EA-NGWCLC (Box 1)

The Development and Verification of Methodologies for Defining Groundwater Nitrate Vulnerable Zones

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National Groundwater and Contaminated Land Centre Project NC/7079NVZ/UEA

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Contents

Preface

This report summarises research undertaken in a series of stages over a period of nearly two years. For convenience the report is divided into four main parts. The first part introduces the research context and describes several of the main data sources used. Part II describes the initial generation of groundwater vulnerability classifications and the work undertaken to evaluate the different approaches using data on nitrate concentrations in boreholes. In Part III some refinements to the initial vulnerability classification methods are presented, followed again by verification analyses using details of nitrate concentrations in boreholes. This section also includes a consideration of the extent to which groundwater nitrate levels vary by borehole depth as well as the vulnerability of the site. The final part of the report presents a methodology for the preliminary definition of groundwater nitrate vulnerability zones using details from the best of the vulnerability classifications and interpolated nitrate levels.

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1. Introduction

Groundwater provides over 30% of the drinking water in England and Wales and is an important source for many rivers. Pollution of groundwater from diffuse sources, such as agriculture, may therefore pose risks to human health and the environment. In order to combat this threat, groundwater sources are currently protected from surface contamination by a series of zones within which land use is controlled. One example is Nitrate Vulnerable Zones (NVZs) where agricultural practices are controlled and farmers must ensure that nitrate applications do not exceed the crop requirements. There are also restrictions on the times of the year that fertilisers can be applied, rules on how they should be spread, and regulations on the storage of farm slurry (DETR & MAFF, 1998). All these measures are designed to minimise nitrate migration to groundwater and by their nature also protect surface water.

The current UK practice for defining groundwater Nitrate Vulnerable Zones (NVZs) is based on the modelling of capture zones around public water supply boreholes (Environment Agency, 1998). In comparison with the EU Nitrate Directive (91/676/EEC), this definition is restricted in that it does not protect all groundwater from the effects of nitrate leaching from the soil zone. Given the concerns raised by the European Commission, a programme of research was commissioned to develop and validate new methodologies for NVZ definition.

This report is part of the wider research programme and describes:

- The initial development of six models representing the vulnerability of groundwater to nitrate pollution.
- The translation of these models into digital maps stored within a Geographical Information System (GIS) that depict the relative vulnerability of areas.
- The integration of predicted groundwater nitrate levels derived from the Environment Agency borehole database with the vulnerability classifications.
- The statistical analysis undertaken to assess the ability of the models to identify geographical areas with distinctively different groundwater nitrate levels.
- The refinement of the initial vulnerability classifications to produce further model variants and the statistical analyses carried out to validate these outcomes against predicted groundwater nitrate levels.
- The assessment of variations in predicted groundwater nitrate levels in relation to both the best vulnerability classification and the sampling depth in boreholes.
- The development of a methodology for a revised NVZ definition using details from the best vulnerability classification and interpolated nitrate levels.

2. Modelling Vulnerability to Nitrate Pollution

The vulnerability of groundwater to diffuse pollution sources was modelled as being influenced by four main factors:

1. Surface leaching - the quantity and quality of water leaving the root zone of a piece of land.
2. Soil characteristics - which may attenuate the pollution or lead to horizontal water movement.

3. Drift cover - low permeability material that may impede the movement of water to the underlying aquifer.
4. Aquifer type - distinguishing between highly permeable and/or fractured aquifers, and those that have a negligible permeability.

Similar variables have been used in a number of previous groundwater vulnerability studies (e.g. Robins *et al.*, 1994; Merchant, 1994; Hiscock *et al.*, 1995; Osborn and Cook, 1997). The research discussed in this report did not consider groundwater flow because it was not practical to incorporate such information in a national scale assessment.

Following discussions with the Environment Agency, three contrasting models of nitrate vulnerability were investigated. All of these incorporated the four elements mentioned above; leaching, soil, drift and aquifer data. The particular form of the data for these elements differed, however, so that in the initial research there were six vulnerability models grouped into the three main types listed below.

- *Intrinsic vulnerability* models (1 & 2) representing the vulnerability to surface-derived contamination of any area of land.
- *Specific vulnerability* models (3 & 4) which included a nitrate leaching model and a uniform loading of nitrate across England and Wales.
- *Risk models* (5 & 6) which incorporated actual land use data for England and Wales to more precisely model the amount of nitrate leaching to groundwater.

Given the incorporation of data on land use and a nitrate-leaching model, it was anticipated that one of the *risk* models would be the best predictor of groundwater nitrate concentrations. The other models were examined to assess the extent to which a simpler approach could be effective, particularly to determine whether information on current land use was a prerequisite for identifying areas vulnerable to groundwater pollution.

3. Data Sources

3.1 The Initial Six Models

Table 1 summarises the components of the six models. The nature of the input data layers is described in more detail below, with further discussion of the model characteristics in Section 4.2.

Table 1: Component data layers in the six models.

	Intrinsic vulnerability		Specific vulnerability		Risk	
Layer	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
Leaching	ADAS2	ADAS2	ADAS5	ADAS5	ADAS4	ADAS4
Soil	SOIL1	SOIL2	SOIL3	SOIL3	SOIL3	SOIL3
Drift	LKDRIFT	LKDRIFT	LKDRIFT	LKDRIFT	LKDRIFT	LKDRIFT
Aquifer	GVQ	BGS	GVQ	BGS	GVQ	BGS

Leaching Layers

ADAS2: Simulated mean annual soil drainage from all land (mm).

ADAS4: Simulated mean nitrate-nitrogen concentrations in land drainage (mg/l NO_3) using current land use.

ADAS5: Simulated mean nitrate-nitrogen concentrations in land drainage (mg/l NO_3) assuming 100 kg N/ha applied to all land.

Soil Layers

SOIL1: This layer contains the seven soil categories present on the Environment Agency groundwater vulnerability maps.

SOIL2: SOIL1 reclassified to divide the leaching potential of the soil into high, intermediate and low.

SOIL3 SOIL2 reclassified to simplify information about the soil's ability to attenuate. Consists of two classes namely HI [high + intermediate] and L [low].

Low Permeability (K) Drift Layer

LKDRIFT: Low permeability drift taken from the Environment Agency map of drift cover.

Aquifer Layers

GVQ: The aquifer classification from the Environment Agency groundwater vulnerability maps. It consists of three classes namely major, minor and non-aquifer.

BGS: The British Geological Survey aquifer response time map.

3.2 Aquifer Layers

Two aquifer classifications were investigated. The first, the GVQ layer, was derived from the Environment Agency's Groundwater Vulnerability Maps and differentiates geological formations into major, minor or non-aquifers (Robins *et al.*, 1994; National Rivers Authority, 1995). These classes are defined in Table 2.

The second aquifer classification was produced by the British Geological Survey as part of the wider nitrate vulnerability research programme. It combines information about dominant flow mechanisms with typical transmissivity values and is based on the National Aquifer Vulnerability Matrix (see Table 3). The resulting BGS aquifer response time map classifies geological formations as having either a fast, medium or slow response (in the case of an aquifer) or as a non-aquifer.

Table 2: A description of the aquifer classifications in the GVQ layer.

Major Aquifer	These are highly permeable formations usually with a known or probable presence of significant fracturing. They may be highly productive and able to support large abstractions for public supply or other purposes.
Minor Aquifer	These can be fractured or potentially fractured rocks, which do not have a high primary permeability, or other formations of variable permeability including unconsolidated deposits. Although these aquifers will seldom produce large quantities of water for abstraction they are important both for local supplies and in supplying base flow to rivers. Major aquifers may occur beneath minor aquifers but the underlying major aquifer is only shown where the overlying minor aquifer is a drift deposit.
Non Aquifer	Formations which are generally regarded as containing insignificant quantities of groundwater form this third group. However, groundwater flow through such rocks, although imperceptible, does take place and needs to be considered in assessing the risk associated with persistent pollutants. Some non-aquifers can yield water in sufficient quantities for domestic use and provide base flow to rivers. Major or minor aquifers may occur beneath non-aquifers.

Table 3: The BGS National Aquifer Vulnerability Matrix used to assess the relative response rate of aquifers.

		Transmissivity (Kb)		
Dominant Flow Mechanism		**High**	**Medium**	**Low**
Intergranular / Dual Porosity, Intergranular Predominates		Fast	Moderate	Slow
Fracture / Dual Porosity Fractures Predominate		Fast		
Multi-Layered	**Intergranular**	Fast	Moderate	Slow
	Fracture	Fast		
Non Aquifer with Minor Thin Productive Horizons	**Intergranular**	Fast	Moderate	Slow
	Fracture	Fast		
Non Aquifer		Non Aquifer	Non Aquifer	Non Aquifer

Notes: Transmissivity (Kb) is the product of the aquifer permeability (K) and aquifer thickness (b). A 'fast' recharge in an unconfined aquifer corresponds to a time period of days or weeks, a 'moderate' time to months or years, and a 'slow' response to decades or centuries. © NERC, 1999.

Comparing the two approaches, the BGS aquifer matrix classifies some geological units as non-aquifers with minor productive horizons (and hence with a response time), whereas the GVQ layer shows the same geological units as simply a non-aquifer. Such differences are particularly noticeable in parts of Cumbria, Northumbria and Wales.

3.3 Low Permeability Drift Layer

This layer (LKDRIFT) depicts the presence or absence of low permeability drift cover that may protect the aquifer from pollution. It was derived from the Environment Agency Groundwater Vulnerability Maps. However, the data only indicate the presence or absence of low permeability drift and do not describe the thickness or attenuation properties of the deposit.

Due to uncertainties regarding the low permeability drift layer, it was decided to treat the impact of drift cover in two different ways. As a consequence, there were two variants for each of the six models. This is discussed in more detail in Section 4.3.

3.4 Soil Layers

All of the soil information was derived from the Environment Agency Groundwater Vulnerability Maps. Three different layers (SOIL1, 2 & 3) were produced. Only one of these three was used in any particular model.

3.4.1 SOIL1

This layer utilised all the soil classes on the Environment Agency Groundwater Vulnerability Maps. A description of each soil class is presented in Table 4.

Table 4: Description of SOIL1 leaching classes.

Soils of high leaching potential (H) – Soils with little ability to attenuate diffuse source pollutants and in which non-adsorbed diffuse source pollutants and liquid discharges have the potential to move rapidly to underlying strata or to shallow groundwater.	
H1	Soils which readily transmit liquid discharges because they are either shallow, or susceptible to rapid flow directly to rock, gravel or groundwater.
H2	Deep, permeable, course textured soils which readily transmit a wide range of pollutants because of their rapid drainage and low attenuation potential.
H3	Coarse textured or moderately shallow soils which readily transmit non-adsorbed pollutants and liquid discharges but which have some ability to attenuate adsorbed pollutants because of their clay or organic matter contents.
HU	Urban areas where there are few soil observations. Thus, a worse case scenario is assumed and a high leaching potential assigned.
Soils of intermediate leaching potential (I) – Soils which have a moderate ability to attenuate diffuse source pollutants or in which it is possible that some non-adsorbed diffuse source pollutants and liquid discharges could penetrate the soil layer.	
I1	Soils which can possibly transmit a wide range of pollutants.
I2	Soils which can possibly transmit non- or weakly adsorbed pollutants and liquid discharges but are unlikely to transmit adsorbed pollutants.
Soils of low leaching potential (L) – Soils in which pollutants are unlikely to penetrate the soil layer because either water movement is largely horizontal, or they have the ability to attenuate diffuse pollutants. Lateral flow from these soils may contribute to groundwater recharge elsewhere in the catchment. They generally have high clay or organic matter contents.	

3.4.2 SOIL2

This categorisation was identical to SOIL1 except that the sub-classes were ignored and soils merely classified as being of high, intermediate or low leaching potential. A description of each soil class is presented in Table 5.

Table 5: Description of SOIL2 leaching classes.

H	Soils of high leaching potential – Soils with little ability to attenuate diffuse source pollutants and in which non-adsorbed diffuse source pollutants and liquid discharges have the potential to move rapidly to underlying strata or to shallow groundwater.
I	Soils of intermediate leaching potential – Soils which have a moderate ability to attenuate diffuse source pollutants or in which it is possible that some non-adsorbed diffuse source pollutants and liquid discharges could penetrate the soil layer.
L	Soils of low leaching potential – Soils in which pollutants are unlikely to penetrate the soil layer because either water movement is largely horizontal, or they have the ability to attenuate diffuse pollutants. Lateral flow from these soils may contribute to groundwater recharge elsewhere in the catchment. They generally have high clay or organic matter contents.

3.4.3 SOIL3

This layer represented a further simplification where SOIL2 was reclassed by merging the high and intermediate leaching potential categories. A description of each soil class is presented in Table 6.

Table 6: Description of SOIL3 leaching classes.

H+I	Soils of high and intermediate leaching potential – Soils with little or a moderate ability to attenuate diffuse source pollutants and in which non-adsorbed diffuse source pollutants and liquid discharges could penetrate the soil layer or have the potential to move rapidly to underlying strata or to shallow groundwater.
L	Soils of low leaching potential – Soils in which pollutants are unlikely to penetrate the soil layer because either water movement is largely horizontal, or they have the ability to attenuate diffuse pollutants. Lateral flow from these soils may contribute to groundwater recharge elsewhere in the catchment. They generally have high clay or organic matter contents.

As mentioned above, the BGS aquifer response time map classifies some areas as non-aquifers with thin minor productive horizons, while the same areas are considered as purely non-aquifers in the existing Environment Agency GVQ layer. Furthermore, the soils data from the Environment Agency only covers those areas regarded as aquifers. Consequently, there were significant areas (e.g. non-aquifers with thin productive horizons) of the BGS aquifer response time map for which no soil data were available. This problem was addressed in a conservative manner by assuming in such situations that a soil with the highest leaching potential was present.

3.5 Leaching Layers

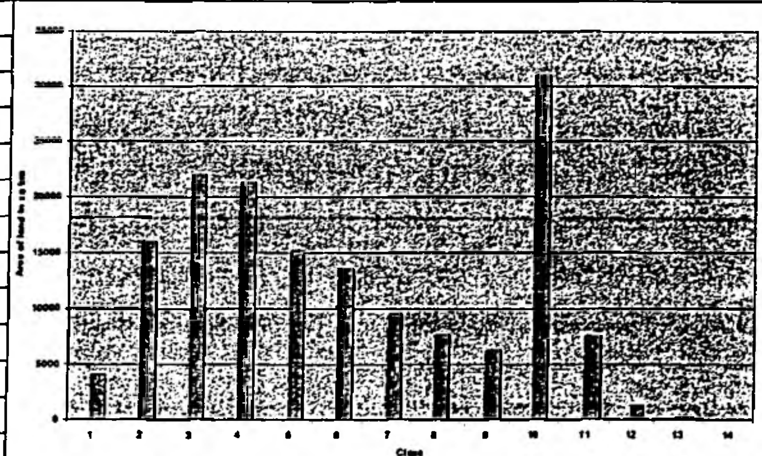
Data on leaching characteristics were obtained from the Modelling Agricultural Pollution and Interactions with the Environment (MAGPIE) Decision Support System (Lord and Anthony, 2000). This software uses information on land use, farming practices, climate and soil characteristics to produce estimates of nitrate concentrations leaving the soil zone on a 1 km^2 resolution grid.

Three different data layers (ADAS2, 4 & 5) were created by ADAS staff using the MAGPIE software to provide information on the amount and nitrate concentrations of soil drainage. Only one leaching layer was used in any particular model. The data were supplied as a 1 km^2 grid covering England and Wales, and, unlike the categorical nature of the other model layers, were in the form of numerical values. To facilitate the integration of the four layers it was therefore necessary to classify the leaching data into discrete categories. The groupings used were decided upon through close consultation with ADAS, and either 14 or 21 categories were created for each data layer. Further description of the three layers follows.

3.5.1 ADAS2

This layer was used in the *intrinsic* vulnerability models and simulated the mean annual soil drainage (mm) from all land under long term mean climate conditions and land use/land cover correct for the 1994/95 cropping year. The numerical values were categorised into 14 groups and these are listed in Table 7 alongside a histogram of the land area in each class.

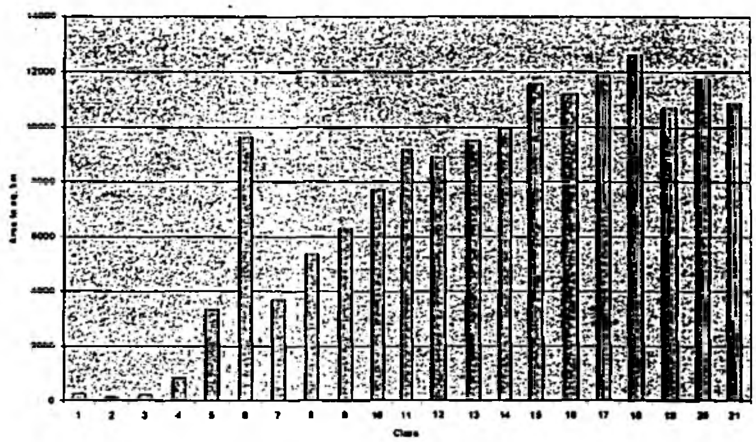
Table 7: Classification of ADAS2 data into soil drainage categories.

Class	Soil Drainage (mm)	Histogram of the area of land in each class
1	<100	
2	100 – 150	
3	150 – 200	
4	200 – 250	
5	250 – 300	
6	300 – 350	
7	350 – 400	
8	400 – 450	
9	450 – 500	
10	500 – 1000	
11	1000 – 1500	
12	1500 – 2000	
13	2000 – 3000	
14	>3000	

3.5.2 ADAS4

The ADAS4 layer was used in the *risk* vulnerability models and simulated the mean nitrate-nitrogen concentrations in land drainage (mg/l NO_3) under long term mean climate conditions and land use/land cover correct for the 1994/1995 cropping year. Implicit in the calculations was the assumption that all waters pass through to groundwater with a long residence time such that seasonal variations in drainage concentrations can be ignored. Values of soil drainage nitrate concentrations were classified into 21 categories as shown in Table 8 alongside a histogram of the land area in each class.

Table 8: Classification of ADAS4 into land drainage NO_3 classes.

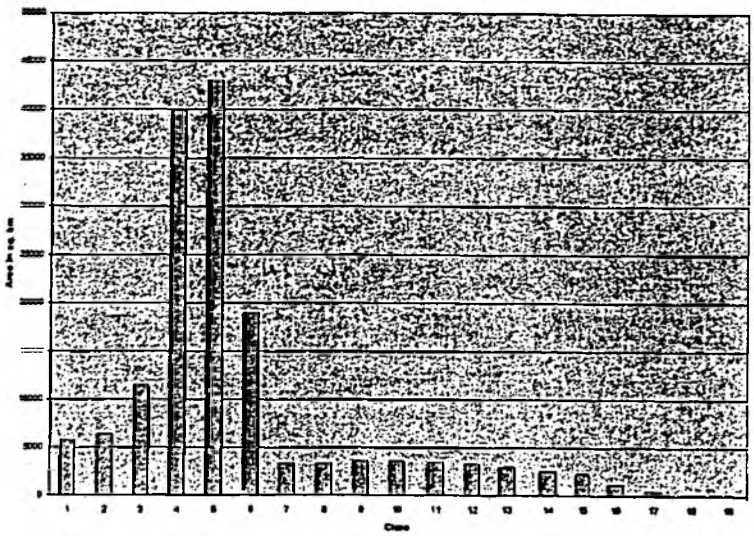
Class	mg/l NO_3	Histogram of the land area in each class
1	>200	
2	175-200	
3	150-175	
4	125-150	
5	100-125	
6	75-100	
7	70-75	
8	65-70	
9	60-65	
10	55-60	
11	50-55	
12	45-50	
13	40-45	
14	35-40	
15	30-35	
16	25-30	
17	20-25	
18	15-20	
19	10-15	
20	5-10	
21	<5	

3.5.3 ADAS5

This layer was used in the *specific* vulnerability models and represented the mean nitrate-nitrogen concentrations in land drainage (mg/l NO_3) under long-term mean climate conditions and assuming that land use throughout England and Wales is constant (i.e. it simulated variations in nitrate leaching risk due simply to climatic and soil characteristics). The maximum potential annual nitrogen loss was set at 100 kg N/ha for all of England and Wales. The numerical values were classified using the same scale as for ADAS4 and are listed in Table 9 alongside a histogram of the land area in each class.

Note that the classes for the soil leaching values are not based simply on even increments. For example, the increments defining the classes of ADAS2 increase by 50 mm between Class 1 and Class 9, after which they change to steps of 500 mm and subsequently 1000 mm. The reason for such an approach is the greater relative importance of small changes in the quantity of soil drainage when the overall amount of drainage is limited. For the purposes of subsequently defining vulnerability categories, the entire ADAS2 classification (from Classes 1-14) was treated linearly. ADAS 4 and 5 were handled in a similar manner, with increments of 5 mg/l and 25 mg/l for nitrate concentrations of less than and greater than 75 mg/l, respectively.

