidly: allowance was made for expert hydrogeological interpretation at each site. Fundamental to the process was a site assessment carried out by a hydrogeologist. Specific criteria were developed for springs, wells and boreholes, which are described in detail in MacDonald et al (2005a). The criteria developed were based on a variety of sources:

- Risk assessment for new sites for the Scottish groundwater monitoring network (Ball and MacDonald 2002);
- Cryptosporidium risk assessments (e.g. Morris & Foster 2000);
- Sanitary inspection methods (e.g. Howard 2002);
- Private water supply risk assessments for microbiological contamination (Jarman 1996, Lamb et al 1998, Reid et al 2001).

Where the monitoring point is a **spring,** the true source must be identified; there must be no significant point source hazards within 10 m and the source must be protected from direct contamination; the spring must have a reliable year-round flow; and the sampling procedures must be adequate, depending on the source characteristics. For example, if an assessment of a high yielding, constantly flowing spring shows that the water chemistry does not change between the spring source and a sampling point many hundreds of metres away, it would be acceptable to use the distant sampling point. Such a procedure may not be appropriate for a low yielding or seasonal spring.

The terms **well** and spring are often used interchangeably by the general public in Scotland, which can make assessment difficult. The source of the water in the well must therefore be clearly identified, including any inflow pipes which indicate the source may actually be a spring. Wells used as monitoring points must be in regular use; there must be no point source hazards within 10 m and the well must be protected from direct contamination. Point source hazards at greater distances can be acceptable if the pumping rate from the well is sufficient to dilute the effect of the point source. The sampling procedures must be adequate, depending on the well characteristics. For example, if a well is not in daily use and therefore not regularly flushed, it must be effectively purged to ensure that a fresh groundwater sample is collected: for a wide diameter, low-yielding well, this may mean pumping for an hour or longer.

The location of all **boreholes** used as monitoring points must be clearly identified, and the borehole depth and screened interval should be known, or estimated with a degree of confidence: for example, from drillers' logs, or information from the site owner. If there are any point source hazards within 10 m of a regularly pumped borehole, it must not be susceptible to *direct* contamination. If a borehole is not pumping, there should be no major point sources of contamination within 10 m even if the construction is excellent, to prevent results being dominated by a local point source hazard. If there are significant point source hazards within 10 m of a pumped borehole (50 m of a non-pumped borehole), it must not be susceptible to *indirect* contamination. That is, there must be reasonable confidence that the borehole casing has been sealed at depth to stop shallow groundwater leaking down the side of the casing: for example, information from drillers' logs, site owners, or knowledge of particular drillers' standard procedures. Sampling procedures must be adequate: there must be adequate purging and a sample taken before any water treatment or retention in a water storage tank.

The optimum monitoring frequency depends on issues including aquifer characteristics and the susceptibility of monitoring points to pollution pressures. New EU guidance recommends monitoring frequencies for different aquifer types that range from annually (in confined aquifers, or unconfined aquifers dominate by intergranular flow and/or where groundwater vulnerability is low) to quarterly (in fracture flow or karstic aquifers and/or where groundwater vulnerability is high) (WFD CIS 2007). These guidelines are aimed at general operational monitoring of groundwater body status, but are also applicable to nitrate monitoring. In Scotland, which is dominated by fracture flow aquifers and high groundwater vulnerability (Ó Dochartaigh et al 2005), quarterly monitoring is likely to be appropriate for the majority of monitoring points.