Table 9: Classification of ADAS5 into land drainage NO_3 classes.

Class	mg/l NO_3	Histogram of the land area in each class
1	>200	
2	175-200	
3	150-175	
4	125-150	
5	100-125	
6	75-100	
7	70-75	
8	65-70	
9	60-65	
10	55-60	
11	50-55	
12	45-50	
13	40-45	
14	35-40	
15	30-35	
16	25-30	
17	20-25	
18	15-20	
19	10-15	
20	5-10	
21	<5	

4. Derivation of Initial Vulnerability Models

4.1 Converting Data Structures

In order to combine the four layers they had to be converted to a common data structure within the GIS. This was necessary because the digital map databases were supplied in two different formats. The ADAS data were in a raster structure where the country was divided into a series of 1 km^2 grid cells with a single attribute value in each. The other three layers were in a vector structure which consisted of digitised polygons representing contiguous areas with identical attributes. These two formats are illustrated in Figure 1.

To standardise the data structures it was decided that it would be simplest to convert the ADAS raster files into a vector format. However, when this was done and the four layers combined, there were many small areas with aquifer, drift and soil information but no ADAS data. This problem is also shown in Figure 1.

Most of the gaps in the ADAS data were along the coastline and were a consequence of the original raster structure. The missing areas were filled by extending the ADAS data by 1 km into all those areas without leaching information. This approach is justifiable given the cell size of the original data and overcame most of the existing gaps. A few mismatches remained in isolated areas of land such as coastal spits and small islands. Given the resolution of the original ADAS data, extension to these areas could not be justified and they were consequently excluded from further analysis.

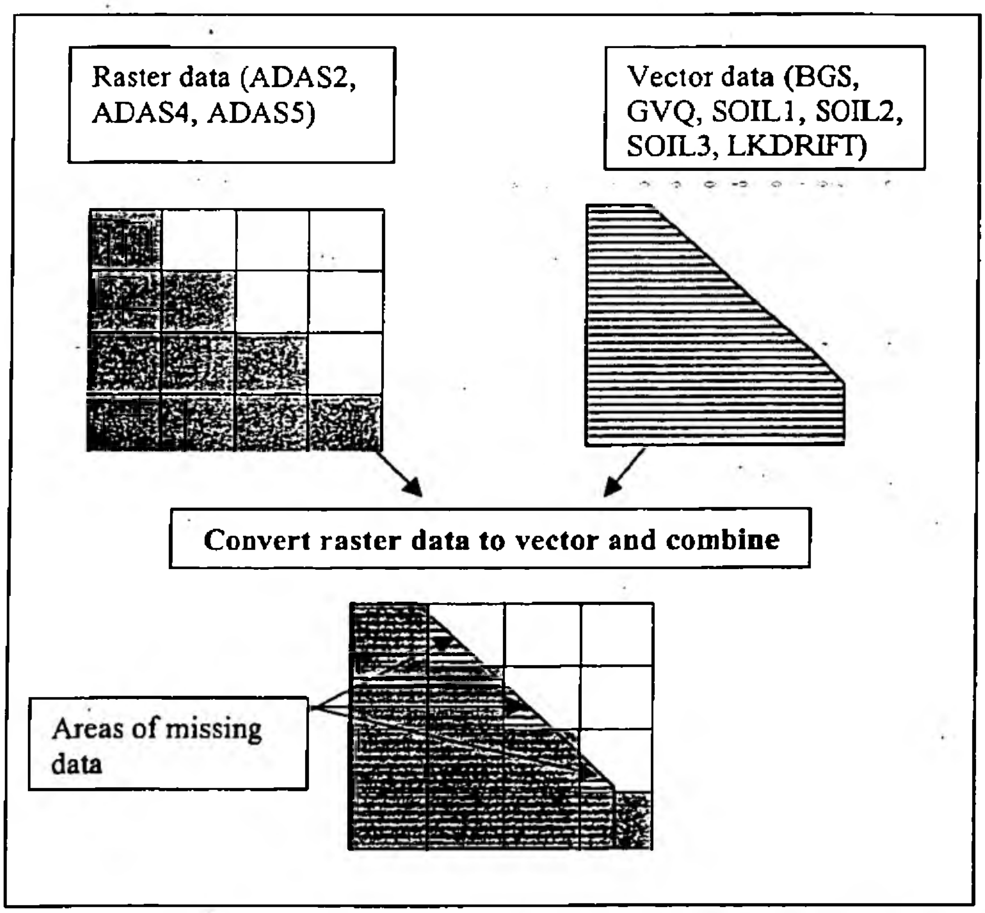


Figure 1: Difficulties associated with combining raster and vector data.

4.2 Overlaying Data Layers

Vector layers were next overlaid within the GIS to produce the six different models (see Table 1 for details of the data files involved). The outcome of each set of overlay operations was a new map layer with a large number of polygons, each coded according to the attributes present. This process is illustrated in Figure 2 using the example of Model 1.

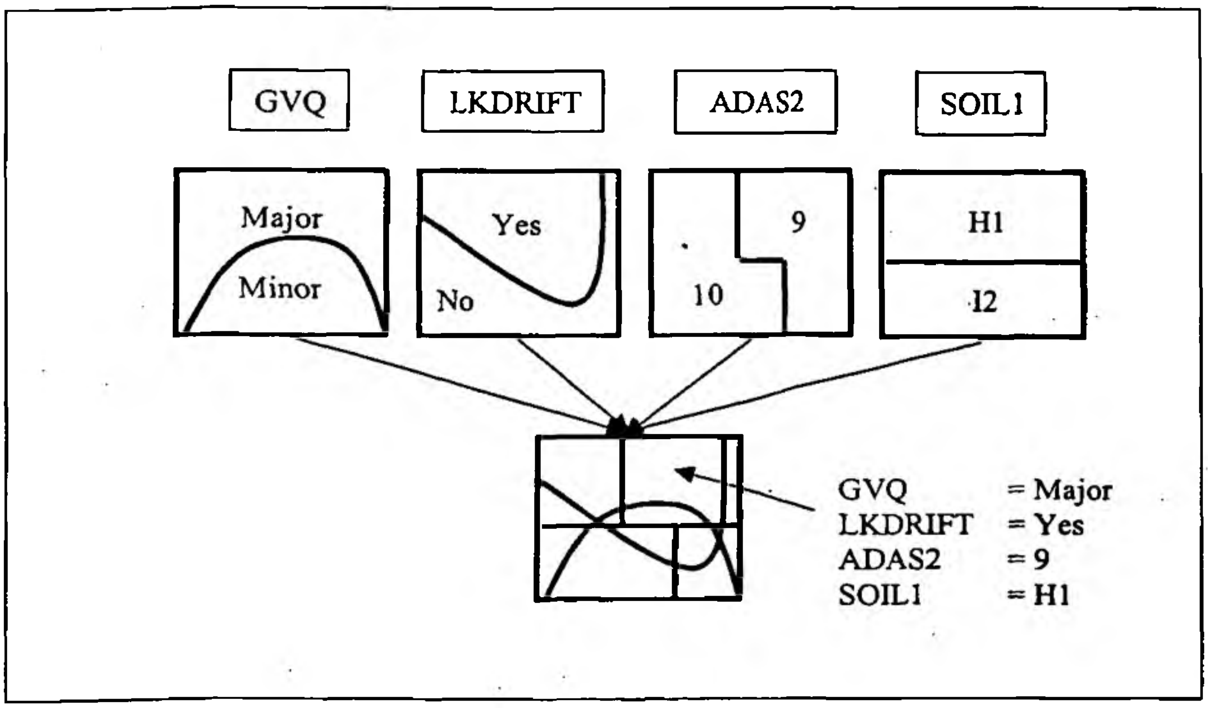


Figure 2: Overlay of data layers to generate Model 1.

Two types of vulnerability model (*intrinsic* and *specific*) and one type of *risk* model were defined. Each of the three categories involved one model employing the GVQ layer and another incorporating the BGS aquifer response time map. Thus half of the models utilised the GVQ map and the remainder the BGS map. A brief description of each model and its components follows.

4.2.1 Intrinsic Vulnerability Models

These models represented the intrinsic vulnerability of groundwater to surface-derived contamination. This was achieved by including no nitrate information in the land drainage data. Models 1 and 2 therefore provide an assessment of vulnerability based upon the amount of land drainage occurring under actual climate, land use and land cover conditions.

- Model 1 combined ADAS2 (providing information on the amount of water draining from the soil) with LKDRIFT indicating the presence or absence of low permeability drift material. These layers were integrated with the GVQ aquifer classification and the SOIL1 classification of soil leaching potential.

- Model 2 was similar to Model 1 except that the BGS aquifer response time map was substituted for the GVQ aquifer classification and the simpler SOIL2 layer replaced SOIL1.

4.2.2 Specific Vulnerability Models

Models 3 and 4 incorporated a uniform nitrogen loading of 100 kg/ha to provide an assessment of vulnerability that reflected only aquifer, soil and climatic factors.

- Nitrate leaching data in Model 3 were provided by the ADAS5 layer. As the latter incorporated the ability of the soil to attenuate nitrate pollution it would have constituted double counting to also reflect such a process in the soil layer. This problem was overcome by using the binary SOIL3 classification in which a non-adsorbed diffuse source pollutant such as nitrate has the potential to move rapidly to underlying strata. The LKDRIFT layer and GVQ classification were also included in the model.
- Model 4 was identical to Model 3 except that the BGS aquifer response time map was substituted for the GVQ aquifer classification.

4.2.3 Risk Models

These final two models examined the risk to groundwater utilising an estimate of the concentration of nitrate in land drainage given actual land cover and use, correct for the 1994/95 cropping year.

- Model 5 was similar to Model 3 except that the ADAS4 layer replaced ADAS5.
- Model 6 was identical to Model 5 except that the BGS aquifer response time map replaced the GVQ layer.

It was expected that the risk models would provide the best predictions of differences in nitrate levels within groundwater samples, though given that the land cover data were only for a single year it was recognised that the models might fail to reflect contamination caused by past land use practices. Due to the likelihood of future changes in land use, it was also anticipated that the specific vulnerability models might ultimately provide the best basis for revised groundwater NVZ definition.

4.3 Developing Relative Vulnerability Classifications

Having combined the four data layers for each model, the next stage was to convert the different combinations of attributes into a relative vulnerability scheme (i.e. a ranking from highest to lowest). Initial attention focused on placing the aquifer, soil type and low permeability drift categories into a sequence. Given uncertainties regarding the low permeability drift layer (see Section 3.3) it was decided to develop two variants of the sequence for each model. Variant 1 assumed that *any aquifer with drift was less vulnerable than any aquifer without.* Variant 2 recognised uncertainties in the extent of protection provided by the drift layer and gave priority to the *inherent vulnerability of aquifers (i.e. the degree of permeability) rather than the absence of drift.* In both sequences, the most vulnerable combinations of attributes were assigned the lowest integer codes (i.e. a value of 1 represented the most vulnerable situation). Examples of the two sequence variants for Model 4 are given in Table 10.

Table 10: The two vulnerability sequences based upon different treatments of the low permeability drift layer.

Variant 1

BGS	SOIL3	LK DRIFT	Code
Fast	H+I	Absent	1
	L	Absent	2
Medium	H+I	Absent	3
	L	Absent	4
Slow	H+I	Absent	5
	L	Absent	6
Fast	H+I	Present	7
	L	Present	8
Medium	H+I	Present	9
	L	Present	10
Slow	H+I	Present	11
	L	Present	12

Variant 2

BGS	SOIL3	LK DRIFT	Code
Fast	H+I	Absent	1
	L	Absent	2
Fast	H+I	Present	3
	L	Present	4
Medium	H+I	Absent	5
	L	Absent	6
Medium	H+I	Present	7
	L	Present	8
Slow	H+I	Absent	9
	L	Absent	10
Slow	H+I	Present	11
	L	Present	12

Once a unique code for each of the combinations of aquifer, soil and low permeability drift had been generated, it was necessary to incorporate the land drainage/NO_3 concentration (ADAS) data. This was achieved by using the category codes previously assigned to the ADAS data layers (see Section 3.5). The two sets of codes (one representing aquifer, soils and drift, the second representing ADAS data) were then summed to give a new set of values for each model. This procedure is illustrated in Table 11 using the example of Variant 2 for Model 2.

Table 11: An extract from the classification table for Model 2 Variant 2 illustrating the derivation of a numerical value for intrinsic vulnerability given combinations of aquifer, soil, drift and quantity of soil drainage (mm) characteristics.

				ADAS2 (mm)				
				<100	100-150	150-200	200-250	250-300
BGS	SOIL2	LKDRIFT	Code	1	2	3	4	5
Fast	**H**	**Absent**	1	**2**	**3**	**4**	**5**	**6**
Fast	**I**	**Absent**	2	**3**	**4**	**5**	**6**	**7**
Fast	**L**	**Absent**	3	**4**	**5**	**6**	**7**	**8**
Fast	**H**	**Present**	4	**5**	**6**	**7**	**8**	**9**
Fast	**I**	**Present**	5	**6**	**7**	**8**	**9**	**10**
Fast	**L**	**Present**	6	**7**	**8**	**9**	**10**	**11**
Medium	**H**	**Absent**	7	**8**	**9**	**10**	**11**	**12**

Notes: The table shows only part of the range of scores. Low scores indicate greatest vulnerability.

As can be seen in Table 11, the smallest value of soil drainage (<100 mm) is assigned the lowest category number and is therefore assumed to be associated with the least dilution of a contaminant. This accords with the principle of the lowest assigned value equalling the greatest vulnerability. Where a model uses values of nitrate concentration derived from ADAS4 and ADAS5 (Models 3-6), the highest nitrate concentration is assigned the lowest category number.

The method of summing the assigned values to obtain the matrix of aquifer vulnerability values was compared to methods involving a) the product of the assigned values and b) a weighted scoring of values. However, both of these methods produced results that were substantially skewed. As the summation method is transparent, defensible and facilitates further necessary classification (see below), this was the option employed.

As shown in Table 11, the ADAS data were positioned on the horizontal axis to facilitate the method of combination (i.e. summation). It should, however, be recognised that each of the ADAS data layers comprises a greater number of categories than occurs in the other data layers. In effect, the ADAS data have a relatively stronger influence on the final aquifer vulnerability classification.

For each model, once a complete table of aquifer vulnerability values was obtained, a range of ten vulnerability classes was decided upon as the comparative standard between models. Division of the summed values into these ten vulnerability classes was simply achieved by taking tenth percentile groups of the highest number in the table.

The division of summed values into ten vulnerability classes is arbitrary, but was considered sufficient for the purpose of distinguishing differences in aquifer vulnerability between areas. It should be noted, however, that not all the models have geographical areas within all ten vulnerability classes. This is partly because in several models (especially Models 3 and 4) there are large areas with identical codes on the input data layers and these cannot be separated subsequently. It is also because some theoretically possible combinations of characteristics (especially at the less vulnerable end of the spectrum) do not occur in reality.

4.4 Characteristics of the Vulnerability Classifications

The twelve vulnerability maps produced through the overlay and classification exercise are shown in Appendix A (Figures A1-A12). There are a number of comments that can be made from a qualitative inspection of these maps.

The most notable contrast in the twelve figures is the difference in aquifer area between those models employing the Environment Agency's Groundwater Vulnerability Maps (Models 1, 3 and 5) and those employing the BGS aquifer response time map (Models 2, 4 and 6). This is unsurprising given that the BGS aquifer response time map classifies much of Wales and the Lake District as 'non-aquifers with thin minor productive horizons' (thereby possessing some vulnerability) whereas on the Groundwater Vulnerability Maps the same areas are non-aquifers. Models 3 and 4 (Variant 1 of each) provide a good example of this difference, as all other parameters are similar in these two models.

In addition, the BGS aquifer response time map classifies some areas as non-aquifers which previously were aquifers. Examples of this are most apparent in the central and east Midlands and the Wash (compare the maps for Models 1 and 2).

From a qualitative inspection, Variants 1 and 2 of each model (i.e. differences in the treatment of the drift layer) appear to display only minor differences in the pattern of aquifer vulnerability. It is not evident that either variant obviously increases the vulnerability of a map as a whole. This may be illustrated by examining Variants 1 and 2 of Model 1. Looking at Cornwall and Devon, for example, shows that Variant 1 displays a greater vulnerability than Variant 2, by one or two vulnerability classes. However, in East Anglia, Variant 2 displays the greater vulnerability.

A uniform application of 100 kg N/ha across England and Wales (Models 3 and 4) results in a marked increase in the occurrence of higher vulnerability categories. Compared with Models 5 and 6 (with nitrogen applications based on actual land use cover) much of the western and northern areas of England and parts of Wales show increased vulnerability to nitrate leaching.

5. Integrating Data on Nitrate Levels in Groundwater

5.1 The Borehole Data

A database of groundwater nitrate levels recorded at sites across England and Wales during the 1990s was compiled by the Environment Agency. This included information held by the Environment Agency from private and observation boreholes, as well as public water supplies. Many of the site records were of a partial and incomplete nature when compared to the much more comprehensive data sets available for public water supply boreholes.

The details in the nitrate database as of autumn 1999 were scrutinised by experienced staff from the National Groundwater & Contaminated Land Centre of the Environment Agency, and all the locations with inadequate or unreliable information were excluded from further consideration. For each of the remaining sites the nitrate values were plotted graphically against time and trend lines were drawn by eye to predict a value of nitrate in groundwater for the year 2017 (this timescale was also used in the previous NVZ designation and the 1997 review). Where a clear trend could not be identified, the current nitrate level was used as the 2017 value. A spreadsheet was then created containing records for 3,884 locations with the following details for each site:

- National grid reference easting for the site location.
- National grid reference northing for the site location.
- A site ID number.
- The Environment Agency region in which the site occurred.
- The water company involved (if relevant).
- A site reference number.
- The national site list name.
- The number of observations that the trend nitrate value for 2017 was based upon.
- The trend nitrate level for 2017 (mg/l).
- A code indicating whether any nitrate values in the site record (i.e. the past time series) were equal to or exceeded 50 mg/l.

The spreadsheet received from the Environment Agency was converted to a GIS format at UEA and then the distribution of points was plotted against a background of Environment Agency regional boundaries. This exercise revealed some errors in site grid references (at least 20 were in the sea) and ultimately 54 were corrected with assistance from Environment

Agency staff. Another three sites were identified as having the wrong location, but a correct grid reference could not be found at the time. These three records were therefore excluded from further consideration, leaving a total of 3,881.

Once the grid references had been corrected, point-in-polygon operations were implemented within the Arc/Info GIS software to match the locations of the nitrate measurements with their corresponding regions on the 12 vulnerability classification maps (two variants for each of the six models). In essence, the grid reference of a site was used to determine the region that it fell within on a vulnerability classification and the code for that region (0 to 10) was then assigned as an attribute of the monitoring point (for further details of point-in polygon techniques see Laurini and Thompson, 1992 or Burrough and McDonnell, 1998). This exercise was repeated for each trend value location on all the 12 classifications, a total of (12 x 3881) 46,572 instances. Due to possible concerns about the accuracy of the site grid references and, indeed, the positions of boundaries on the digital layers used to produce the vulnerability classifications, it was also decided to calculate the distance from each monitoring point to the nearest region boundary. The thinking behind this was that the matching of points to vulnerability categories would be most robust if a site was some distance from a boundary rather than close to it. Results from this assessment are discussed in Section 6.2.

5.2 The Kriged Lattice of Nitrate Values

Dr Margaret Oliver of Reading University also used the spreadsheet of groundwater nitrate data as the basis of an interpolation exercise. Disjunctive kriging techniques (Oliver, 1991; Rivoirard, 1994) were applied to generate estimates of the trend nitrate values on a 2.5 km resolution regular lattice across England and Wales. In addition to the trend estimates, the kriging procedure also calculated the probability that particular nitrate threshold values (e.g. 30 mg/l or 50 mg/l) would be exceeded at each lattice point.

Dr Oliver provided a data file for 39,804 lattice points. These details were converted to a GIS format and a clip operation was undertaken to exclude all those points outside the England and Wales boundary. This left 23,825 points in an even distribution across all parts of England and Wales except three small areas in Cornwall, Pembrokeshire and East Anglia. Values for these perimeter locations could not be estimated in the kriging procedure because there were insufficient borehole observations nearby. Point-in-polygon techniques were subsequently used to match the lattice points to the vulnerability classifications in the same manner as described previously for the borehole data.

6. Nitrate Variations Across the Vulnerability Categories

6.1 Characteristics of the Borehole Data

Table 12 presents a range of descriptive statistics for the nitrate levels and reveals a skewed distribution with 25% of the values under 5 mg/l and 75% less than 43 mg/l. There were 767 sites (19.8% of 3881) with trend nitrate values for 2017 greater than or equal to 50 mg/l and 887 sites (22.9%) had levels in their time series ≥ 50 mg/l. After discussions with Environment Agency staff it was decided to define 'high' nitrate level sites as those with either a 2017 trend or past recorded value ≥ 50 mg/l. There were 994 such sites (25.6% of the total) and Figure 3 plots their geographical distribution. This map also illustrates the uneven spread of the borehole sites, with particular clusters in certain geological environments and aquifers.

Table 12: Descriptive statistics for nitrate levels (mg/l NO_3) in the borehole data.

Mean NO_3	27.02	**25th Percentile**	5.00
Std. Deviation	23.58	**75th Percentile**	43.00
Median NO_3	23.00	**Maximum**	148.00

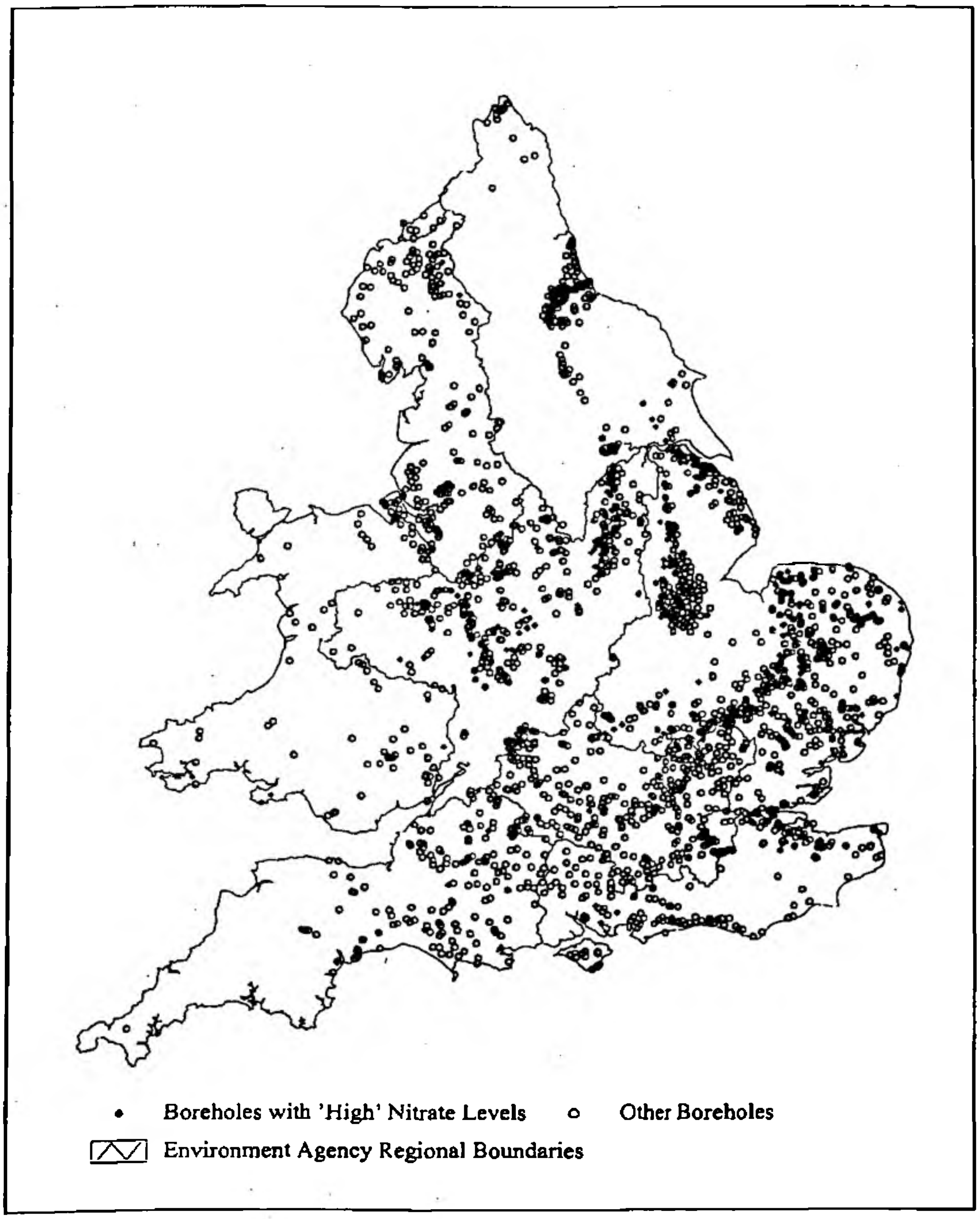


Figure 3: The geographical distribution of the boreholes with nitrate data.

6.2 Trends in Borehole Nitrate Levels Across Vulnerability Classes

The output from the borehole point-in-polygon operations was converted to a database format that could be imported by the Statistical Package for the Social Sciences (hereafter SPSS) software. This file contained details of the borehole attributes (e.g. nitrate levels) together with a vulnerability code for the site location on each of the twelve classifications. It was then straightforward to generate tabulations listing the number of boreholes in each vulnerability category or different descriptive statistics for these groups.

Table 13 shows the number of boreholes in each vulnerability category for the twelve model variants. Class 0 primarily represents non-aquifer areas, but also a few instances where the vulnerability class could not be assigned because of missing information in the input data layers. The skewed frequency distributions of sites (e.g. for Models 3 and 4) partly reflect the uneven assignment of areas to vulnerability classes discussed previously in Section 4.3. However, the bias is often more pronounced than would be expected on the basis of area alone, and this can be attributed to a natural tendency to undertake additional monitoring in regions where groundwater is thought to be more vulnerable to contamination. It is nevertheless important to keep in mind some of the differences in numbers of observations when interpreting the descriptive statistics presented subsequently.

Table 13: Number of borehole observations in each vulnerability class.

	Model 1		**Model 2**		**Model 3**		**Model 4**		**Model 5**		**Model 6**	
Class	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**
1	73	75	75	170	379	382	388	390	14	14	15	15
2	1139	1141	1141	915	1142	1098	1426	1254	48	47	120	116
3	878	776	776	796	1147	1203	653	995	477	482	522	418
4	356	456	456	742	554	517	531	467	599	599	635	782
5	407	466	466	421	77	88	170	64	677	691	669	704
6	329	182	182	113	26	25	8	4	658	649	637	553
7	103	154	154	23	12	24	6		501	478	426	470
8	36	71	71		1	2			246	247	96	98
9	23	23	23						107	111	57	29
10									13	22	4	
0	537	537	537	701	543	542	699	707	541	541	700	696
Total	3881	3881	3881	3881	3881	3881	3881	3881	3881	3881	3881	3881

The mean nitrate levels in vulnerability classes for each model variant are summarised in Table 14. These statistics show a general tendency for nitrate levels to decline from the highest vulnerability categories downwards, though none of the peak values exceed 50 mg/l and the gradients are rarely perfect. Similar patterns are apparent in the medians (middle values in an ordered sequence) listed in Table 15 and in the percentages of sites with 'high' nitrate values (those with either a 2017 trend or past recorded value ≥ 50 mg/l) shown in Table 16. This consistency of results suggests that the trends are fairly robust. Appendix B presents further descriptive statistics on a model-by-model basis and indicates that the standard deviations (a measure of dispersion) in many categories are quite wide (often in the order of 15 to 25). This implies that alongside trends in average values there are often some relatively low and high nitrate levels within the same vulnerability class. Such a finding is not especially surprising given that many other characteristics (e.g. borehole depth and the time of year at which a sample is taken) can influence nitrate levels.

Table 14: Mean NO_3 values (mg/l NO_3) in each vulnerability class.

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
Class	**v1**	**v2**	**v1**	**v2**	**V1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**
1	33.78	33.89	33.89	31.78	41.23	41.05	37.98	37.92	35.57	35.57	36.07	36.07
2	37.40	37.34	37.34	30.64	34.74	35.93	31.09	28.77	33.00	35.30	37.25	37.62
3	24.91	28.17	28.17	27.73	23.84	23.95	27.17	31.03	43.93	43.21	39.88	35.90
4	23.43	24.37	24.37	32.12	22.27	20.52	24.80	21.75	30.19	33.28	29.34	31.99
5	27.70	21.24	21.24	25.99	16.96	17.01	16.46	12.02	27.09	25.51	27.91	28.38
6	21.17	23.41	23.41	20.27	12.88	10.52	3.88	8.50	27.27	26.13	25.72	24.92
7	21.14	19.84	19.84	10.09	3.92	9.04	7.33		25.17	25.06	24.84	24.95
8	22.03	16.63	16.63		1.00	2.00			19.43	21.90	17.36	18.94
9	12.57	12.57	12.57						15.89	13.86	16.70	21.41
10									12.62	12.00	15.25	
0	15.09	15.03	15.03	17.21	15.11	15.36	17.18	17.21	15.19	15.11	17.27	17.21

Table 15: Median NO_3 values (mg/l NO_3) in each vulnerability class.

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
Class	**v1**	**v2**	**v1**	**v2**	**V1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**
1	36.0	36.0	36.0	32.5	42.0	42.0	39.0	39.0	42.0	42.0	42.0	42.0
2	38.0	38.0	38.0	30.0	36.0	37.0	31.0	26.5	32.5	37.0	38.0	38.0
3	21.5	26.0	26.0	23.0	19.0	18.0	25.0	30.0	44.0	43.5	41.0	36.0
4	18.0	15.0	15.0	32.0	14.0	13.0	17.0	18.0	29.0	33.0	29.0	32.0
5	22.0	12.5	12.5	24.0	8.0	8.0	12.0	6.0	24.0	22.0	26.0	27.0
6	12.0	17.0	17.0	18.0	7.5	7.0	3.0	2.5	25.0	23.0	23.0	21.0
7	14.0	14.0	14.0	6.0	3.0	4.5	4.0		22.0	22.0	20.0	20.5
8	16.5	7.0	7.0		0.0	2.0			12.0	16.0	11.5	12.0
9	5.0	5.0	5.0						10.0	7.0	10.0	14.0
10									3.0	5.0	15.5	
0	5.0	5.0	5.0	6.0	5.0	5.0	6.0	6.0	5.0	5.0	6.0	6.0

Table 16: Percentage of sites with 'high' nitrate values.

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
Class	**v1**	**v2**	**v1**	**v2**	**V1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**
1	31.5	32.0	29.2	28.8	46.7	46.1	42.8	42.8	28.6	28.6	26.7	26.7
2	40.6	40.5	34.6	32.5	38.5	39.3	31.6	27.8	41.7	44.7	47.5	47.4
3	21.8	23.5	31.5	25.9	17.9	18.8	20.5	31.7	54.3	52.7	48.3	44.5
4	18.5	23.2	16.2	32.6	17.9	16.2	22.6	10.1	30.7	35.7	28.2	33.6
5	24.8	18.2	24.1	17.6	13.0	12.5	5.3	3.1	25.7	22.3	23.9	23.2
6	17.9	22.0	19.8	8.8	0	0	0	0	24.2	23.3	20.7	19.3
7	19.4	14.9	9.8	0	0	0	0		19.8	19.9	20.0	19.6
8	19.4	11.3	0		0	0			9.3	13.0	4.2	6.1
9	4.3	4.3	0						4.7	2.7	8.8	10.3
10									15.4	9.1	0	
0	11.9	11.7	16.3	16.5	11.6	12.0	16.5	16.3	12.0	11.8	16.6	16.5

Additional checks on the trends were undertaken by repeating the calculation of descriptive statistics after excluding all boreholes within 125 metres of a vulnerability class boundary (a distance reflecting the best accuracy expected given the resolution of the input data sources) or all those sites where the trend estimate was based on fewer than 10 observations. Removing the sites with relatively few data points had the effect of increasing the average values, but neither modification substantially altered the general trends and so they were not considered further.

Statistical calculations were carried out to assess the overall predictive performance of each vulnerability model. The results are summarised in Table 17. If a model performs well across all the different parameters then this indicates a strong ability to identify a consistent gradient in nitrate values across vulnerability classes. Further details of the parameters and how they should be interpreted are given below.

- Highest mean NO_3 value in a vulnerability class: the greater this value the better as it indicates that a vulnerability category is separating out high nitrate values.
- Highest mean NO_3 value in Class 1: ideally a model should have the highest mean value in Class 1 and then descending levels through the remaining groups.
- Range of mean NO_3 values: preferably the range should be as great as possible because it represents the ability of the model to differentiate nitrate values.
- Spearman Rank Correlation: this statistic represents the association between the vulnerability category codes and the mean nitrate values. The coefficient can range from +1.0 (perfect positive association), through zero (no association) to –1.0 (perfect negative association) (see Siegel, 1956). In the context of the vulnerability models, the stronger the negative correlation the better, because this indicates that the nitrate values decline as the vulnerability codes increase (e.g. from 1 to 10). The best possible result is a correlation coefficient of –1.0 which signifies a perfect trend of declining nitrate values through the classes.
- Analysis of Variance (ANOVA) F statistic: the larger this parameter, the less overlap there is between the nitrate values in different vulnerability classes. In more formal terms the F statistic is the ratio of between to within sample variances (Bryman and Cramer, 1997).

Table 17: Comparative statistics for vulnerability model performance.

Model	Highest Mean NO_3 Value	Is Highest Mean Value in Class 1 ?	Range of Mean NO_3 Values Across Classes	Spearman Rank Correlation	ANOVA F Statistic
Model1 v1	37.40	No	12.57 – 37.40	-.879	34.349
Model1 v2	37.34	No	12.57 – 37.34	-.967	37.554
Model2 v1	37.34	No	12.57 – 37.34	-.967	14.431
Model2 v2	32.12	No	10.09 – 32.12	-.847	10.077
Model3 v1	41.23	Yes	1.00 – 41.23	-1.000	49.261
Model3 v2	41.05	Yes	2.00 – 41.05	-1.000	59.461
Model4 v1	37.98	Yes	3.38 – 37.98	-.964	26.384
Model4 v2	37.92	Yes	8.50 – 37.92	-.943	30.117
Model5 v1	43.93	No	12.62 – 43.93	-.960	35.701
Model5 v2	43.21	No	12.00 – 43.21	-.960	38.324
Model6 v1	39.88	No	15.25 – 39.88	-.948	23.106
Model6 v2	37.62	No	18.94 – 37.62	-.950	15.212

Note: All values shown in this table exclude Class 0.

It needs to be emphasised that a good performance on one of these parameters alone may not be especially meaningful. For example, a large F statistic (indicating limited overlap in nitrate values between vulnerability classes) is of little merit unless there is also a consistent downward gradient in average values (i.e. a strong negative correlation). It is also worth noting that a non-parametric analysis of variance (the Kruskal-Wallis H Test, see Siegel, 1956) produces similar trends to the F statistic.

The results in Table 17 indicate that all the model variants perform at least satisfactorily (e.g. all the correlation coefficients and F statistics are significant at the 95 % confidence level). Model 3 stands out as a consistently strong predictor of variations in nitrate levels, with Model 5 probably the best of the remainder. These two vulnerability models are therefore the ones that are most confidently validated by the available borehole data. Other features of Table 17 are that:

- It is hard to detect any consistent difference in performance between Variants 1 and 2 for each model.
- The odd numbered models tend to perform better than their even equivalents (e.g. 1 better than 2, 3 better than 4). This suggest that the BGS aquifer vulnerability classification is less appropriate than the Environment Agency one, though this outcome could also reflect some of the difficulties of integrating soil information with the BGS data (see Section 2.4.3).
- The intrinsic vulnerability models (1 and 2) generally perform less well than the remainder (3-6). This is not especially surprising given the nature of the input layers used.

A less expected result was that Models 5 and 6 (based on actual land use information) performed less well than Models 3 and 4 (which assumed a blanket nitrate loading). In part, at least, this is because Models 5 and 6 do not have a consistent gradient in nitrate values from Class 1 downwards (see Tables 14 and 15). It is also evident from Table 13 that Classes 1 and 2 for Models 5 and 6 contain relatively few boreholes. Further investigation of the geographical distribution of these highest risk categories revealed that they tended to occur as very small areas surrounded by Class 3 regions. In the cases examined in detail (e.g. parts of East Anglia) it was also far from obvious why the small areas should be classed at greater risk than the regions immediately surrounding them. As a consequence, it was decided to recode the vulnerability classes for Models 3-6 so that no category contained fewer than 100 boreholes. This had the effect of collapsing categories at the lower end of the vulnerability spectrum (e.g. 5-8) for Models 3 and 4, and combining three classes at each extremity (e.g. 1-3 and 8-10) for Models 5 and 6. Table 18 lists the number of nitrate measurements in each of the revised vulnerability classes.

Mean NO_3 values for the revised vulnerability classes are presented in Table 19 and Table 20 summarises the different performance measures. Both of these tables indicate that combining categories substantially improves the predictive ability of the models. It is clear that Model 3 remains the best predictor of nitrate gradients, but Model 5 is now superior in terms of having the highest nitrate levels in Class 1.

Further investigation was then undertaken to compare the distributions of classes in Models 3 and 5. This revealed a high degree of geographical coincidence between the two (irrespective of whether Variant 1 or 2 was used), with the original Classes 1-3 from Model 5 being almost entirely within the larger region covered by the original Classes 1-3 from Model 3. Such an outcome suggests that while the *risk* approach of Model 5 can distinguish higher nitrate levels, the *specific vulnerability* assumptions underpinning Model 3 probably provide a more reliable basis for national NVZ definition.

Table 18: Number of borehole observations in each revised vulnerability class.

Revised Class	Model 3		Model 4		Model 5		Model 6	
	v1	v2	v1	v2	v1	v2	v1	v2
1	379	382	388	390	539	543	657	549
2	1142	1098	1426	1254	599	599	635	782
3	1147	1203	653	995	677	691	669	704
4	554	517	531	535	658	649	637	553
5	116	139	184	0	501	478	426	470
6	0	0	0	0	366	380	157	127
0	543	542	699	707	541	541	700	696
Total	3881	3881	3881	3881	3881	3881	3881	3881

Table 19: Mean NO_3 values (mg/l NO_3) in each revised vulnerability class.

Revised Class	Model 3		Model 4		Model 5		Model 6	
	v1	v2	v1	v2	v1	v2	v1	v2
1	41.23	41.05	37.98	37.92	42.74	42.33	39.32	36.27
2	34.74	35.93	31.09	28.77	30.19	33.28	29.34	31.99
3	23.84	23.95	27.17	31.03	27.09	25.51	27.91	28.38
4	22.27	20.52	24.80	20.49	27.27	26.13	25.72	24.92
5	14.56	14.25	15.62		25.17	25.06	24.84	24.95
6					18.15	18.98	17.07	19.50
0	15.11	15.36	17.18	17.21	15.19	15.11	17.27	17.21

Table 20: Comparative statistics for reclassed vulnerability model performance.

Model	Highest Mean NO_3 Value	Is Highest Mean Value in Class 1 ?	Range of Mean NO_3 Values Across Classes	Spearman Rank Correlation	ANOVA F Statistic
Model3 v1	41.23	Yes	14.56 - 41.23	-1.000	85.172
Model3 v2	41.05	Yes	14.25 - 41.05	-1.000	103.043
Model4 v1	37.98	Yes	15.62 - 37.98	-1.000	38.787
Model4 v2	37.92	Yes	20.49 - 37.92	-.800	46.334
Model5 v1	42.74	Yes	18.15 - 42.74	-.986	61.228
Model5 v2	42.33	Yes	18.98 - 42.33	-.986	65.011
Model6 v1	39.32	Yes	17.07 - 39.32	-1.000	41.288
Model6 v2	36.27	Yes	19.50 - 36.27	-.986	24.205

Note: All values shown in this table exclude Class 0.

6.3 Trends in the Kriged Nitrate Values

Compared to the original borehole values, the kriged nitrate estimates were much more evenly distributed. Table 21 shows that the standard deviation and maximum value were both appreciably smaller than for the borehole data (c.f. Table 12). Gradients in nitrate levels across vulnerability classes were also more muted, as illustrated by the patterns of mean values in Table 22 when compared to Table 14.

Table 21: Descriptive statistics for the kriged nitrate values (mg/l NO_3).

Mean NO_3	24.89	**25th Percentile**	18.01
Std. Deviation	9.59	**75th Percentile**	30.52
Median NO_3	24.01	**Maximum**	68.72

Table 22: Mean kriged NO_3 values (mg/l NO_3) in each vulnerability class.