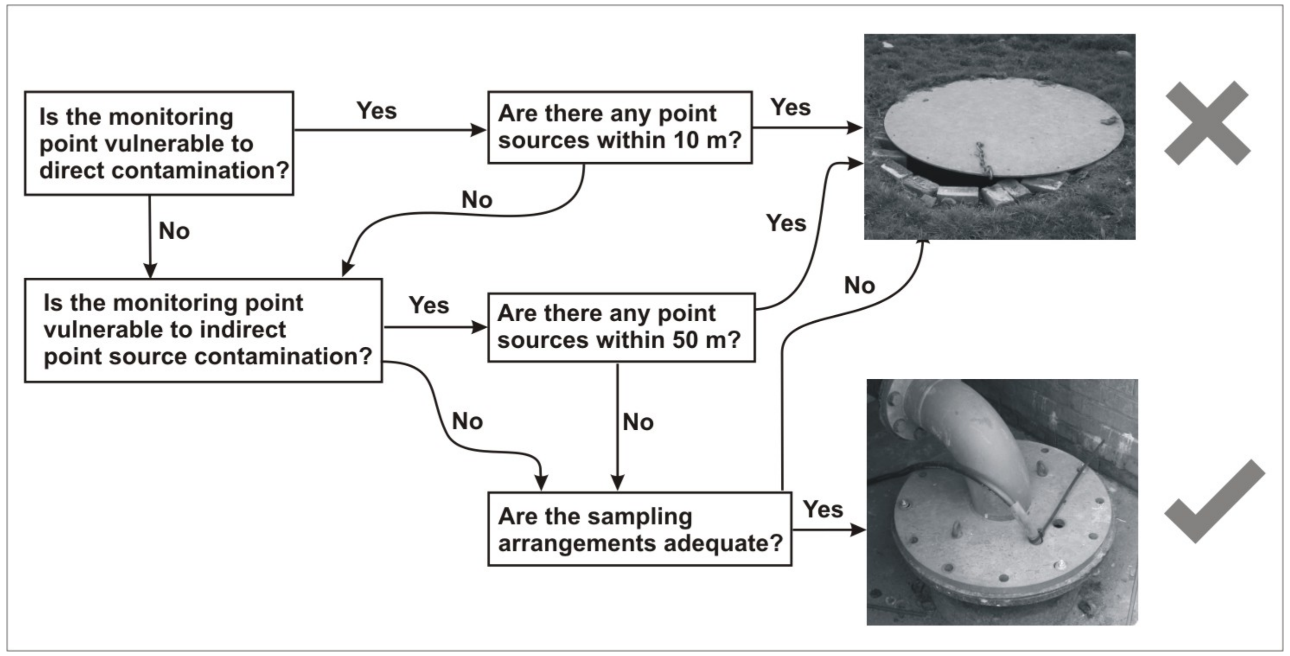


Figure 4 An outline of the methodology for assessing the reliability of individual monitoring points

Monitoring point assessment

A total of 152 monitoring points were individually assessed during the 2005 study. The remaining sites on the groundwater nitrate monitoring network had been assessed using a similar procedure in 2002, before being adopted onto the network. Within this paper, statistics are given both for the 152 newly assessed sites, and for the 219 monitoring points on the nitrate monitoring network as a whole.

The surveys at each of the monitoring points had to be rapid and non invasive. The project timetable was such that each monitoring point survey had to be completed within one hour. There was no possibility of carrying out engineering work to directly examine the condition of borehole casing, or to investigate buried spring sources.

An assessment proforma was developed to direct information gathering. The aim was to collect sufficient information to answer the questions posed in the assessment criteria above. The information collected was divided into several categories:

- *General*: confirming location details and assessing the setting of the monitoring point and what the water is used for;
- *Map check*: confirming that the zone of influence (see below) and thematic maps generated for the monitoring point (based on national datasets, see Table 1) are consistent with what can be seen on the ground;

- *Monitoring point condition*: assessing the condition of the monitoring point headworks, and what the abstraction or flow rate is;
- *Immediate surroundings*: assessing the condition of the land within 10 m and between 10 and 50 m of the monitoring point, and in particular whether there are point sources of pollution within these zones; and whether the monitoring point is susceptible to flooding;
- *Surrounding land use*: determining what the land use is within 50 to 200 m of the monitoring point, and further upstream within the zone of influence, and identifying any point sources of pollution within this area;
- *Upgrading*: noting any additional investigations or small engineering works that would help to improve confidence in the monitoring point.

Monitoring point assessment was prefaced by consultation with SEPA area hydrogeologists to obtain local information, including details of site owners and any particular access arrangements. Assessments were carried out by a BGS hydrogeologist, with occasional assistance from SEPA, at an average rate of four per day.

Results

The assessed monitoring points were reviewed according to the general criteria described above. Two issues in particular are important:

- The judgement made at the end of the assessment of an individual monitoring point is whether the monitoring point itself is reliable, not whether it is in a suitable location – this is dealt with later when the overall effectiveness of the network for monitoring nitrate is considered.
- Monitoring points judged to be unreliable must be both vulnerable to local contamination, *and* exposed to a source of contamination. Therefore, a poorly constructed groundwater source is still deemed acceptable if there is a low probability of local point sources contaminating the site.

The monitoring points were judged as falling in one of four groups (see also Figure 5):

- **Adequate for purpose and need no improvements:** This group comprises 40% of the 152 assessed monitoring points (28% of the whole network of 219 monitoring points).
- **Unreliable and should be considered for removal:** This group comprises 19% of the assessed monitoring points (13% of the whole network). The most common reasons for the unreliability of monitoring points were that the groundwater abstraction point was unused

or had a low flow, so that it was difficult or impossible to obtain a freshly pumped, purged sample; and that the monitoring point was poorly constructed or protected. For a small number of monitoring points there were insufficient data to properly characterise them – for example, the exact location of a spring or borehole was not known – and there was little opportunity to obtain the required information. Only one monitoring point failed because of direct contamination.

- **Requires improvement:** This group comprises 20% of the assessed monitoring points (14% of the whole network). The improvements required would generally entail small engineering works, such as installing or improving manhole covers; fencing off monitoring points to protect from livestock; or installing sample taps at the groundwater abstraction point or at least before any water storage or treatment. In some cases improvements were required to sampling protocols, particularly to ensure that monitoring points are effectively purged prior to sampling.
- **Requires further assessment:** This group comprises 20% of the assessed monitoring points (14% of the whole network). These were mainly springs, where further work was needed to identify the true spring source. For a small number of monitoring points, more information on the sampling protocol was required to ensure that representative samples can be taken. In a small number of cases, access to the monitoring point was not available during the assessment, so that a full assessment could not be made.

The detailed results of the survey highlight some important issues related to groundwater monitoring. The type of monitoring point is a strong control on the monitoring data collected. Shallow, large diameter wells are the least reliable type of monitoring point, largely due to the difficulty in obtaining a representative groundwater sample. Springs are the most difficult monitoring point type to assess. Boreholes tend to be the most reliable monitoring point type, but the lack of good records for most boreholes means there is often large uncertainty about what depth groundwater is being abstracted from – and therefore what aquifer is actually being monitored – and whether the borehole is adequately cased and sealed to protect it from inflows of contaminated surface water or shallow groundwater.