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
Class	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**	**v1**	**v2**
1	25.14	25.14	27.62	27.63	37.17	37.32	34.16	34.04	29.75	27.93	31.84	32.19
2	32.26	32.26	30.15	30.10	29.52	30.70	28.18	28.08	31.63	34.42	32.55	32.37
3	26.08	26.63	27.33	26.57	26.07	25.05	24.77	24.80	32.86	33.78	32.39	30.98
4	26.46	24.84	22.93	23.83	24.34	25.70	22.94	22.10	29.25	28.68	28.32	28.12
5	25.46	25.71	23.28	21.60	22.32	22.68	20.09	19.70	26.83	26.72	26.47	26.47
6	23.56	26.54	23.83	22.17	20.87	21.45	18.44	19.24	26.03	25.93	24.79	24.73
7	22.93	24.78	19.76	22.44	20.18	20.81	20.56	19.75	25.33	25.82	21.71	21.46
8	22.96	22.08	20.88	29.39	20.77	21.15	20.61		23.37	24.60	22.41	21.45
9	19.29	19.27			20.58	19.96			21.17	22.16	19.90	22.60
10	20.98	20.98							19.56	19.78	21.32	22.39
0	23.77	23.77	25.11	25.11	23.78	23.77	25.12	25.12	23.77	23.78	25.12	25.12

The ability of the 12 model variants to differentiate the kriged nitrate values was assessed by calculating the same performance measures as used with the borehole data. Table 23 summarises the results obtained and indicates that in general the models did not perform as well as with the original borehole values. The main exception was the ANOVA results where the reduced within-class variability generated substantially larger F statistics. On a comparative basis it is clear that Model 3 again does well in distinguishing a gradient in NO_3 values and, as with the borehole data, the predictive capability of most models can be enhanced by combining some categories. These modifications were undertaken, but the additional analyses do not significantly alter the relative trends and so will not be discussed further.

Table 23: Comparative statistics for vulnerability models with the kriged values.

Model	Highest Mean NO_3 Value	Is Highest Mean Value in Class 1 ?	Range of Mean NO_3 Values Across Classes	Spearman Rank Correlation	ANOVA F Statistic
Model1 v1	32.26	No	19.29 - 32.26	-.842	189.212
Model1 v2	32.26	No	19.27 - 32.26	-.794	198.420
Model2 v1	30.15	No	19.76 - 30.15	-.857	307.397
Model2 v2	30.10	No	21.60 - 30.10	-.357	254.184
Model3 v1	37.17	Yes	20.18 - 37.17	-.950	259.163
Model3 v2	37.32	Yes	19.96 - 37.32	-.967	274.975
Model4 v1	34.16	Yes	18.44 - 34.16	-.786	411.599
Model4 v2	34.04	Yes	19.24 - 34.04	-.893	455.726
Model5 v1	32.86	No	19.56 - 32.86	-.952	205.311
Model5 v2	33.78	No	19.78 - 33.78	-.927	204.597
Model6 v1	32.55	No	19.90 - 32.55	-.939	285.808
Model6 v2	32.37	No	21.45 - 32.37	-.891	248.113

Note: All values shown in this table exclude Class 0.

7. Interim Conclusions

The results of the statistical analyses confirmed a broad association between the vulnerability classes and the groundwater nitrate measurements. This supported the validity of the methodology used to develop the vulnerability models and suggested that one of the classifications could possibly form the basis for a revised groundwater NVZ definition. Of all the classifications, the two variants of Model 3 generally performed best in identifying gradients in nitrate values and consequently appeared to merit particular consideration. On statistical grounds, it was hard to separate the two variants of Model 3 and any choice between them probably depends more on views regarding the reliability of the information on low permeability drift cover. If the drift coverage is considered as only a partial barrier to contamination, then Variant 2 of Model 3 represents a more cautious approach to groundwater protection than Variant 1.

A meeting to review the analyses and results presented above was held in January 2000. On the basis of these discussions it was decided to undertaken further work to refine the vulnerability classifications and repeat the validation exercise. Part III of this report presents the results of that work.

8. Further Vulnerability Models

8.1 Model Definitions

As part of the process of refining the vulnerability classifications it was decided to just use the Environment Agency Groundwater Vulnerability Maps (i.e. the GVQ layer) to represent aquifer characteristics. It was also concluded that there was no need to continue with two different treatments of the Low Permeability Drift (LKDRIFT) layer and a precautionary approach was adopted using the Variant 2 method (i.e. drift coverage is considered as only a partial barrier to contamination) rather than the more absolute Variant 1. Both these decisions reflected the outcomes of the statistical analyses discussed in Section 6.2

Three main types of vulnerability model, namely *intrinsic*, *specific* and *risk*, were again examined in the second assessment exercise. Table 24 lists the data sources that formed the components of each model. Once the four layers for each model had been overlaid, the next stage was to convert the different combinations of attributes into a relative vulnerability scheme (i.e. a ranking from highest to lowest). The leaching layers were coded so that an increase from one band to another represented a similar increase in the risk of nitrate pollution. In ADAS2 low soil drainage equates with high vulnerability, as any nitrate will be less diluted. In ADAS4 and ADAS5 high nitrate concentrations represent high vulnerability. This classification scheme is presented in Table 25 and it is important to note that the classes are not based on even increments. For instance, greater relative importance is given to small changes in the quantity of soil drainage when the overall amount of drainage is limited.

The Groundwater Vulnerability Maps include a ranking of aquifer and soil types in terms of vulnerability and this classification was utilised as a basis for the ranking. As mentioned above, a conservative approach was adopted to the treatment of the drift layer and the derived ranking gave priority to the inherent vulnerability of aquifers (i.e. the degree of permeability) rather than the absence of drift. This vulnerability coding is presented in Table 26.

An important modification was made concerning the manner in which the data layers were weighted when they were combined to produce the vulnerability models. As discussed in Section 4.3, the initial method gave greater emphasis to the ADAS leaching data, but this extra influence was not precisely specified. Little evidence could be found in the literature to indicate the relative importance of the leaching score relative to the combined soil/drift/aquifer layer and so three variants of each model were produced each with different weightings. Variant 1 assumed the leaching layer to be half as important as the combined soil/drift/aquifer layer. Variant 2 weighted the two layers equally, while Variant 3 assumed the leaching layer to be twice as important as the soil/drift/aquifer characteristics. An additional benefit of using these variants was that they made it possible to examine how sensitive the models were to changes in layer weighting. The failure to do this is a criticism that has been directed at similar studies in the past (Merchant, 1994).

Another issue involved the method used to divide the final combined vulnerability scores into classes. In the initial research, ten classes were derived for each model by simply taking tenth percentile groups of the highest score in each classification table (see Section 4.3). Two limitations of this approach, however, were that it subsequently contributed to very uneven distributions of boreholes across classes and also produced situations where the comparison of predictive performance between models was often based on different numbers of classes (see Table 13).

Table 24: Components of the three refined nitrate vulnerability models.

	Vulnerability Models		
Layer	**Intrinsic**	**Specific**	**Risk**
Leaching	ADAS2	ADAS5	ADAS4
Soil	SOIL1	SOIL3	SOIL3
Drift	LKDRIFT	LKDRIFT	LKDRIFT
Aquifer	GVQ	GVQ	GVQ

Leaching Layers

ADAS2: Simulated mean annual soil drainage from all land (mm).

ADAS4: Simulated mean nitrate-nitrogen concentrations in land drainage (mg/l NO_3) using current land use.

ADAS5: Simulated mean nitrate-nitrogen concentrations in land drainage (mg/l NO_3) assuming 100 kg N/ha applied to all land.

Soil Layers

SOIL1: The seven soil categories present on the Environment Agency GVMs.

SOIL3 SOIL1 reclassified to remove information about the soil's ability to attenuate. Consists of two classes HI (high + intermediate) and L (low).

Drift Layer

LKDRIFT: Low permeability drift taken from the GVMs.

Aquifer Layer

GVQ: Aquifer classification from the GVMs. It consists of three classes namely major aquifer, minor aquifer and non-aquifer.

Table 25: Classification of the leaching layers.

	Class	ADAS 4 & 5 Nitrate concentration (mg/l NO_3)	ADAS2 Soil drainage (mm)
Most Vulnerable	1	>200	<100
↓	2	175-200	100 – 150
	3	150-175	150 – 200
	4	125-150	200 – 250
	5	100-125	250 – 300
	6	75-100	300 – 350
	7	70-75	350 – 400
	8	65-70	400 – 450
	9	60-65	450 – 500
	10	55-60	500 – 1000
	11	50-55	1000 – 1500
	12	45-50	1500 – 2000
	13	40-45	2000 – 3000
	14	35-40	>3000
	15	30-35	
	16	25-30	
	17	20-25	
	18	15-20	
	19	10-15	
	20	5-10	
Least Vulnerable	21	<5	

Table 26: Classification of soil, drift and aquifer type in the vulnerability models

Risk and Specific Vulnerability Models			Vulnerability Classification	Intrinsic Vulnerability Models		
GVQ	DRIFT	SOIL3		GVQ	DRIFT	SOIL1
Major	Absent	HI	1	Major	Absent	H1
Major	Absent	L	2	Major	Absent	H2
Major	Present	HI	3	Major	Absent	H3
Major	Present	L	4	Major	Absent	I1
Minor	Absent	HI	5	Major	Absent	I2
Minor	Absent	L	6	Major	Absent	L
Minor	Present	HI	7	Major	Present	H1
Minor	Present	L	8	Major	Present	H2
			9	Major	Present	H3
			10	Major	Present	I1
			11	Major	Present	I2
			12	Major	Present	L
			13	Minor	Absent	H1
			14	Minor	Absent	H2
			15	Minor	Absent	H3
			16	Minor	Absent	I1
			17	Minor	Absent	I2
			18	Minor	Absent	L
			19	Minor	Present	H1
			20	Minor	Present	H2
			21	Minor	Present	H3
			22	Minor	Present	I1
			23	Minor	Present	I2
			24	Minor	Present	L

In order to facilitate more consistent comparisons, several other methods of converting vulnerability scores to classes were investigated. One approach was to rank the boreholes with predicted nitrate levels on their vulnerability scores and then subdivide the ranked sequence into classes each containing approximately 10% of observations. This method produced a more even spread of boreholes between classes (though some problems arising from tied scores still occurred), but the class boundaries tended to be heavily influenced by the uneven geographical distribution of boreholes and lacked any straightforward interpretation so far as the national vulnerability maps were concerned.

A further method was therefore developed that made use of the capability of the GIS to generate tabulations relating vulnerability scores to the cumulative percentage area of polygons. From these tables it was possible to identify vulnerability scores which defined class boundaries that matched as closely as possible to particular percentages of the aquifer area (i.e. the most vulnerable 5%, the next 10% etc). In the first instance classes were delimited based on each 10% of area, but this still produced a rather uneven distribution of boreholes because of the clustering of sites within the most vulnerable areas. A variable set of class intervals was therefore adopted with the percentages of aquifer area being 0-2.5%, 2.5-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-75% and 75-100%. It should also be noted that it was rarely possible to match these limits exactly because of polygon areas spanning the precise boundary.

8.2 Characteristics of the Refined Vulnerability Maps

Examples of five of the vulnerability maps produced using the methodology described in Section 8.1 are presented in Appendix C. The maps include Variant 1 (i.e. with the leaching layer weighted as half as important as the combined soil/drift/aquifer characteristics) for the *intrinsic* and *risk* models, together with all three variants for the *specific* model. Inspection of the maps reveals some obvious similarities, but differences are also evident, one example being in the three variants of the *specific* model with a greater prominence of higher vulnerability areas in East Anglia when the leaching scores are given most weight.

Spearman rank correlations (Siegel, 1956) were calculated to undertake a more quantitative assessment of the similarities in map patterns between different vulnerability models and variants. This statistical test examines the difference in rank of vulnerability scores between two models and was modified to account for the land area in each vulnerability category (Bonham-Carter, 1994). The correlation coefficient ranges from +1.0 (perfect positive association), through zero (no association) to -1.0 (perfect negative association).

The correlation results are summarised in Tables 27 and 28. They indicate that all the map patterns show general similarities with the lowest correlation being +0.55. Table 27 suggests, as might be anticipated, that the intrinsic and risk vulnerability models tended to be the most different to each other. The effect of weighting variants is shown in Table 28 and implies that the specific vulnerability model variants were the most similar to each other. This may be due to the homogeneous nature of the leaching layer incorporated.

Table 27: Comparing vulnerability scores between models.

	Variant 1		Variant 2		Variant 3	
	Risk	Specific	Risk	Specific	Risk	Specific
Specific	0.6609		0.6409		0.6428	
Intrinsic	0.6446	0.7030	0.6069	0.7152	0.6172	0.7038

Table 28: Comparing vulnerability scores within models.

	Risk Model		Specific Model		Intrinsic Model	
	Variant 1	Variant 2	Variant 1	Variant 2	Variant 1	Variant 2
Variant 2	0.5827		0.7256		0.6817	
Variant 3	0.5711	0.5504	0.7361	0.7419	0.6928	0.6782

9. Revised Data on Nitrate Levels in Groundwater

9.1 Amended Borehole Data

Several revisions to the database on nitrate levels in groundwater across England and Wales were supplied by the Environment Agency during the first half of 2000. These included some amendments to the trend values for 2017, corrections to approximately 200 values from three regions originally reported as N rather than NO_3, removal of about 35 duplicate records (previously listed with both N and NO_3 levels), and new data for around 190 sites. It was also decided that if a site had a trend value for 2017 lower than 50 mg/l NO_3, but exceeded this limit in its time series, then the value for 2017 should be set to 50 mg/l NO_3 as a precautionary measure. The final database received in July 2000 contained 3,714 records. Point-in-polygon operations were then implemented within the GIS software to match the locations of the nitrate measurements with their corresponding regions on the nine revised vulnerability classification maps (three variants for each of the three models).

10. Nitrate Variations with the Revised Vulnerability Classes

10.1 Characteristics of the Amended Borehole Data

Table 29 presents a range of descriptive statistics for the nitrate levels and indicates that, on average, the amended values were slightly higher than the initial version of the database. There were 1016 sites (27.4% of 3,714) with 'high' nitrate levels (those with revised 2017 values ≥ 50 mg/l NO_3) and Figure 4 plots their distribution. This map again reveals an uneven spread of sites, with particular clusters in certain aquifers.

Table 29: Descriptive statistics for nitrate levels (mg/l NO_3) in the amended database.

Mean NO_3	30.66	**Std. Deviation**	24.13	**Maximum**	221.24

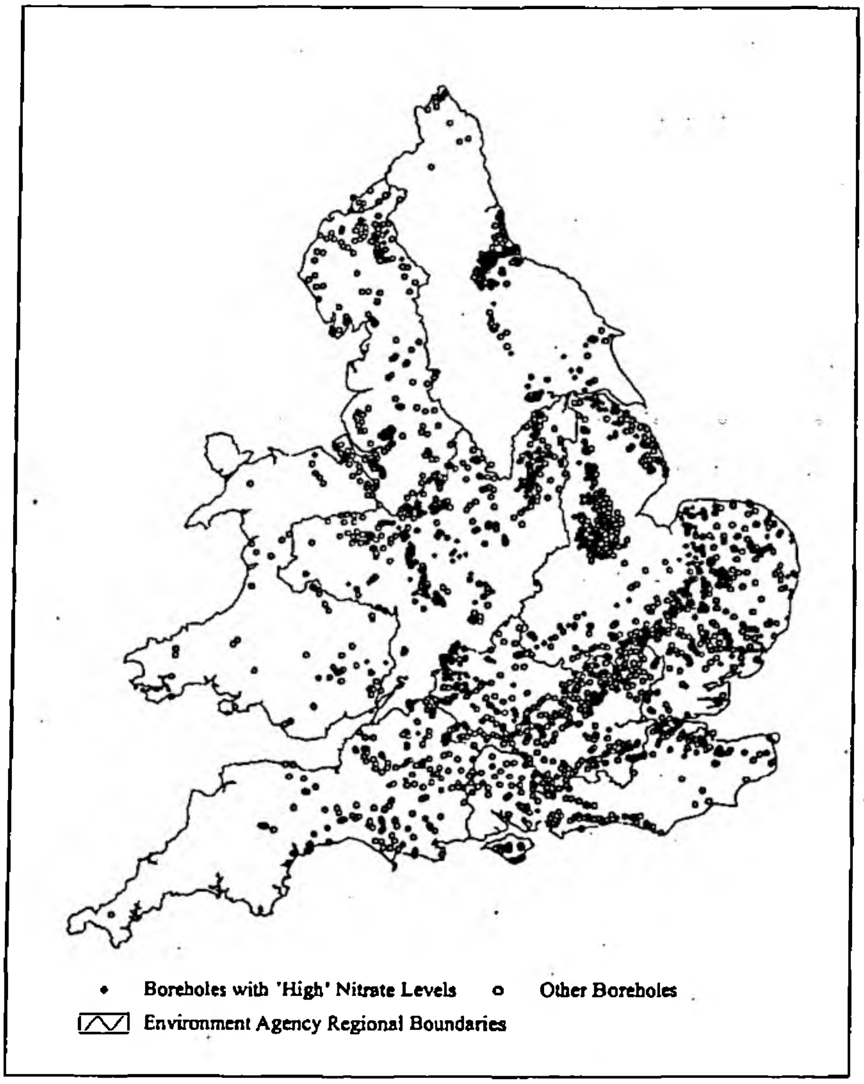


Figure 4: The geographical distribution of boreholes in the amended database.

10.2 Trends in Nitrate Levels Across Revised Vulnerability Classes

Tables with descriptive statistics showing the trends in nitrate levels across classes in the revised vulnerability models are presented in Appendix D. Unlike the initial analyses, each model variant had the same number of vulnerability classes. The general distribution of nitrate measurements across categories was also more even, though there were inevitably some variations reflecting the geographical clustering of borehole sites.

Trends in the mean nitrate values for each model variant are summarised in Table 30. These statistics again show a general tendency for levels to decline from the highest vulnerability classes, though none of the peak values exceed 50 mg/l and the gradients are rarely perfect.

Table 30: Mean nitrate values (mg/l NO_3) in each vulnerability class.

	Intrinsic Model			Specific Model			Risk Model		
Class	v1	v2	v3	v1	v2	v3	v1	v2	v3
1	33.96	37.34	36.69	43.16	43.16	43.16	42.32	42.09	42.06
2	39.07	38.77	34.16	41.91	41.91	41.75	46.26	46.26	45.14
3	41.98	37.98	38.09	41.58	41.50	40.95	38.89	38.29	39.31
4	35.39	35.12	33.36	31.65	31.65	32.82	32.46	32.38	32.85
5	31.62	30.91	30.75	32.19	32.09	30.85	32.74	32.09	28.05
6	26.09	26.24	30.45	27.20	27.33	26.61	26.16	26.23	31.02
7	23.18	24.44	30.73	22.91	22.40	22.69	20.47	25.86	27.61
8	25.28	25.10	24.21	23.01	22.39	22.38	24.56	22.98	24.12
9	17.28	16.38	13.18	15.37	15.92	15.45	16.26	15.66	15.00

To assess the overall predictive performance of each vulnerability model the same calculations as used previously were carried out. The results are summarised in Table 31. If a model performs well across all the different parameters then this indicates a strong ability to identify a consistent gradient in nitrate values across vulnerability classes.

Table 31: Comparative statistics for revised vulnerability model performance.

Model	Highest Mean NO_3 Value	Is Highest Mean Value in Class 1 ?	Range of Mean NO_3 Values Across Classes	Spearman Rank Correlation	ANOVA F Statistic
Intrinsic v1	42.0	No	17.3 - 42.0	-0.867	33.00
Intrinsic v2	38.8	No	16.4 - 38.8	-0.933	25.48
Intrinsic v3	38.1	No	13.2 - 38.1	-0.933	18.04
Specific v1	43.2	Yes	15.4 – 43.2	-0.967	45.02
Specific v2	43.2	Yes	15.9 – 43.2	-0.983	44.78
Specific v3	43.2	Yes	15.5 – 43.2	-1.000	45.93
Risk v1	46.3	No	16.3 – 46.3	-0.950	46.13
Risk v2	46.3	No	15.7 – 46.3	-0.983	42.50
Risk v3	45.2	No	15.0 – 45.2	-0.967	36.35

Note: All values shown in this table exclude Class 0.

Table 31 indicates that all the model variants performed fairly well at differentiating boreholes with contrasting groundwater nitrate concentrations. Overall, the performance of the vulnerability models was slightly better than in the initial analysis, though variations in numbers of classes make precise comparison difficult. Within Table 31 it is evident that the *intrinsic* vulnerability model variants tended to perform least well, while the *specific* and *risk* models did better. This implies that a nitrate-leaching model is a crucial element in vulnerability classification. However, the *risk* and *specific* models produced quite similar outcomes, a result that requires addition comment given that the former incorporated additional land use information. This situation may be due to the time difference between the land use (1994/95) and borehole nitrate data (2017). It is also possible that the *risk* model would have performed better if it had been possible to incorporate information on the thickness of the unsaturated zone (i.e. depth to the water table will influence the time lag between land use change and nitrate concentration response). Overall, however, a simple explanation is not apparent. It is also difficult to detect any clear pattern as to which weighting variant produced the best results.

Another perspective is provided by Table 32 which, for each model, tabulates the percentage of boreholes with NO_3 levels of at least 50 mg/l (i.e. 'high' levels) within different proportions of aquifer area ranked by vulnerability score. These results again suggest that the revised vulnerability models have a generally good ability to identify areas containing boreholes with 'high' predicted nitrate levels and, if anything, suggest that some variants of the *specific* model have a slight edge in performance over the other vulnerability classifications.

Table 32: Ability of vulnerability models to identify areas with 'high' nitrate levels.

Model	% of High Boreholes Within Most Vulnerable 15 % of Area	% of High Boreholes Within Most Vulnerable 20 % of Area	% of High Boreholes Within Most Vulnerable 30 % of Area
Intrinsic v1	55.4	64.1	77.6
Intrinsic v2	54.9	67.5	78.5
Intrinsic v3	48.9	62.6	80.4
Specific v1	59.8	67.6	73.3
Specific v2	60.0	67.8	80.2
Specific v3	61.8	71.4	82.0
Risk v1	54.5	62.5	78.2
Risk v2	54.8	64.1	77.9
Risk v3	56.6	64.2	73.9

Note: The percentages of area are based on aquifer area. It needs to be recognised that the distribution across vulnerability scores is somewhat 'lumpy' (i.e. to exceed the 15 % threshold may involve a value of 16 or 17 %). The borehole statistics are based on the 950 boreholes with vulnerability scores and NO_3 levels of at least 50 mg/l.

On the basis of all these results, Variant 3 of the *specific* model was selected for further consideration. One advantage was that the absence of land use information implied that any decisions based upon this model would still be applicable even if current land use changed. Statistically, the model variant performed strongly with a perfect Spearman correlation and the second highest ANOVA F statistic. In addition, *specific* vulnerability models were best able to identify the areas with the highest borehole nitrate concentrations and were the least sensitive to the weighting variant used. A map of the vulnerability classes for this model variant is shown in Figure 5.

Figure 5: Distribution of classes for the Specific vulnerability model, Variant 3.

11. Relationships with Borehole Sampling Depth

11.1 Rationale for the Analysis

One possible concern with the assessments described in previous sections was that contrasts in nitrate levels between vulnerability categories might also reflect differences in the depth of boreholes. Previous studies (e.g. Foster *et al.*, 1982; Parker *et al.*, 1991) have found that nitrate levels tend to decrease with depth. It was therefore thought important to examine the extent to which the predicted nitrate levels for 2017 were influenced by both vulnerability and well depth characteristics. This research is discussed in more detail by Betson and Lovett (2001) with a summary presented below.

11.2 Depth Details

Through scrutiny of Environment Agency records on borehole construction details it proved possible to define sampling depths for some 55% of the 3,714 sites in the revised database. A distinction was first made between wells open to groundwater ingress (i.e. screened or unlined) and those sections of wells cased or grouted (i.e. closed to ingress). This information was then used to derive the depth range over which each well was open to groundwater and could therefore sample nitrate concentrations. Two different measurements were defined as shown in Figure 6. Minimum depth represents the uppermost depth open to groundwater in the well, while maximum depth is the deepest point. The dashed line in Figure 6 indicates the depth over which the well is open to groundwater ingress. From the original set of 3,714 records it was possible to create a *Max Depth* subset of 2,008 values and a *Min Depth* subset of 2,036 observations due to the availability and quality of the construction details for each well.

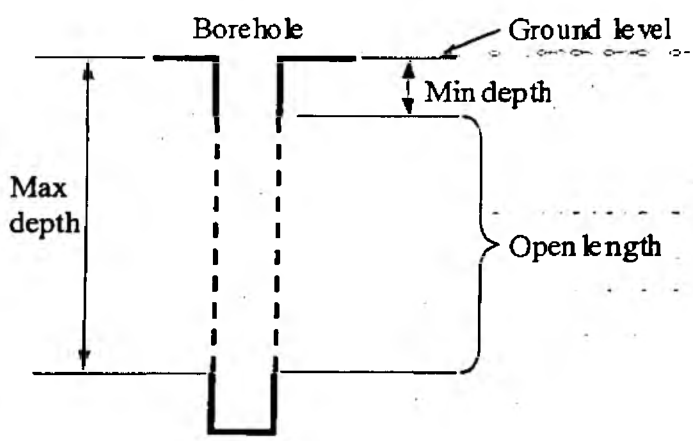


Figure 6: The definition of well sampling depths.

The depth measurements were subsequently grouped into categories to allow cross-tabulations with the nine classes from Variant 3 of the *specific* vulnerability model. Initially, the depth categories were based on fixed definitions for very shallow, shallow and deep ranges, but this produced highly skewed results with large numbers of wells falling into the deep category for *Max Depth* and the very shallow group for *Min Depth*. To overcome this problem, four categories were defined using the quartile values for each depth definition (this approach gave approximately similar numbers of observations in each class).

11.3 Trends in Nitrate Levels with Vulnerability and Depth

Table 33 shows the mean predicted nitrate concentration (mg/l NO_3) in 2017 for wells grouped by vulnerability class and *Min Depth* quartile. Table 34 does the same using the *Max Depth* measurements. It should be noted that both tables exclude wells in non-aquifer areas (as defined in Figure 5) so Table 33 is based on 1,849 observations and Table 34 on 1,827. The great majority of cells in both cross-tabulations contain at least 30 observations, but there are four cells in Table 33 and three in Table 34 with fewer than 20 observations (these all occur in vulnerability classes 8 and 9).

Table 33: Mean nitrate level (mg/l NO_3) by vulnerability class and Min Depth quartile.

	Min Depth Quartile (m)				
Vulnerability Class	**0**	**1-12**	**13-28**	**29-1056**	**Total**
1	43	48	42	37	43
2	45	48	42	38	43
3	41	43	46	34	41
4	35	36	36	25	33
5	31	32	31	22	30
6	29	41	24	19	27
7	27	20	24	16	21
8	31	31	16	10	23
9	9	22	15	11	14
Spearman Correlation	-0.93	-0.90	-0.93	-0.97	-0.98

Table 34: Mean nitrate level (mg/l NO_3) by vulnerability class and Max Depth quartile.

	Max Depth Quartile (m)				
Vulnerability Class	**0-45**	**46-76**	**77-120**	**121-1140**	**Total**
1	50	40	41	42	44
2	44	42	48	40	43
3	41	51	33	39	41
4	38	39	27	34	34
5	33	29	28	27	30
6	41	22	33	16	28
7	22	25	21	15	20
8	32	26	15	8	23
9	12	25	3	7	14
Spearman Correlation	-0.88	-0.82	-0.87	-1.00	-0.98

Spearman rank correlation coefficients (r_s) were calculated to assess the association between mean nitrate values and vulnerability classes for each depth quartile. In this instance, strong negative correlations were anticipated, representing a situation where nitrate values declined across the vulnerability classes. The correlation coefficients are shown in the bottom rows of Tables 33 and 34.

Multiple regression techniques (see Schroeder *et al.*, 1986; Rogerson 2001) were used to examine the extent to which variations in well nitrate concentrations could be predicted from their vulnerability scores and depth measurements. These analyses provided an indication of the relative importance of vulnerability scores and depth measurements as predictors of nitrate concentrations, and also made it possible to assess the relative merits of the *Min Depth* and *Max Depth* variables. It should be noted that the regressions used numerical vulnerability scores and depths (not categories), and that the possibility of using various variable transformations (e.g. logarithmic) or functional forms (e.g. quadratic) was thoroughly explored. In the event, however, no obvious improvement on a standard linear model could be identified and the results obtained are summarised in Table 35.

Table 35: Results of the multiple regression analyses.

Regression Parameters	**Model with Min Depth**	**Model with Max Depth**
Intercept	50.55	53.34
Slope Coefficient for Vulnerability	-1.15	-1.29
T Statistic	14.07	15.74
Slope Coefficient for Depth	-0.16	-0.04
T Statistic	7.97	5.97
R^2 (% of Variance Accounted For)	13.60	13.00

11.4 Discussion of Trends

Examination of the mean values in Tables 33 and 34 indicates that nitrate concentrations are associated with variations in both vulnerability and well depth. There are consistent trends for average nitrate levels to decline down each column (e.g. as vulnerability decreases and well depth remains relatively constant) and these gradients are confirmed by the strongly negative coefficients for the Spearman correlations. Several of the correlations are slightly stronger in Table 33 (based on *Min Depth*) than Table 34 (*Max Depth*), but there is not a substantial difference in the results.

Looking across the rows in the table it is apparent that nitrate concentrations tend to decline with increasing depth in each vulnerability class. In general, the variation with depth is less than that by vulnerability and often the second depth quartile has similar or higher average nitrate concentrations than the first. This situation is particularly evident in Table 33 where the first quartile represents minimum depth values of 0 (i.e. the well is open to groundwater at the surface) and tends to show slightly lower values than the second quartile (1 to 12 m depth).

Several comments can be made about the regression results in Table 35. The first point is that with R^2 values of around 13% neither model is an especially good predictor of overall variability in nitrate levels. This suggests that other factors aside from the vulnerability score and well depth may be important. On the other hand, the slope coefficients in Table 35 accord with prior expectations. For example, the slope coefficients for vulnerability score indicate how the predicted nitrate level (in mg/l) changes for a one-unit increase in score (i.e. the negative slope values denote a *decline* in nitrate levels with a *reduction* in vulnerability). The slope coefficients for depth are also negative, signifying lower predicted nitrate levels with increasing depth, and there is a steeper gradient for minimum depth than maximum.

T values measure the statistical significance of the slope coefficients and indicate that all the variables are highly significant predictors (i.e. a T value of at least two generally denotes a significant predictor at the 95% confidence level). Comparing the T statistics suggests that the vulnerability score is a more important factor than the depth measurement and it is also worth noting that the value for *Min Depth* is slightly larger than that for *Max Depth*. This implies that when the variations in vulnerability are controlled for, there is a little stronger association between nitrate concentration and *Min Depth* than *Max Depth*. Overall, the regression results suggest that *Min Depth* is a preferable measure of well depth for the purposes of investigating variations in nitrate concentrations, though the difference from *Max Depth* is not especially large.

From these results it is clear that nitrate concentrations are associated with variations in both the vulnerability classes and well depth. The findings also suggests that the trends in nitrate levels across vulnerability classes are not simply an artefact of contrasts in borehole depth and more generally help to confirm the robustness of the methodology used to generate the vulnerability classifications. It was therefore decided to use Variant 3 of the *specific* vulnerability model as one contributing element of a preliminary definition for revised groundwater NVZs. Part IV of this report presents the methodology and outcomes of this work.

PART IV

12. A Methodology for Preliminary NVZ Definition

12.1 Thresholds for Vulnerability Scores

The EU Drinking Water Directive [98/83/EC] sets a nitrate concentration of 50 mg/l as the limit for water destined for human consumption. As an initial step, therefore, it was necessary to identify a threshold in the vulnerability scores that would encompass a large proportion of the boreholes with historical or predicted nitrate value above this limit (these are termed 'high' boreholes in what follows). This was done by generating and examining tables or plots showing how nitrate levels changed as an increasing proportion of the aquifer area was included. Table 36 presents an excerpt from such a listing, the columns representing

- the vulnerability score (note that lower values indicate greater vulnerability)
- the cumulative percentage of aquifer area
- the number of boreholes (out of 3295 on aquifers)
- the cumulative percentage of the 3295 boreholes
- the number of boreholes with 'high' nitrate levels (out of 950)
- the cumulative percentage of the 950 'high' boreholes
- the average NO_3 level (mg/l) for boreholes with the relevant vulnerability score
- the cumulative average NO_3 level (mg/l) for boreholes

Table 36: Changes in nitrate levels with decreasing vulnerability of aquifer area.

Vuln Score	Cum % Aq Area	All Boreholes		'High' Boreholes		NO_3 Level	
		Number	Cum %	Number	Cum %	Average	Cum Av.
4.625	2.773	355	10.774	172	18.105	43.16	43.16
6.625	4.621	198	16.783	94	28.000	41.91	42.72
7.250	4.670	5	16.935	2	28.211	35.60	42.65
8.625	8.432	377	28.376	169	46.000	41.58	42.22
9.250	8.453	0	28.376	0	46.000		42.22
9.875	9.015	53	29.985	17	47.789	36.47	41.91
10.625	16.209	469	44.219	133	61.789	32.39	38.85
11.250	16.353	20	44.825	9	62.737	34.25	38.79
11.875	16.677	19	45.402	8	63.579	43.53	38.85
12.500	16.725	1	45.432	0	63.579	1.00	38.82
12.625	23.294	451	59.120	74	71.368	30.87	36.98
13.250	23.907	39	60.303	7	72.105	26.85	36.78
13.875	25.043	67	62.337	23	74.526	33.20	36.66
14.500	25.067	1	62.367	0	74.526	28.00	36.66
14.625	27.525	69	64.461	10	75.579	30.08	36.45
15.125	28.724	42	65.736	17	77.368	35.45	36.43
15.250	29.077	18	66.282	1	77.474	22.78	36.31
15.875	32.679	147	70.744	43	82.000	33.22	36.12
16.500	32.944	37	71.866	19	84.000	37.14	36.14
16.625	33.018	0	71.866	0	84.000		36.14
17.125	34.837	65	73.839	14	85.474	21.51	35.74

On the basis of these investigations it was decided to set a threshold at a vulnerability score of 14 (represented by the darker line in Table 36). One of the main reasons for the decision was that this point appeared to represent a distinct 'break' in the trend for the cumulative percentage of 'high' boreholes to increase with greater aquifer area (see Figure 7). Setting such a limit encompassed virtually 75% of the 'high' boreholes within 25% of the aquifer area and, for example, it would have required increasing the share of area to nearly 33% in order to include at least 80% of the 'high' boreholes.

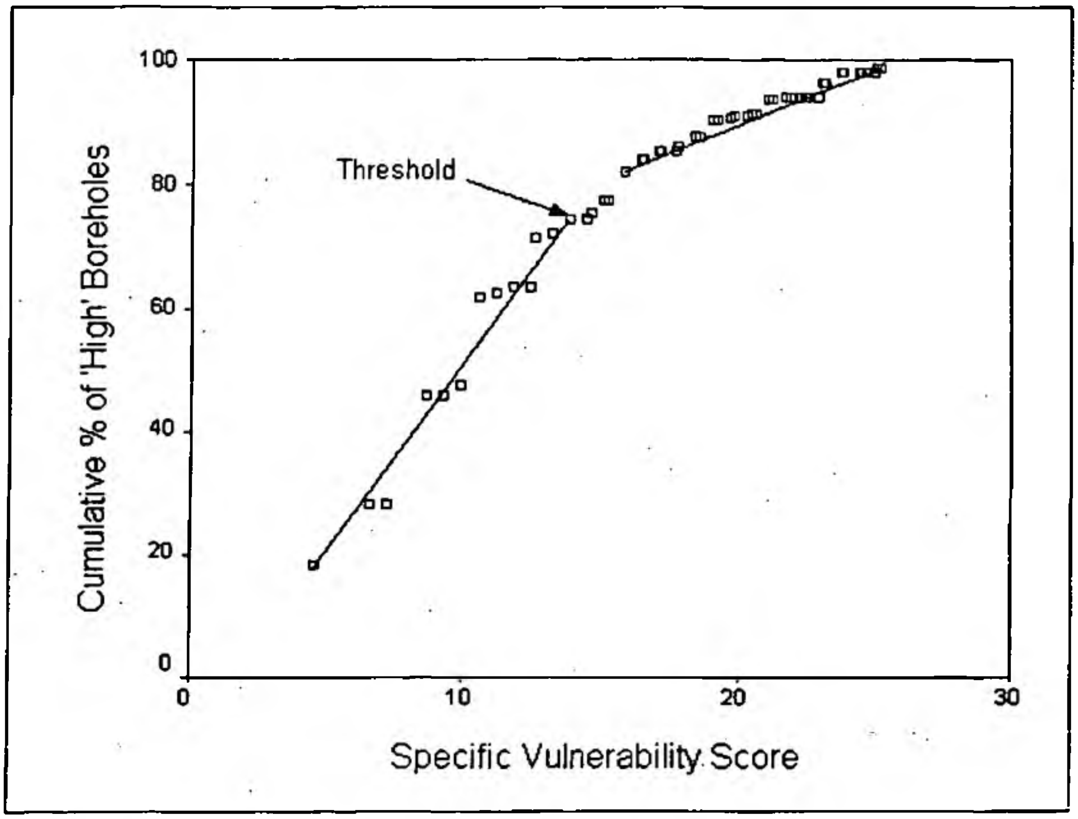


Figure 7: A plot of vulnerability score against the cumulative % of 'high' boreholes.

Figure 8 shows the regions within the selected threshold (these are labelled 'most vulnerable' on the map). Most of the areas are in the south or east of England and there are relatively few in Wales. This map alone, however, was regarded as an insufficient basis for delimiting NVZs because a number of the highlighted regions were areas where groundwater nitrate levels had never been measured or were known to be below the 50 mg/l limit. It was therefore necessary to refine the analysis to incorporate evidence of high nitrate values in boreholes.

12.2 Interpolating Nitrate Levels

As noted previously, the boreholes in the Environment Agency database had an uneven spatial distribution. A geostatistical approach, disjunctive kriging (Matheron, 1976), was consequently used to interpolate a groundwater nitrate concentration surface for England and Wales. This kriging technique estimates the probability that a critical value will be exceeded

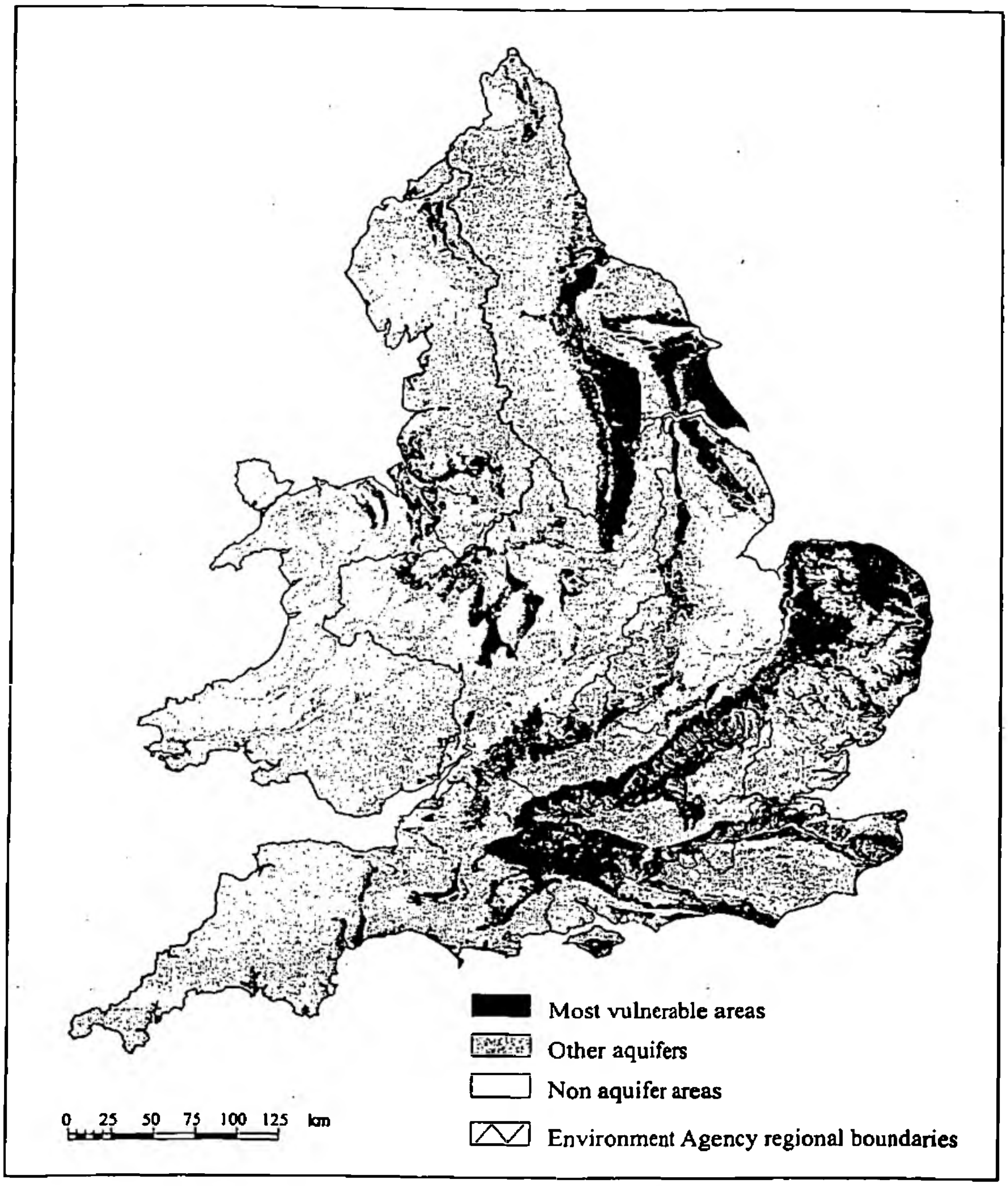


Figure 8: Distribution of areas meeting the Specific vulnerability score threshold.

and has been proposed as suitable for modelling pollutants in groundwater (Oliver, 1991). In addition, a variance estimate can be calculated and this was used to identify areas where there were too few nearby boreholes to produce reliable results. The data were modelled with 50 mg/l as the critical threshold and results produced as a 1.5 km resolution grid covering England and Wales (Frogbrook and Oliver, 2000). Results from these analyses were imported to the GIS.