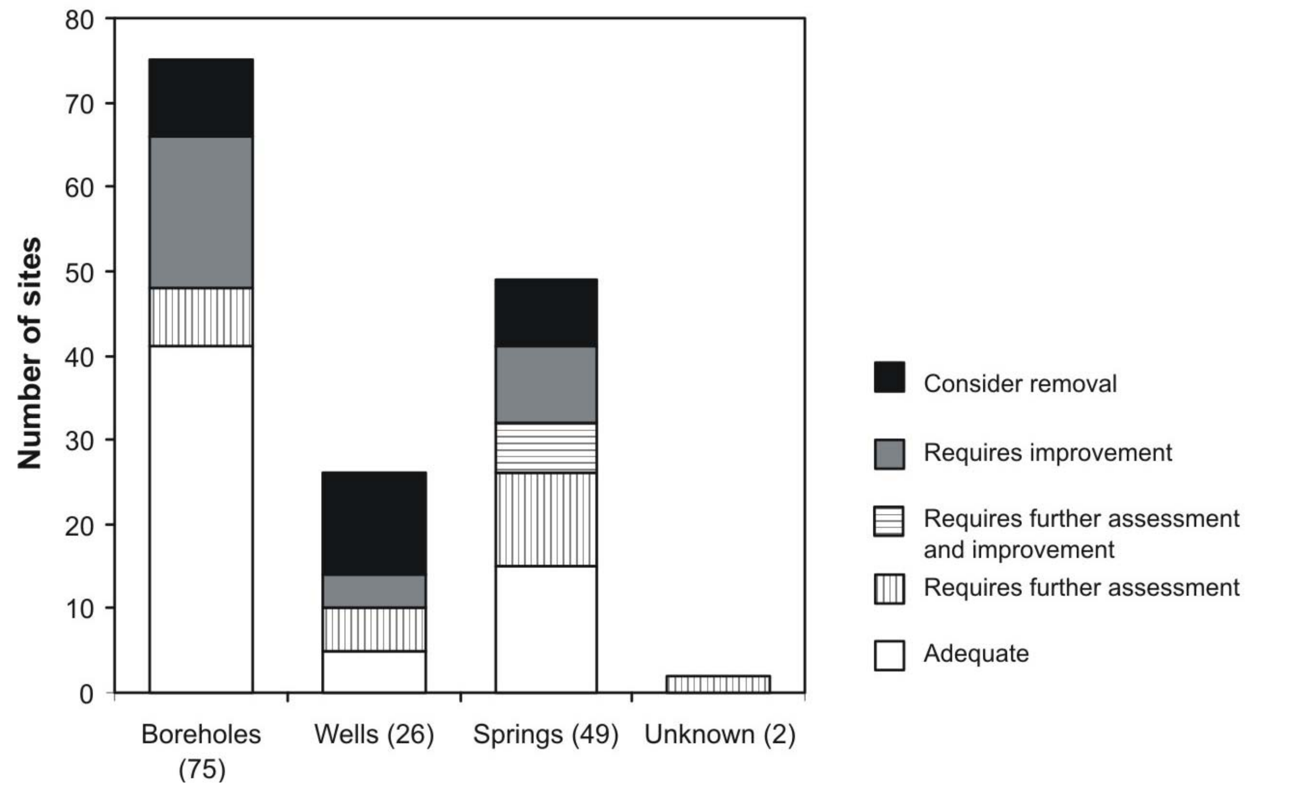


Figure 5 A summary of the assessment of 152 sites on the Scottish groundwater nitrate monitoring network

Assessing the effectiveness of the network as a whole

Just as important as the quality of individual monitoring points is whether they are located in the right place to assess the impact on groundwater of elevated nitrogen inputs to the environment. To judge the quality of the network as a whole, detailed and systematic information is required about each monitoring point. Good quality digital datasets of land use, geology, soils and topography are available for Scotland, and have enabled the recent development of derived products, including a national groundwater vulnerability map (Ó Dochartaigh et al 2005), aquifer productivity map (MacDonald et al 2005b) and a nitrate loading map (Lilly et al 2001, Ball et al 2005). Analysis of these digital datasets for each monitoring point was done in a GIS environment. Additionally, since each site had already been assessed, some of the information could be verified in the field.

Estimating the zone of influence

To characterise the land use and geology of each monitoring point, its catchment must first be determined. Various approaches to defining the catchment area can be used: for example, using the surface water catchment relating to the monitoring point; drawing arbitrary circles; or groundwater modelling to estimate capture zones. Clearly, in carrying out rapid assessments of over 219 sites in the network, detailed groundwater modelling was not a realistic option. Arbitrary circles were rejected as overly simplistic. A compromise approach was adopted to estimate a zone of influence for each monitoring point, using a standard shape of a shuttlecock: this approach was based on arbitrary shapes but which were scaled to reflect real hydrogeological attributes including pumping or flow rate, estimated recharge, groundwater head gradient, and uncertainty in flow paths. The shuttlecocks are described in more detail in Figure 6.

The advantages of the shuttlecock shape over an arbitrary circle are that is allows for uncertainty in flow path; the inner circle defines a minimum zone of influence regardless of shape; the shuttlecock can be easily scaled according to the pumping rate of the source and to the estimated recharge; and it can easily be applied to all sites in a short period of time, and incorporated into a GIS. There are limitations, in particular that the method assumes a groundwater gradient can be inferred across the site; it ignores the extent and nature of superficial deposits and/or confining layers; river-aquifer interaction is not accounted for; and nor is interference with other abstraction boreholes which may change the shape of the zones. However, the shuttlecock is generally suitable for Scotland, which is dominated by low productivity aquifers, groundwater flow is generally controlled by topography, and there are no karstic aquifers.

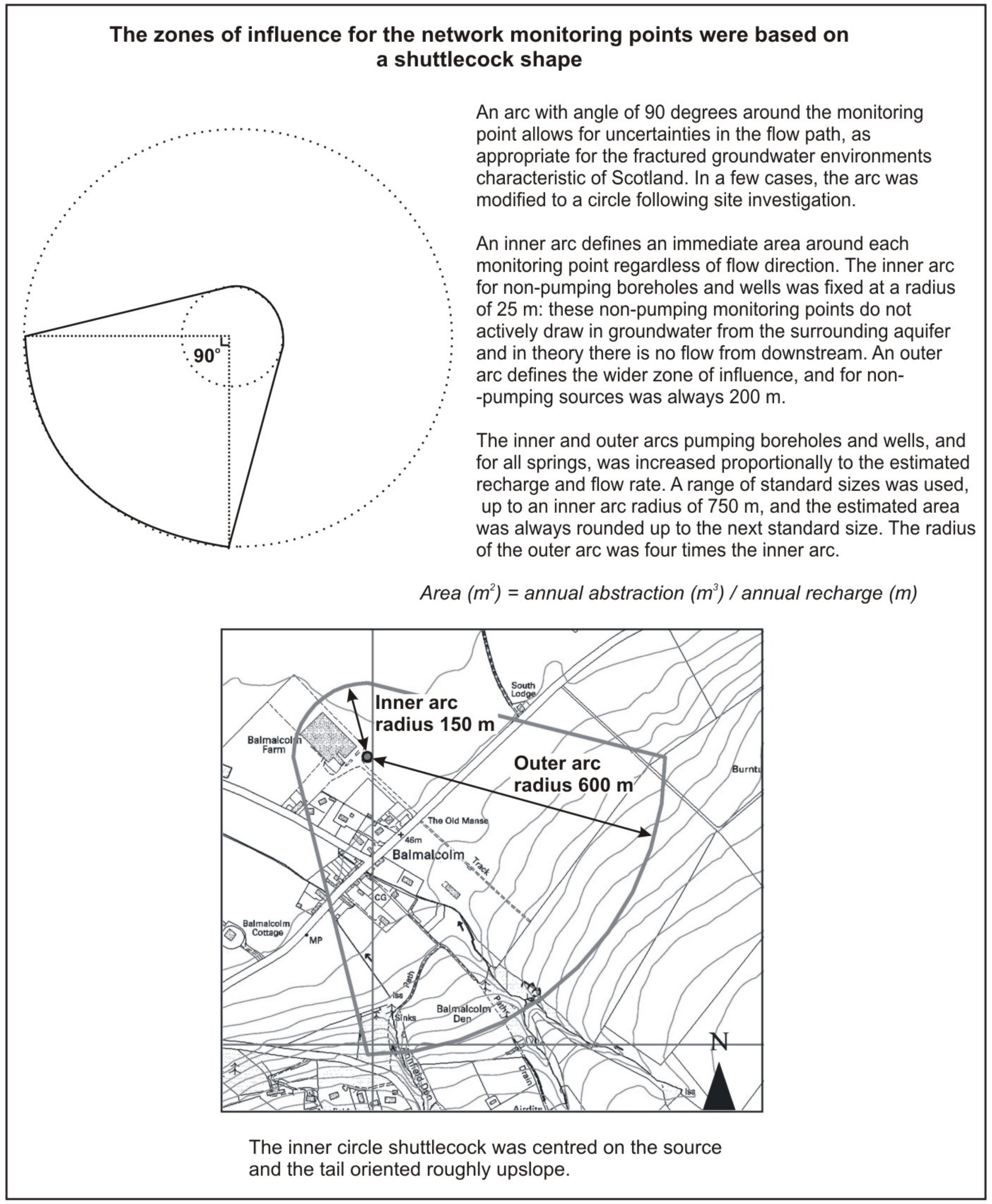


Figure 6 The methodology for determining the zones of influence for the monitoring network

Characterising the network

The parameters used for the assessment of the monitoring network are summarised in Table 1.

Summary statistics for each parameter were calculated for each zone of influence. For numerical datasets (such as standard percentage infiltration (SPI) or dairy intensity), a numerical average was calculated for the zone of influence. For datasets with descriptive categories (such as aquifers or land use), the monitoring point was attributed to the category comprising more than 60% of the land area in the zone of influence. If no one category comprised more than 60% of the zone of influence, the monitoring point was classed as 'mixed'. Four datasets are of particular interest:

Land use: categories have been chosen to separate activities that are likely to produce different levels of nitrate leaching. Agricultural practises are the most significant factor in controlling groundwater nitrate concentrations (Dunn et al 2004), and different categories of agricultural land use are defined. For example, pasture was separated into land used for dairy, pigs and poultry production, and that used for less intensive sheep or beef cattle production (improved grassland), as the former activities typically produce more nitrate loading, through the application of slurry to the ground, than the latter. Two combined land use categories are defined: mixed cultivated (where the combination of arable land and improved grassland together comprises more than 60% of the zone of influence) and mixed land use (where no single agricultural land use, woodland or semi-natural vegetation dominates the zone of influence, or where recreational or built up land dominate). The land use categories are shown in Figure 7 and Table 2.