Areas were regarded as having evidence of high groundwater nitrate values if the kriged probability of a groundwater nitrate concentration of at least 50 mg/l NO_3 was above 0.20. A map of these areas is shown in Figure 9. In addition, regions were excluded if the estimation variance was high (greater than 500) (i.e. confidence in the kriged estimates was limited due to a low density of monitoring points). These areas are shown in Figure 10.

12.3 Combining the Vulnerability and Interpolated Nitrate Data

Figure 11 displays the result of processing the areas where the probability of a groundwater nitrate concentration of at least 50 mg/l NO_3 was above 0.20 to remove those regions where the estimation variance was high (i.e. greater than 500). This map was then combined with the distribution of areas within the vulnerability score threshold to produce Figure 12. The result shows the areas meeting the vulnerability criterion where there was also stronger evidence of 'high' groundwater nitrate levels. Most of the highlighted areas are in the south or east of England, with few in Wales or the south west, north or north west of England.

12.4 Taking Account of Data Accuracy

Overlaying the areas meeting the kriged estimate and vulnerability score thresholds provided a starting point for revised NVZ definition, but it was also considered important to recognise that there would be some uncertainty in boundary positions due to the accuracy of the input data layers. One technique to account for such uncertainty involves generating epsilon bands (Blakemore, 1984) around each boundary, the size of the band radius reflecting the scale of the data used. It was not possible to estimate an epsilon band for the disjunctive kriging results, but a radius of 707.1 m was calculated for the 1 km resolution leaching data. The soil, drift and aquifer layers were derived from the Environment Agency GVMs with a nominal 1:100,000 scale, but it is known that some of the source data were less accurate (Palmer *et al.*, 1995) and so it was decided to make the conservative assumption of an effective resolution corresponding to a scale of 1:250,000. This generated epsilon distances of 125 m (Goodchild, 1993). Making the assumption that the errors in the four data layers were independent of each other they could be combined using the formula suggested by Smith and Campbell (1989). This involves taking the square root of the sum of the squared individual epsilon distances i.e.

$$\text{Overall Epsilon} = \sqrt{(707.1)^2 + (125)^2 + (125)^2 + (125)^2}$$

$$\text{Overall Epsilon} = \sqrt{(546875)} = 739.51 \text{ m}$$

The result was rounded to produce an overall epsilon radius of 740 m and because the purpose of the exercise was to protect groundwater from nitrate pollution the existing boundaries were buffered outwards by this distance (see Figure 13a).

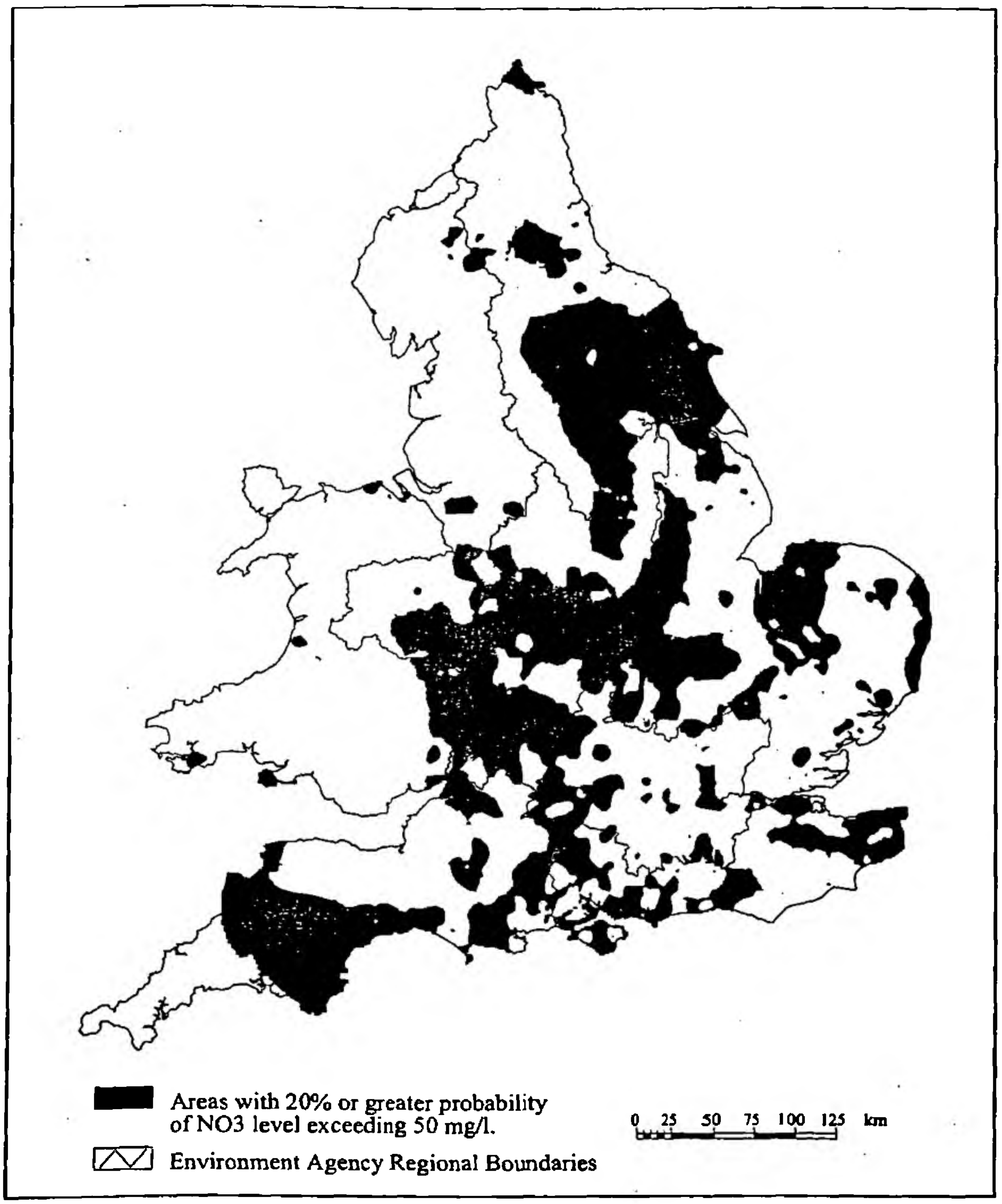


Figure 9: Areas with 20% or greater probability of NO_3 levels exceeding 50 mg/l.

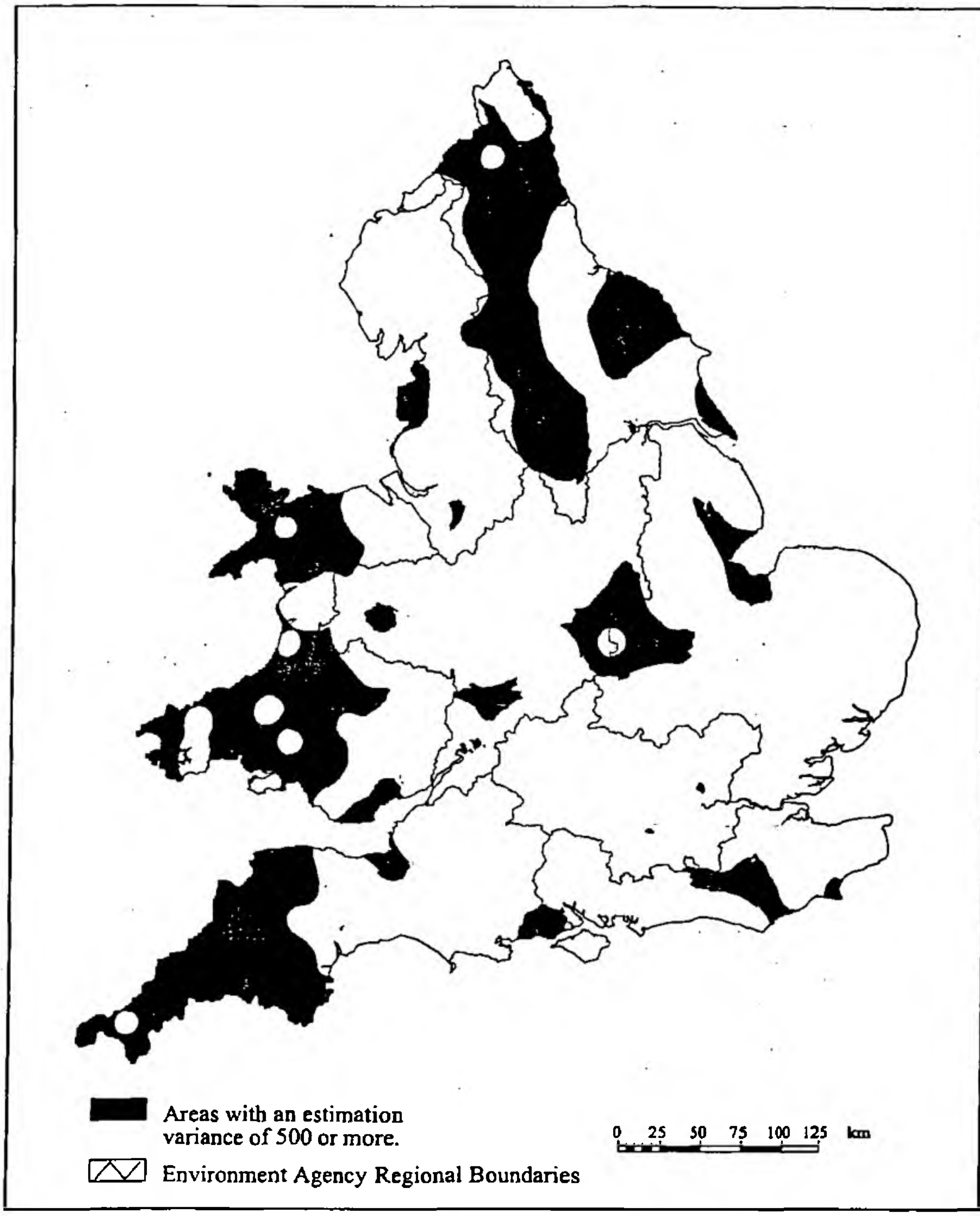


Figure 10: Areas with an estimation variance of 500 or more.

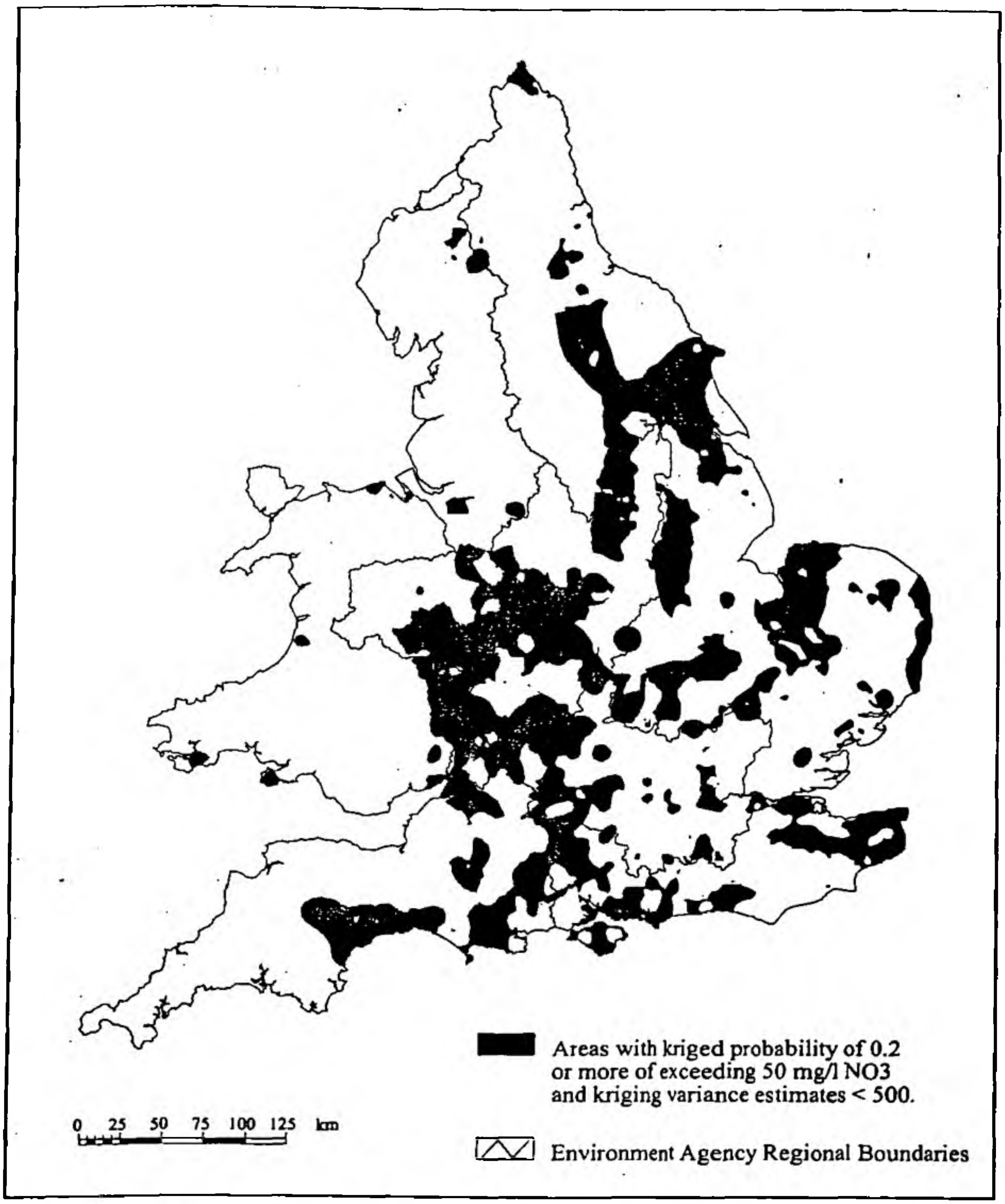


Figure 11: Areas meeting both the nitrate probability and estimation variance criteria.

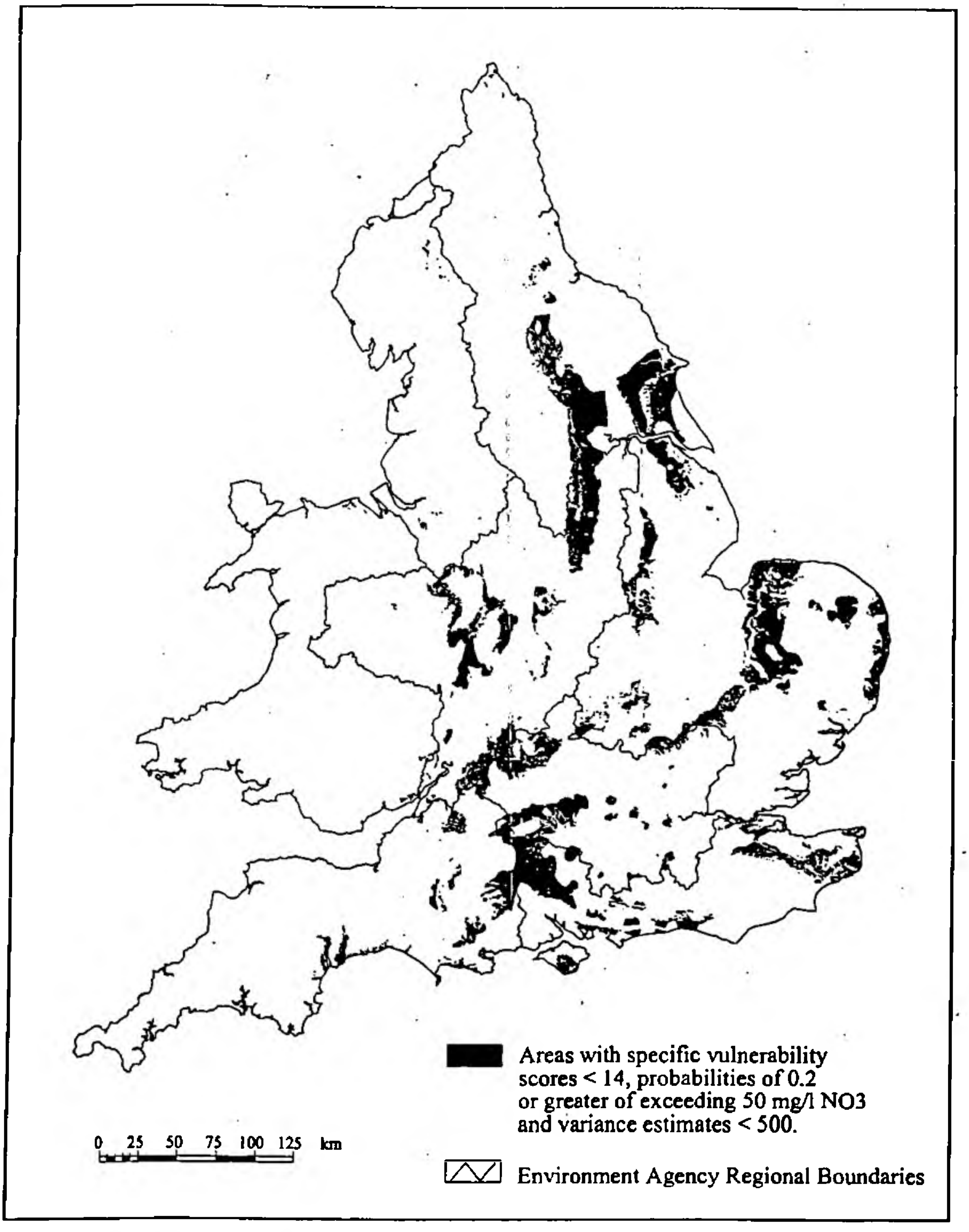


Figure 12: Areas meeting criteria for both interpolated nitrate levels and vulnerability score.

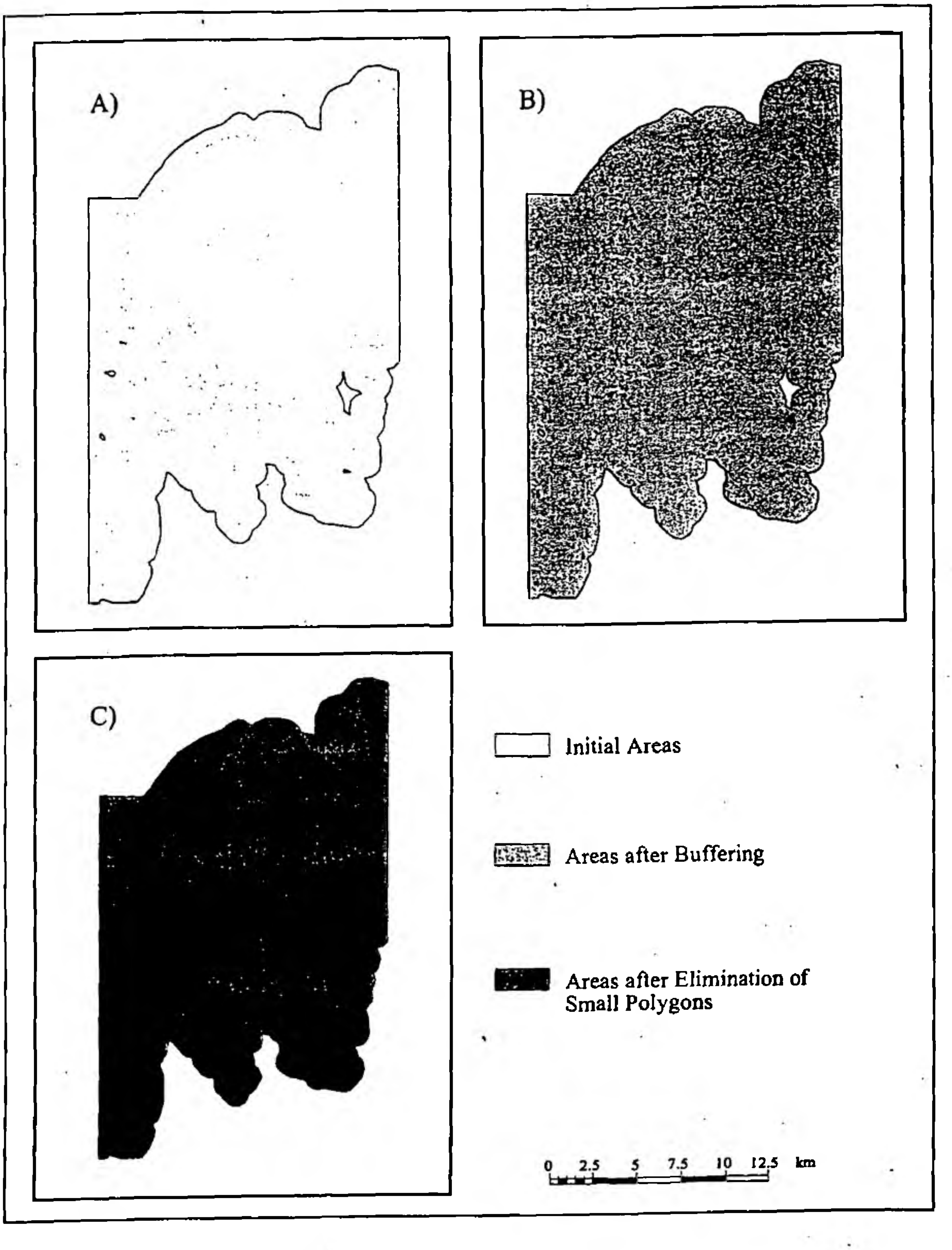


Figure 13: The impact of buffering and polygon elimination processes on zone boundaries.