Monitoring point type: whether from shallow or deep borehole, spring or well. In this survey, a shallow borehole was defined as less than 30 m; a borehole of intermediate depth as between 30 and 100 m, and a deep borehole as more than 100 m depth. This can affect the magnitude of measured nitrate, due both to the depth(s) from which groundwater is sampled and the effect of source construction and therefore the different ways in which sources are protected from contamination.

Aquifer productivity: identifies whether the source is sampling a high, moderate or low productivity aquifer, and the dominant groundwater flow type in that aquifer. Aquifer productivity also affects groundwater residence time and chemistry, which in turn are important controls on nitrate concentrations. Aquifers in Scotland range from shallow valley-fill sands and gravels, which are highly permeable and in which groundwater typically has a low residence time; to low permeability, fractured hard rocks, which may have similarly low residence times, but source groundwater from depths of up to 100 m; to highly productive, deep, sandstones with mixed intergranular and fracture flow, in which groundwater may be thousands of years old (MacDonald et al 2005b). Older groundwaters, recharged before the onset of intensive agriculture in the early to mid 20th century, typically have lower nitrate concentrations.

Groundwater vulnerability: describes the relative importance of the unsaturated zone in reducing or retarding downward movement of contaminants. A new assessment of groundwater vulnerability in Scotland was made by Ó Dochartaigh et al (2005), which uses groundwater vulnerability classes that range from very low to high. The assessment took into account the nature and thickness of the unsaturated zone, including any overlying deposits such as soils or Quaternary deposits. Where the superficial deposits and the unsaturated part of the bedrock aquifer have low permeability, the movement of any recharging water that has a high nitrate concentration is restricted, increasing the lag time between nitrate loading and its effect at the water table, and in some cases preventing such recharge reaching the water table.

These four datasets were used to characterise each monitoring point, and are fundamental to interpreting the nitrate measurements from the network. They allow the extrapolation of information from the network across the whole country, and can help identify groundwater sources where nitrate concentrations are not consistent with nitrogen inputs predicted from land use, soil and geological conditions, and which therefore require further, more detailed, investigation. The distribution of the monitoring points by the main descriptors land use, monitoring point type, aquifer productivity and groundwater vulnerability is shown in Figure 7. A summary of the relationships between land use, aquifer productivity and monitoring point type is presented in Table 2.

Table 1 National datasets used in assessment of the Scottish monitoring network

Dataset	Source	Notional Scale	Dataset	Source	Notional Scale
Topography for initial site location	OS[1]	1:50 000	Land use	MLURI	1:25 000
Topography for detailed site location	OS	1:10 000	Residual nitrate loading	MLURI	1:25 000
Bedrock geology	BGS[2]	1:50 000	HOST (Hydrology of Soil Types)	MLURI	1:250 000
Superficial geology	BGS	1:50 000	SLP (Soil Leaching Potential)	MLURI	1:250 000
Bedrock aquifer productivity	BGS	1:100 000	SPI (Standard Potential Infiltration)	MLURI	1:250 000
Superficial aquifer productivity	BGS	1:100 000	Soil drainage	MLURI	1:250 000
Groundwater vulnerability	BGS / MLURI[3]	1:100 000	Dairy intensity	MLURI	1:100 000
Depth to water table	BGS / MLURI	1:100 000			

Key: [1] OS – Ordnance Survey; [2] BGS – British Geological Survey; [3] MLURI – the Macaulay Institute

Discussion

Figure 7 and Table 2 indicate that the Scottish groundwater nitrate monitoring network in 2005 was diverse, encompassing a broad range of groundwater abstraction point types, land uses and aquifer types. This diversity means that the network covers the many different combinations of factors that can influence measured nitrate concentrations in groundwater, including agricultural practices and groundwater age.

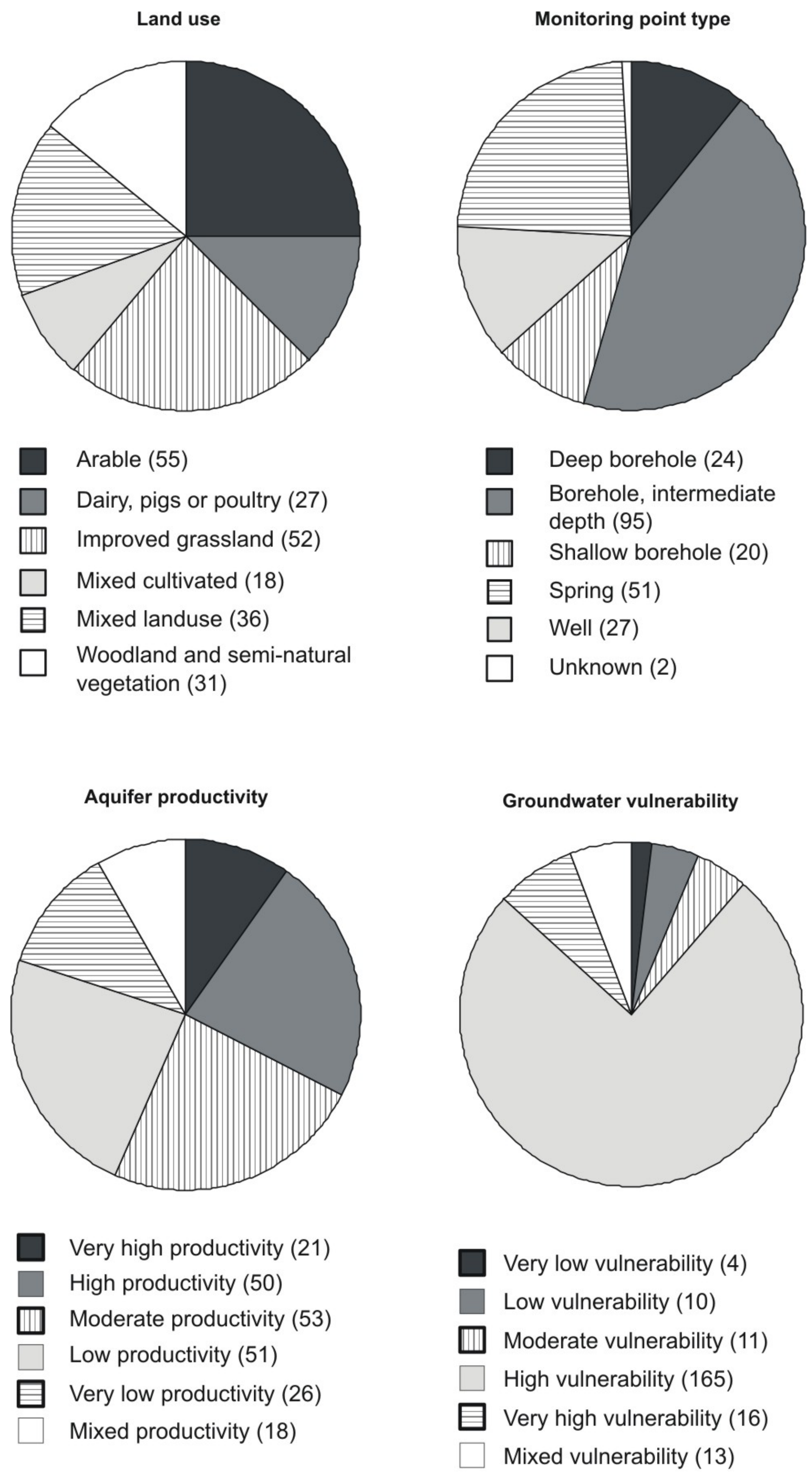
The network is focussed on areas of intensive agriculture, where nitrate loading is greatest (Dunn et al 2004), with 70% of the sites in arable or pasture areas. This weighting is justifiable because the network is designed to monitor nitrate pollution from diffuse sources. The balance of 30% of sites in non-agricultural areas acts as a control.

Boreholes are the most common monitoring point, and are particularly dominant in arable land, in areas with dairy, pigs and poultry production, and in high and moderate productivity aquifers. Boreholes make up less than half of the sources in areas of improved grassland and semi-natural or woodland areas, and in low productivity aquifers (Table 2). As discussed earlier, boreholes usually provide the most reliable groundwater samples so long as information is available about construction and the source is adequately purged. Springs are the most common source in woodland and areas of semi-natural vegetation, and within low and very low productivity aquifers. Springs and wells also comprise about half the sources in areas of improved pasture (Table 2).

The correlation of springs and boreholes with land use and aquifer type introduces a bias towards sampling younger groundwater in less intensively farmed areas and older groundwater (which is less likely to have high nitrate concentrations) in intensively farmed areas. However, due to funding restraints and to ensure the geographical distribution of reliable monitoring points needed to adequately represent the different land uses, it has been necessary to use existing groundwater abstraction points. Therefore, springs and boreholes with their inherent bias will have to continue to be used within the network. It is important that these inherent biases are understood and accounted for by ensuring that data are interpreted in their correct environmental context (Fraters et al 2005).

Large diameter wells were found to be the least reliable type of monitoring point in the individual site assessments. Table 2 indicates that wells are more evenly distributed across different land use types and aquifers, with no clear pattern. Removing all large diameter wells would not, therefore, significantly undermine the ability of the network to monitor different environments.

Most of the sites on the Scottish network (75%) are in areas of high groundwater vulnerability (Figure 7). This reflects the hydrogeology of Scotland, where the dominance of fracture flow in aquifers and the generally thin, moderately to highly permeable superficial deposits result in generally high groundwater vulnerability.



More information on parameters and categories is given in the text.

Figure 7 Distribution of monitoring points in the nitrate monitoring network.