Figure 14 shows the result of the buffering operation. Several of the zones produced contained small polygons classed as non-vulnerable areas. Many of these cannot be substantiated by the accuracy of the input data and would cause problems from a management point of view. The calculated epsilon radius of 740 m around a single point equates to an area of around 172 hectares and so it was decided to delete non-vulnerable 'islands' smaller than 200 hectares in size. Figures 13b and 13c illustrate the process involved.

A second simplification carried out for data accuracy and management reasons was to remove all the freestanding vulnerable zones (i.e. potential NVZs) with an area smaller than 400 hectares. This threshold was chosen on the basis of the size of region that would be generated by adding a 740 m buffer around an existing circular area of 50 hectares. Figure 15 displays the outcome at the national scale after undertaking the two simplification processes. This latter map looks very similar to Figure 14 because the effect of eliminating small polygons can only be seen when zooming in on particular areas.

Table 37 summarises the areas meeting different criteria and the impact of different processing operations. It can be seen that the areas provisionally identified as a basis for revised groundwater NVZ definition constitute some 15.4% of the total land area in England and Wales.

Table 37: Changes in area through the process of provisional groundwater NVZ definition.

Characteristic	Area (Hectares)	% of Total
Probability of 'high' NO_3 >= 0.20	5,447,343.0	34.97
Estimated Variance < 500	11,266,284.3	72.32
Specific Vulnerability Score < 14	2,702,090.4	17.34
Probability & Estimated Variance	4,093,794.3	26.28
Probability, Est. Variance & Score	1,419,661.6	9.11
Buffer Combined Areas by 740 m	2,405,117.9	15.44
Eliminate 'Island Polygons' < 200 ha	2,409,451.7	15.47
Eliminate 'Potential NVZs' < 400 ha	2,402,643.9	15.42

Note: Total area of England & Wales = 15,579,101.3 hectares from the *specific* vulnerability model.

13. Conclusions

This report has described the implementation of a GIS-based methodology to help identify areas vulnerable to groundwater pollution. The work first involved developing and verifying various approaches to vulnerability mapping, and then used results from what was regarded as the best method as a basis for preliminary definition of revised groundwater NVZs.

The vulnerability model that best predicted variations in groundwater nitrate concentrations contained a nitrate leaching model, but did not include information on land use. This may be

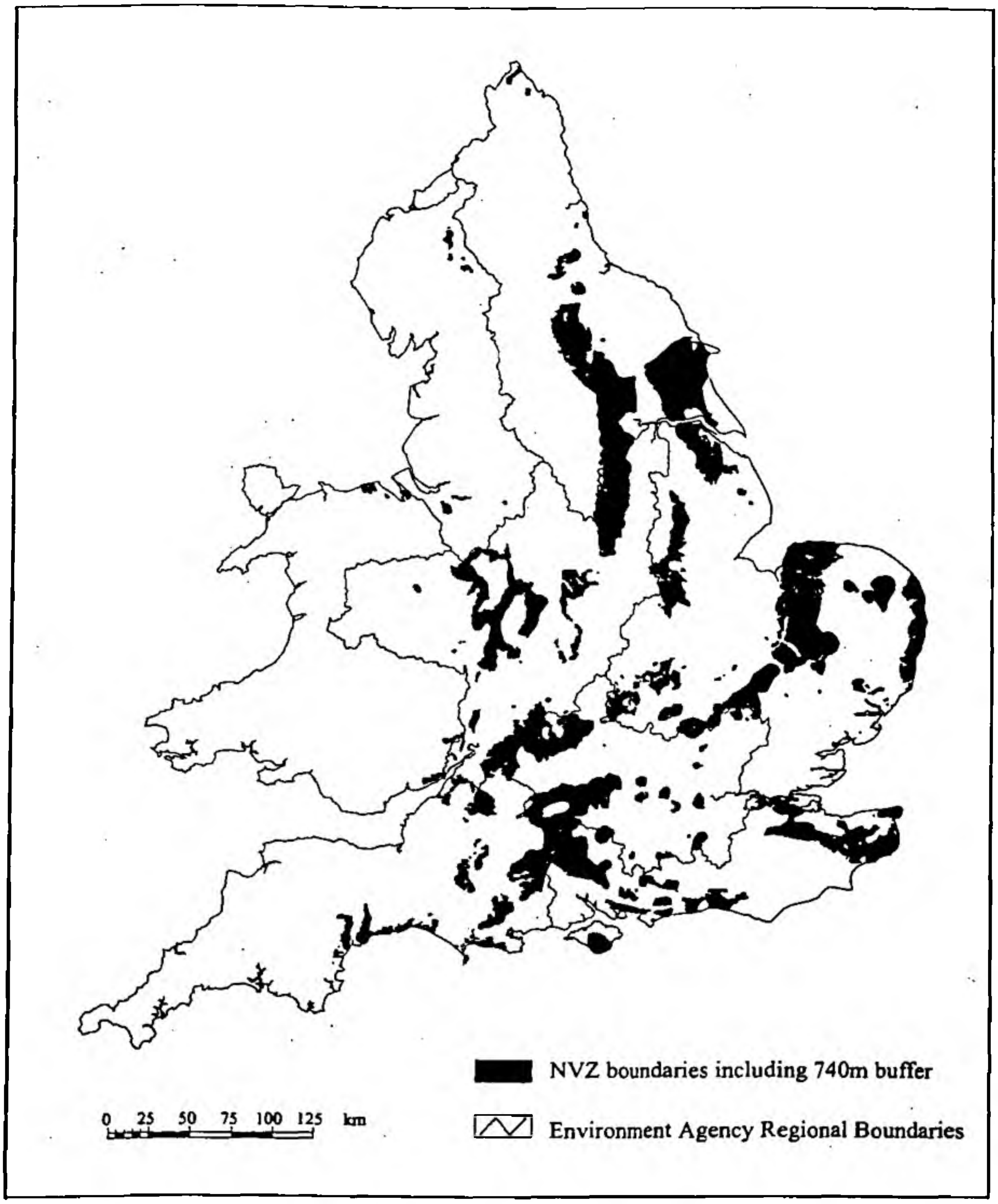


Figure 14: Potential NVZ boundaries after the buffering operation.

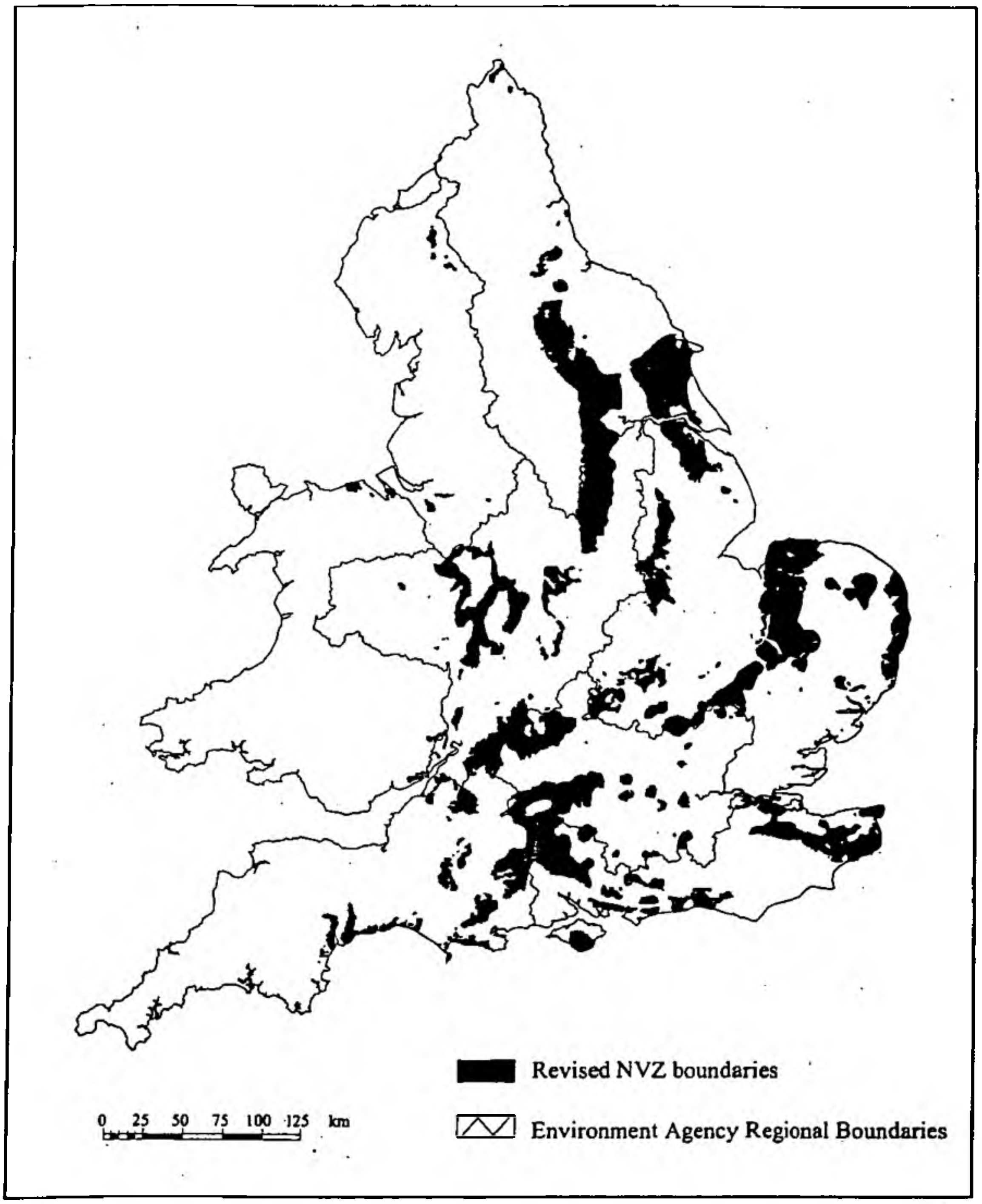


Figure 15: Potential NVZ boundaries after the elimination of small polygons.

explained by the time lag between the land use data in the model and the projected borehole nitrate data. If it had been possible to incorporate information on depth to water table then this might have helped to take account of such time lags. In addition, the *risk* models using actual land use performed relatively poorly in areas where there were localised pockets of heavy nitrate leaching potential. This highlights a limitation of omitting groundwater flow, as the borehole nitrate concentration is likely to be representative of a wider catchment. A future research priority, therefore, might be to try to incorporate these types of variables into national scale vulnerability models. It is also worth noting that the experience of conducting the research revealed a number of difficulties in compiling consistent data on nitrate levels and groundwater characteristics at a national scale. Several of the problems encountered have now been resolved, but further effort in compiling consistent national information would make any similar future investigations of groundwater vulnerability and contamination rather more straightforward.

From the research described in this report it is hopefully evident that the use of GIS provides considerable benefits to the assessment of groundwater vulnerability and the particular problems of protection zone definition. It is important to keep in mind the scales of data used when interpreting the results and consequently a precautionary approach (via buffering and elimination operations) was taken in the identification of potential groundwater NVZs. The final results represent areas that might need to be considered as groundwater NVZs, and the boundaries generated have been supplied to the Environment Agency for further consideration or refinement.

References

Betson,M. and Lovett, A. (2001) "Monitoring point construction as a constraint for vulnerability mapping with GIS", pp. 277-285 in *Protecting Groundwater: Proceedings of an International Conference on Applying Polices and Decision Making Tools to Land-Use Planning*, National Groundwater and Contaminated Land Centre Project NC/00/10, Environment Agency, Birmingham.

Blakemore,M. (1984) "Generalisation and error in spatial databases", *Cartographica*, Volume 21, pp.131-139.

Bonham-Carter,G.F. (1994) *Geographical Information Systems for Geoscientists: Modelling with GIS*, Pergamon, Oxford.

Bryman,A. and Cramer,D. (1997) *Quantitative Data Analysis with SPSS for Windows*, Routledge, London.

Burrough,P.A. and McDonnell,R.A. (1998) *Principles of Geographical Information Systems: Spatial Information Systems and Geostatistics*, Oxford University Press, Oxford.

Department of the Environment, Transport and the Regions, and Ministry of Agriculture Fisheries and Food (1998) *The Action Programme for Nitrate Vulnerable Zones (England and Wales)*, Regulations Statutory Instrument 1998 (1202), The Stationery Office, London.

Environment Agency (1998) *Policy and Practice for the Protection of Groundwater*, The Stationery Office, London.

Foster,S.S.D, Cripps,A.C. and Smith-Carington,A. (1982) "Nitrate leaching to groundwater", *Philosophical Transactions Royal Society of London*, Volume 296, pp 477-489.

Frogbrook,Z. and Oliver,M. (2000) *Disjunctive Kriging of Nitrate Concentration in Aquifers*, Project report for the Environment Agency, University of Reading, Reading.

Goodchild,M.F. (1993) "Data models and data quality: problems and prospects", pp.94-103 in Goodchild,M.F., Parks,B.O. and Steyaert,L.T. (eds.) *Environmental Modelling with GIS*, Oxford University Press, Oxford.

Hiscock,K.M., Lovett,A.A., Brainard,J.S. and Parfitt J.P. (1995) "Groundwater vulnerability assessment: two case studies using GIS methodology", *Quarterly Journal of Engineering Geology*, Volume 28, pp 179-194.

Laurini,R. and Thompson,D. (1992) *Fundamentals of Spatial Information Systems*, Academic Press, London.

Lord,E.I., and Anthony,S.G. (2000) "MAGPIE: A modelling framework for evaluating nitrate losses at national and catchment scales", *Soil Use and Management*, Volume 16, pp.167-174.

Matheron,G. (1976) "A simple substitute for conditional expectation: the disjunctive kriging", pp.221-236 in Guarascio,M., David,M. and Huijbregts,C. (eds.) *Advanced Geostatistics in the Mining Industry*, Reidel, Dordrecht.

Merchant,J.W. (1994) "GIS-based groundwater pollution hazard assessment: a critical review of the DRASTIC model", *Photogrammetric Engineering and Remote Sensing*, Volume 60, pp 1117-1127.

National Rivers Authority (1995) *Guide to Groundwater Vulnerability Mapping in England and Wales*, HMSO, London.

Oliver,M.A. (1991) "Disjunctive kriging: an aid to making decisions on environmental matters", *Area*, Volume 23, No. 1, pp.19-24.

Osborn,S. and Cook,H.F. (1997) "Nitrate vulnerable zones and nitrate sensitive areas: a policy and technical analysis of groundwater source protection in England and Wales", *Journal of Environmental Planning and Management*, Volume 40, pp.217-233.

Palmer,R.C., Holman,I.P. and Lewis,M.A. (1995) *Guide to Groundwater Vulnerability Mapping in England and Wales*, HMSO, London.

Parker,J.M., Young,C.P. and Chilton,P.J. (1991) "Rural and agricultural pollution of groundwater", in Downing,R.A. and Wilkinson,W.B. (eds.) *Applied Groundwater Hydrology*, Clarendon Press, Oxford.

Rivoirard,J. (1994) *Disjunctive Kriging and Non-Linear Geostatistics*, Clarendon Press, Oxford.

Robins,N., Adams,B., Foster,S. and Palmer,R. (1994) "Groundwater vulnerability mapping: the British perspective", *Hydrogéologie*, Volume 3, pp. 35-42.

Rogerson,P.A. (2001) *Statistical Methods for Geography*, Sage Publications, London.

Schroeder,L.D., Sjoquist,D.L. and Stephan,P.E. (1986) *Understanding Regression Analysis: An Introductory Guide*, Quantitative Applications in the Social Sciences No. 57, Sage Publications, Beverly Hills.

Siegel,S. (1956) *Nonparametric Statistics for the Behavioural Sciences*, McGraw-Hill, London

Smith,J.W.F. and Campbell,I.A. (1989) "Error in polygon overlay processing of geomorphic data", *Earth Surface Processes and Landforms*, Volume 14, pp.703-717.

APPENDIX A

Figure A1: Vulnerability classes for Model 1, Variant 1.

Figure A2: Vulnerability classes for Model 1, Variant 2.

Figure A3: Vulnerability classes for Model 2, Variant 1.

Figure A4: Vulnerability classes for Model 2, Variant 2.

Figure A5: Vulnerability classes for Model 3, Variant 1.

Figure A6: Vulnerability classes for Model 3, Variant 2.

Figure A7: Vulnerability classes for Model 4, Variant 1.

Figure A8: Vulnerability classes for Model 4, Variant 2.

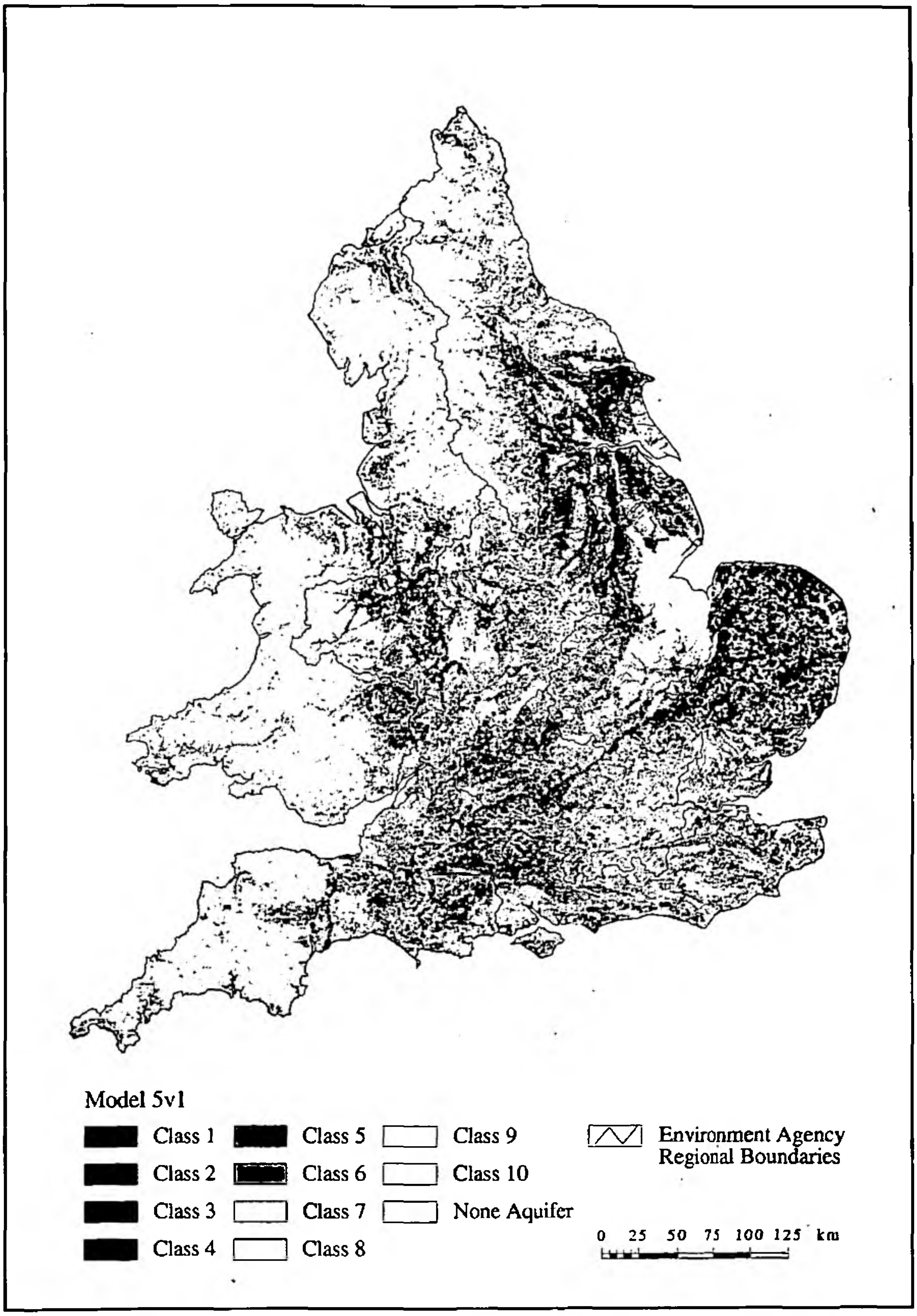


Figure A9: Vulnerability classes for Model 5, Variant 1.