Table 2 Summary of the Scottish groundwater nitrate monitoring network by land use, aquifer productivity and monitoring point type

Aquifer productivity [2]		Very high			High			Moderate				Low			Very low			Mixed		
Land use [1]	***Row totals***	**B**	**W**	**S**	**B**	**W**	**S**	**B**	**W**	**S**	**U**	**B**	**W**	**S**	**B**	**W**	**S**	**B**	**W**	**S**
Arable	**55**	3			18	1	1	18	1	2		2	3		3			3		
Dairy, pigs or poultry	**27**	7	1		6			3	1			3	1		2	1		2		
Improved grassland	**52**				3		2	7	3	1		8	4	12	3	2	1	2		4
Mixed cultivated	**18**	3			4			4			1	1	1	1		1		1	1	
Mixed land use	**36**	2			10	1		4		1	1	2	4	4	1		3	3		
Woodland and semi-natural vegetation	**31**	5			3		1	2		4				5		1	8	1		1
Column sub-totals		20	1	0	44	2	4	38	5	8	2	16	13	22	9	5	12	12	1	5
Column totals			**21**			**50**			**53**				**51**			**26**			**18**	
Total network	**219**																			

Notes

B – Borehole W – Well S – Spring U – Unknown (considerable uncertainty about the exact nature of the source)

[1] Calculated as the land use over >60% of the zone of influence

[2] The productivity of the bedrock aquifer. Almost all of the monitoring points are thought to abstract from bedrock aquifers.

An ideal network?

In order to test how representative Scotland's groundwater nitrate monitoring network is, the network as it was in 2005 was compared to a hypothetical idealised network. This idealised network was designed to have a wide geographic spread throughout Scotland based primarily on nitrate loading.

To ensure the geographic spread, Scotland was divided into seven regions based on the existing NVZs and other areas with high nitrate loading (Figure 8). These regions account for 97% of the residual nitrate in Scotland (the nitrate available for leaching after the crop has been harvested or stopped growing) (Dunn et al 2004, MacDonald et al 2005a). To ensure the network is monitoring the areas of high nitrate loading, it was proposed that 75% of the network is targeted at these areas. The remaining 25% would be used as a baseline against which the rest of the network is compared. This split is necessarily arbitrary, but the 3:1 ratio is a practical compromise.

The total residual nitrate for each of the seven designated regions was calculated from the annual Agricultural and Horticultural Census statistics collated by the Scottish Executive Rural Affairs Department and expressed as a percentage of the whole (Dunn et al 2004). For each region, land use was separated into arable land and improved grassland, and the total residual nitrogen calculated for each: this is an indicator of whether crops or livestock represent the greater nitrate loading in each area (Table 3).

The proportion of residual nitrate in each region can be directly related to the number of monitoring sites required: i.e., the regions with the greatest residual nitrate should have the most monitoring sites. Two examples of an idealised network have been used for illustration (Table 3). The first is the same size as the current Scottish network (219 sites) and the second is 50% larger, with 329 sites (Table 3), which is the size of the extended network proposed by SEPA. The number monitoring points in the existing network is also shown for comparison. The expanded nitrate monitoring network proposed here would be different from the complete network in 2005 of approximately 300 groundwater monitoring points across Scotland, because most of the approximately 80 points currently in the network but not monitored for nitrate are used for monitoring sheep dip pesticide residues in areas of low nitrate loading.

The results of this analysis indicate that the overall spread of monitoring points in the 2005 monitoring network was generally good, covering most of the nitrate-pressured areas in Scotland. There were, however, several gaps: for example improved grasslands in the Midland Valley and Ayrshire, and arable areas of Aberdeenshire, were under represented. Mid and East

Lothian and the Borders were over-represented in the network of 219 sites, particularly for areas under arable cropping.

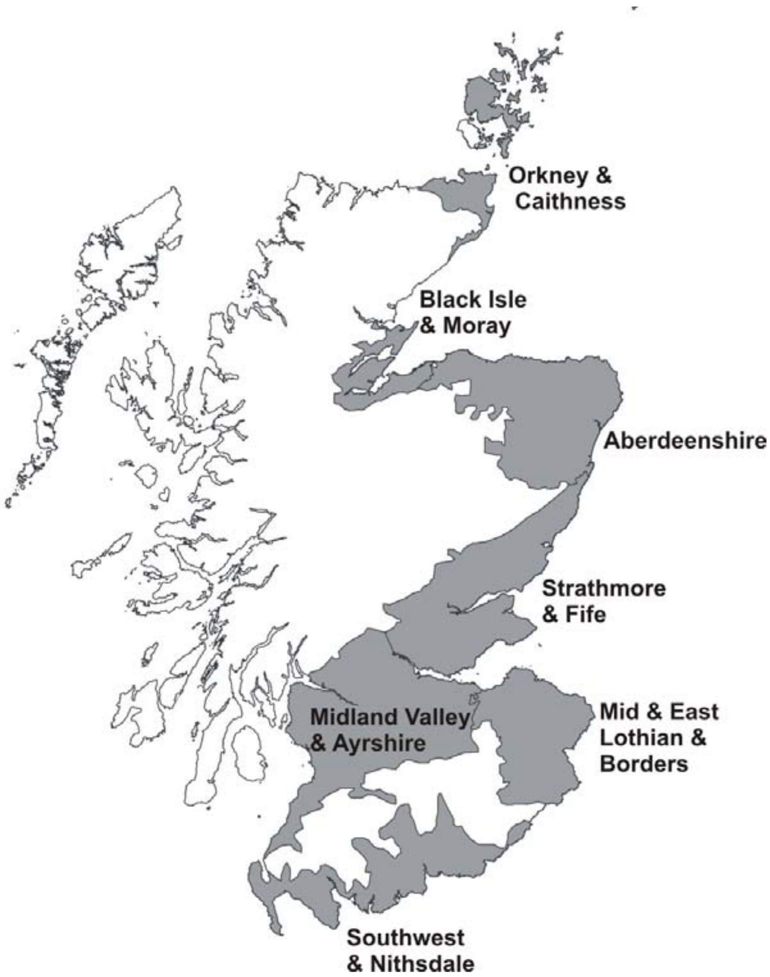


Figure 8 The seven regions used as a basis for estimating the distribution of an ideal groundwater nitrate monitoring network

As discussed earlier, it is also important that the network reflects the variability in geology, soil types and hydrogeology across the country. Further analysis was undertaken to divide the seven regions into different aquifer productivity and soil types. However, the number of parameters means that this quickly became statistically unmanageable. Pragmatically, it is likely to be adequate to ensure that variability in hydrogeological and soil conditions should be represented across the country in the network, but not necessarily within each of the seven regions. Because areas of dairy, pigs and poultry farming have been shown to be the main predictor of nitrate concentration in groundwater, monitoring points within improved grassland that supports these land use activities should be biased towards these areas (MacDonald et al 2005a). The characteristics of the idealised expanded network described here could be used to guide the expansion of the Scottish network as proposed by SEPA.

Table 3 Comparison of the current Scottish groundwater monitoring network against an ideal network, based on the distribution of residual nitrate in Scotland.

			Number of monitoring sites		
REGION	**Land use**	**% of Scottish residual nitrate**	**Network 2005**	**Example 1**	**Example 2**
Orkney & Caithness	Arable	0.0	0	0	0
	Improved Grassland	2.7	2	4	7
Black Isle & Moray	Arable	3.0	4	5	7
	Improved Grassland	0.7	3	1	2
Aberdeenshire	Arable	20.2	18	33	51
	Improved Grassland	3.9	13	6	10
Strathmore & Fife	Arable	24.9	37	41	63
	Improved Grassland	2.0	5	3	5
Mid & East Lothian & the Borders	Arable	9.5	28	16	24
	Improved Grassland	4.1	10	7	10
Southwest & Nithsdale	Arable	1.3	4	2	3
	Improved Grassland	9.3	15	15	24
Midland Valley and Ayrshire	Arable	3.1	2	5	8
	Improved Grassland	11.9	10	20	30
	Total	96.7%	151 of 219	159 of 219	244 of 329

Note: Example 1 is based on a network of 219 monitoring points (the size of the current Scottish network), but with 75% of sites in high nitrate areas.

Example 2 is based on 329 monitoring points (an increase of 50% over the current network), with 75% of sites in high nitrate areas.

Conclusions

An effective groundwater nitrate monitoring network needs to maintain a balance between the availability of reliable monitoring points and the need to reflect the diversity of national hydrogeological conditions and nitrate loading. A pragmatic approach must be taken to any system devised to reflect diversity. While the only way to achieve a 'perfect' monitoring network is to create a purpose-built network of newly drilled, carefully controlled and regularly pumped boreholes, this is currently impractical and unrealistic given the funding constraints that face all environmental regulators. The most constructive alternative is to improve confidence in the existing network, and in the data gathered from it, by collecting and interpreting additional information on the monitoring points and sampling procedures, as described in this paper.

1. The method described here combines a rapid site assessment to identify the susceptibility of individual monitoring points and the presence of local pollution pressures, with a wider characterisation of the network to identify which environments are being measured.
2. The approach is robust, practical, and repeatable. With only minor modifications, such as contending with the different availability of datasets, this approach could be effectively applied to monitoring networks in other countries.
3. New EU guidance recommends that monitoring networks and their operation should be reviewed regularly, at least once every six years, to ensure their continuing effectiveness and to optimise their performance (WFD CIS 2007), and the approach described here could be adapted for this purpose.
4. For most of the Scottish monitoring points, there is no evidence that they are being affected by direct contamination or point sources. However, approximately 13% of the monitoring sites are at risk of contamination and should be replaced. For a number of individual sources, some easily-made improvements to individual sources are needed in order to quickly improve data reliability.
5. Large diameter wells are the least reliable monitoring points. Springs and boreholes are biased to different land uses and aquifer types (boreholes to arable areas and more productive aquifers; springs to semi-natural land use and less productive aquifers). This bias should be taken into consideration when interpreting data, since boreholes often target older groundwater, or water subject to denitrification in confined or chemically-reducing aquifers (MacDonald et al 2003).

6. The Scottish groundwater nitrate monitoring network generally represents the diversity of land use and groundwater abstraction point types across Scotland. Since much of Scotland's agricultural activity is found in conjunction with the more productive aquifers, there are clear correlations in the network between monitoring point types, land use and aquifer.
7. The current geographic distribution of the network compares well with a hypothetical network based on nitrate loading and land use. There are several exceptions: improved grassland areas of the Midland Valley and Ayrshire, and arable areas of Aberdeenshire, are under represented; and Mid and East Lothian and the Borders are over-represented
8. The results from this survey are being used by SEPA to improve the Scottish groundwater nitrate monitoring network. Measures are also being put in place to help actively interpret the monitoring data, so that the environmental context of nitrate monitoring is taken into account.

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