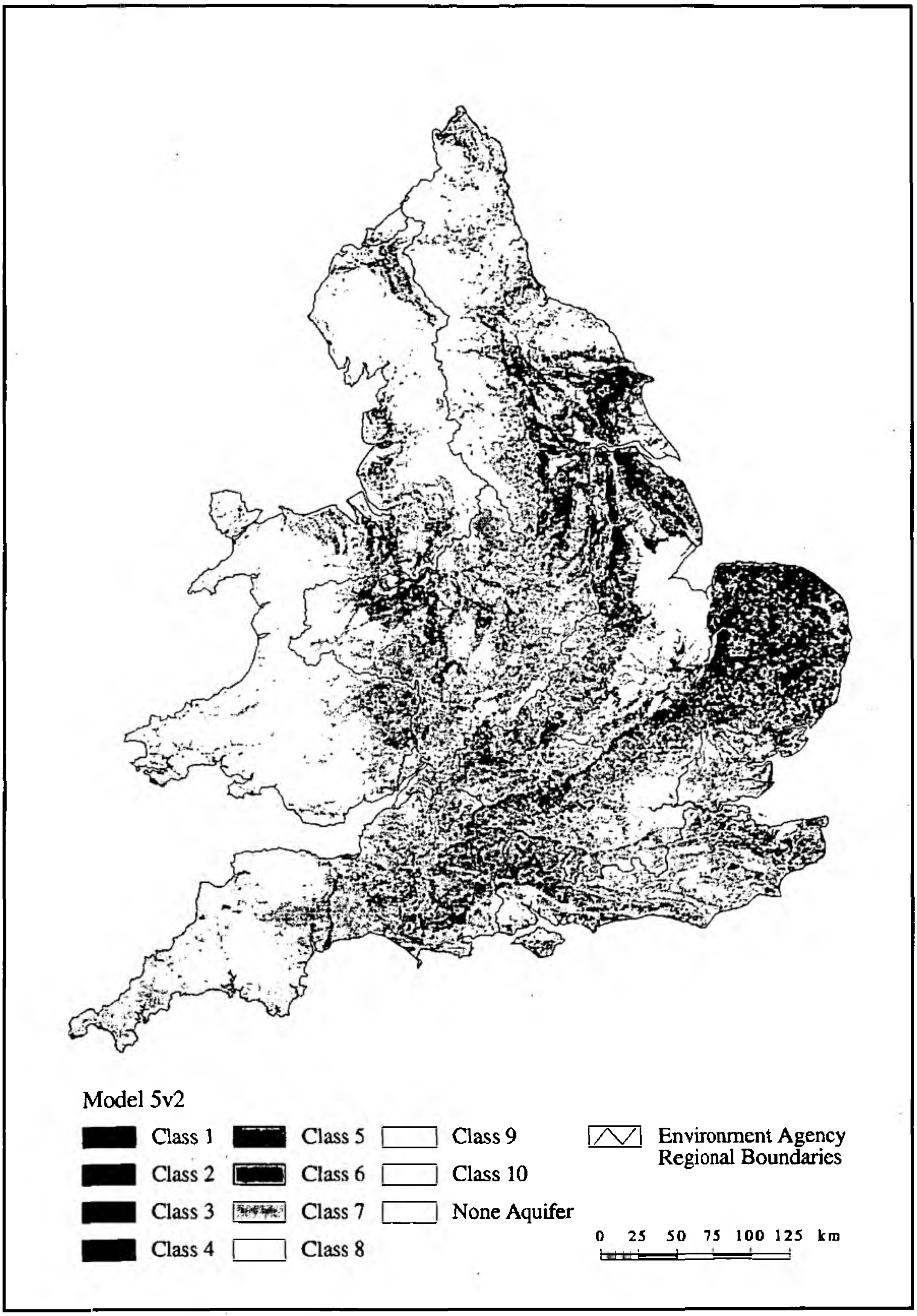


Figure A10: Vulnerability classes for Model 5, Variant 2.

Figure A11: Vulnerability classes for Model 6, Variant 1.

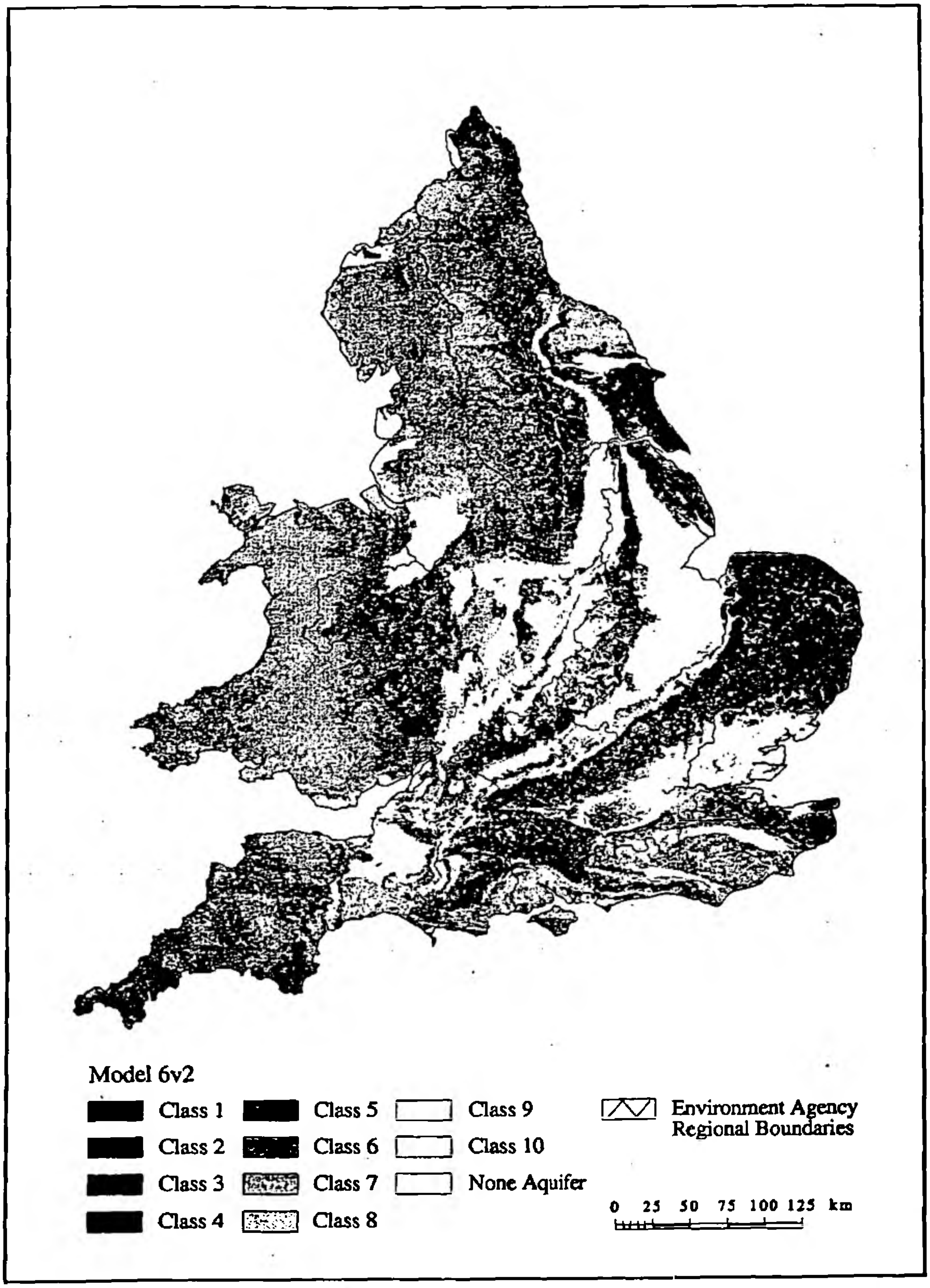


Figure A12: Vulnerability classes for Model 6, Variant 2.

Appendix B

Variations in Nitrate Levels Across Vulnerability Classes for the 12 Initial Model Variants

Key to Variable Names

The variables included in the tables are as follows:

Sites	Number of boreholes in class
Area Km^2	Area of land in vulnerability class
Median NO_3	Median nitrate value (mg/l NO_3) in class
Mean NO_3	Mean nitrate value (mg/l NO_3) in class
Std. Dev.	Standard deviation of nitrate values in class
Sites ≥ 30mg/l	Number of boreholes in class with NO_3 values ≥ 30 mg/l
% ≥ 30mg/l	% of boreholes in class with NO_3 values ≥ 30 mg/l
Sites ≥ 50mg/l	Number of boreholes in class with NO_3 values ≥ 50 mg/l
% ≥ 50mg/l	% of boreholes in class with NO_3 values ≥ 50 mg/l
Sites Past ≥ 50mg/l	Number of boreholes in class with NO_3 values in the site time series ≥ 50 mg/l
% Past ≥ 50mg/l	% of boreholes in class with NO_3 values in the site time series ≥ 50 mg/l

Model 1 Variant 1

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	73	507.0	36.00	33.78	23.15	43	58.9	17	23.3	20	27.4
2	1139	10221.4	38.00	37.40	23.66	721	63.3	367	32.2	413	36.3
3	878	19201.5	21.50	24.91	21.66	356	40.5	145	16.5	176	20.0
4	356	17841.4	18.00	23.43	22.17	123	34.6	50	14.0	60	16.9
5	407	20576.4	22.00	27.70	24.26	160	39.3	82	20.1	86	21.1
6	329	19010.1	12.00	21.17	22.69	96	29.2	47	14.3	55	16.7
7	103	6659.2	14.00	21.14	20.41	29	28.2	15	14.6	16	15.5
8	36	5085.8	16.50	22.03	19.16	11	30.6	7	19.4	5	13.9
9	23	5699.3	5.00	12.57	20.61	1	4.3	1	4.3	1	4.3
10	0	1169.7									
0	537		5.00	15.09	18.89	115	21.4	36	6.7	55	10.2
Total	3881	105971.9	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 1 Variant 2

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	75	507.0	36.00	33.89	23.06	44	58.7	18	24.0	21	28.0
2	1141	10221.4	38.00	37.34	23.68	721	63.2	367	32.2	413	36.2
3	776	13219.5	26.00	28.17	21.43	355	45.7	145	18.7	166	21.4
4	456	11814.7	15.00	24.37	24.99	159	34.9	87	19.1	96	21.1
5	466	15728.5	12.50	21.24	21.87	148	31.8	64	13.7	79	17.0
6	182	12286.8	17.00	23.41	22.89	63	34.6	27	14.8	33	18.1
7	154	21599.7	14.00	19.84	18.81	36	23.4	15	9.7	18	11.7
8	71	13684.2	7.00	16.63	18.05	14	19.7	8	11.3	6	8.5
9	23	5740.4	5.00	12.57	20.61	1	4.3	1	4.3	1	4.3
10	0	1169.7									
0	537		5.00	15.03	18.81	114	21.2	35	6.5	54	10.1
Total	3881	105971.9	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 2 Variant 1

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	75	2200.2	36.00	33.89	23.06	90	52.6	40	23.4	46	26.9
2	1141	16640.9	38.00	37.34	23.68	518	52.7	273	27.8	312	31.8
3	776	21018.3	26.00	28.17	21.43	456	54.4	204	24.3	226	26.9
4	456	34579.6	15.00	24.37	24.99	176	37.9	50	10.8	68	14.7
5	466	22534.0	12.50	21.24	21.87	180	36.2	106	21.3	107	21.5
6	182	5232.6	17.00	23.41	22.89	42	39.6	15	14.2	17	16.0
7	154	7244.3	14.00	19.84	18.81	16	17.4	8	8.7	7	7.6
8	71	1950.6	7.00	16.63	18.05	1	4.3	0	0	0	0
9	23	1.3	5.00	12.57	20.61	0	0	0	0	0	0
10	0	0.0									
0	537	-	5.00	15.03	18.81	176	24.9	71	10.0	104	14.7
Total	3881	111401.7	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 2 Variant 2

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	170	2200.2	32.50	31.78	24.60	89	52.4	39	22.9	39	22.9
2	915	16006.1	30.00	30.64	24.20	464	50.7	238	26.0	238	26.0
3	796	23644.2	23.00	27.73	23.96	344	43.2	168	21.1	168	21.1
4	742	39966.0	32.00	32.12	23.56	397	53.5	186	25.1	186	25.1
5	421	24542.1	24.00	25.99	21.33	162	38.5	57	13.5	57	13.5
6	113	3793.1	18.00	20.27	14.63	24	21.2	7	6.2	7	6.2
7	23	1203.6	6.00	10.09	10.04	1	4.3	0	0	0	0
8	0	46.3									
9	0	0.0									
10	0	0.0									
0	701	-	6.00	17.21	21.36	174	24.8	72	10.3	72	10.3
Total	3881	111401.7	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 3 Variant 1

Class	Sites	Area Km^2	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	379	2676.2	42.00	41.23	23.61	261	68.9	145	38.3	164	43.3
2	1142	15554.1	36.00	34.74	24.08	680	59.5	347	30.4	395	34.6
3	1147	36532.5	19.00	23.84	21.28	414	36.1	149	13.0	180	15.7
4	554	27271.9	14.00	22.27	22.38	169	30.5	81	14.6	87	15.7
5	77	13273.6	8.00	16.96	19.69	14	18.2	10	13.0	7	9.1
6	26	5499.2	7.50	12.88	12.02	3	11.5	0	0	0	0
7	12	3714.9	3.00	3.92	3.15	0	0	0	0	0	0
8	1	1339.7	0.00	1.00	0.00	0	0	0	0	0	0
9	0	107.9									
10	0	0.1									
0	543		5.00	15.11	18.70	114	21.0	35	6.4	54	9.9
Total	3881	105970.1	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 3 Variant 2

Class	Sites	Area Km^2	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	382	2676.2	42.00	41.05	23.40	262	68.6	144	37.7	163	42.7
2	1098	12863.0	37.00	35.93	23.73	671	61.1	342	31.1	386	35.2
3	1203	26868.8	18.00	23.95	21.70	440	36.6	173	14.4	202	16.8
4	517	34452.4	13.00	20.52	21.29	146	28.2	60	11.6	72	13.9
5	88	15048.6	8.00	17.01	19.94	16	18.2	11	12.5	8	9.1
6	25	6713.1	7.00	10.52	8.85	0	0	0	0	0	0
7	24	4951.2	4.50	9.04	11.83	3	12.5	0	0	0	0
8	2	2255.1	2.00	2.00	1.41	0	0	0	0	0	0
9	0	141.5									
10	0	0.1									
0	542		5.00	15.36	19.09	117	21.6	37	6.8	56	10.3
Total	3881	105970.1	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 4 Variant 1

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	388	4767.2	39.00	37.98	25.17	238	61.3	138	35.6	159	41.0
2	1426	30465.3	31.00	31.09	23.15	746	52.3	341	23.9	393	27.6
3	653	30025.5	25.00	27.17	22.07	281	43.0	108	16.5	117	17.9
4	531	28152.0	17.00	24.80	23.99	186	35.0	102	19.2	108	20.3
5	170	11671.2	12.00	16.46	16.08	30	17.6	7	4.1	6	3.5
6	8	4317.2	3.00	3.88	3.04	0	0	0	0	0	0
7	6	1884.6	4.00	7.33	10.25	0	0	0	0	0	0
8	0	114.6									
9	0	0.1									
10	0	0.0									
0	699	-	6.00	17.18	21.25	174	24.9	71	10.2	104	14.9
Total	3881	111397.7	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 4 Variant 2

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	390	4767.2	39.00	37.92	25.14	239	61.3	160	41.0	160	41.0
2	1254	29448.9	26.50	28.77	23.01	595	47.4	313	25.0	313	25.0
3	995	39085.4	30.00	31.03	24.45	505	50.8	271	27.2	271	27.2
4	467	24719.4	18.00	21.75	18.73	133	28.5	37	7.9	37	7.9
5	64	9647.0	6.00	12.02	12.26	7	10.9	2	3.1	2	3.1
6	4	3573.3	2.50	8.50	13.03	0	0	0	0	0	0
7	0	156.5									
8	0	0.0									
9	0	0.0									
10	0	0.0									
0	707	-	6.00	17.21	21.20	176	24.9	104	14.7	104	14.7
Total	3881	111397.7	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 5 Variant 1

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	14	88.5	42.00	35.57	23.71	9	64.3	3	21.4	4	28.6
2	48	445.8	32.50	33.00	21.29	28	58.3	14	29.2	18	37.5
3	477	5565.7	44.00	43.93	24.52	345	72.3	219	45.9	241	50.5
4	599	9826.6	29.00	30.19	24.79	299	49.9	146	24.4	176	29.4
5	677	14599.4	24.00	27.09	22.51	304	44.9	132	19.5	149	22.0
6	658	18519.7	25.00	27.27	22.65	288	43.8	116	17.6	132	20.1
7	501	21395.9	22.00	25.17	20.54	181	36.1	73	14.6	87	17.4
8	246	19630.5	12.00	19.43	19.45	65	26.4	20	8.1	17	6.9
9	107	11217.2	10.00	15.89	18.45	18	16.8	5	4.7	5	4.7
10	13	4682.7	3.00	12.62	21.93	2	15.4	2	15.4	2	15.4
0	541	-	5.00	15.19	19.09	116	21.4	37	6.8	56	10.4
Total	3881	105972.0	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 5 Variant 2

Class	Sites	Area Km²	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	14	88.5	42.00	35.57	23.71	9	64.3	3	21.4	4	28.6
2	47	386.0	37.00	35.30	21.57	29	61.7	15	31.9	19	40.4
3	482	5083.2	43.50	43.21	24.57	343	71.2	214	44.4	236	49.0
4	599	9693.9	33.00	33.28	25.74	331	55.3	174	29.0	205	34.2
5	691	13174.9	22.00	25.51	21.38	288	41.7	119	17.2	125	18.1
6	649	16192.7	23.00	26.13	22.34	268	41.3	105	16.2	135	20.8
7	478	17660.0	22.00	25.06	20.88	178	37.2	69	14.4	80	16.7
8	247	19553.6	16.00	21.90	20.47	72	29.1	28	11.3	23	9.3
9	111	16475.5	7.00	13.86	16.21	19	17.1	3	2.7	3	2.7
10	22	7663.7	5.00	12.00	18.23	3	13.6	2	9.1	2	9.1
0	541	-	5.00	15.11	18.79	115	21.3	35	6.5	55	10.2
Total	3881	105972.0	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 6 Variant 1

Class	Sites	Area Km^2	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	15	153.5	42.00	36.07	22.93	10	66.7	3	20.0	4	26.7
2	120	1396.1	38.00	37.25	24.56	74	61.7	46	38.3	55	45.8
3	522	7306.1	41.00	39.88	26.27	337	64.6	214	41.0	232	44.4
4	635	13433.9	29.00	29.34	23.35	317	49.9	136	21.4	167	26.3
5	669	18318.2	26.00	27.91	22.41	307	45.9	123	18.4	132	19.7
6	637	26678.2	23.00	25.72	20.70	249	39.1	98	15.4	109	17.1
7	426	32638.0	20.00	24.84	21.65	160	37.6	66	15.5	75	17.6
8	96	5860.1	11.50	17.36	18.11	16	16.7	4	4.2	3	3.1
9	57	5542.3	10.00	16.70	21.31	9	15.8	5	8.8	5	8.8
10	4	75.2	15.50	15.25	14.50	1	25.0	0	0	0	0
0	700		6.00	17.27	21.37	175	25.0	72	10.3	105	15.0
Total	3881	111401.7	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

Model 6 Variant 2

Class	Sites	Area Km^2	Median NO_3	Mean NO_3	Std. Dev.	Sites ≥ 30mg/l	% ≥ 30mg/l	Sites ≥ 50mg/l	% ≥ 50mg/l	Sites Past ≥ 50mg/l	% Past ≥ 50mg/l
1	15	153.5	42.00	36.07	22.93	10	66.7	3	20.0	4	26.7
2	116	1428.0	38.00	37.62	25.09	71	61.2	46	39.7	53	45.7
3	418	7645.2	36.00	35.90	27.19	235	56.2	153	36.6	177	42.3
4	782	15658.5	32.00	31.99	24.93	425	54.3	209	26.7	238	30.4
5	704	18573.8	27.00	28.38	21.75	324	46.0	127	18.0	134	19.0
6	553	26432.6	21.00	24.92	20.34	213	38.5	80	14.5	94	17.0
7	470	34069.7	20.50	24.95	21.32	174	37.0	70	14.9	76	16.2
8	98	6632.9	12.00	18.94	17.83	24	24.5	5	5.1	4	4.1
9	29	753.5	14.00	21.41	24.92	6	20.7	3	10.3	3	10.3
10	0	53.8									
0	696		6.00	17.21	21.28	173	24.9	71	10.2	104	14.9
Total	3881	111401.7	23.00	27.02	23.58	1655	42.64	767	19.76	887	22.85

APPENDIX C

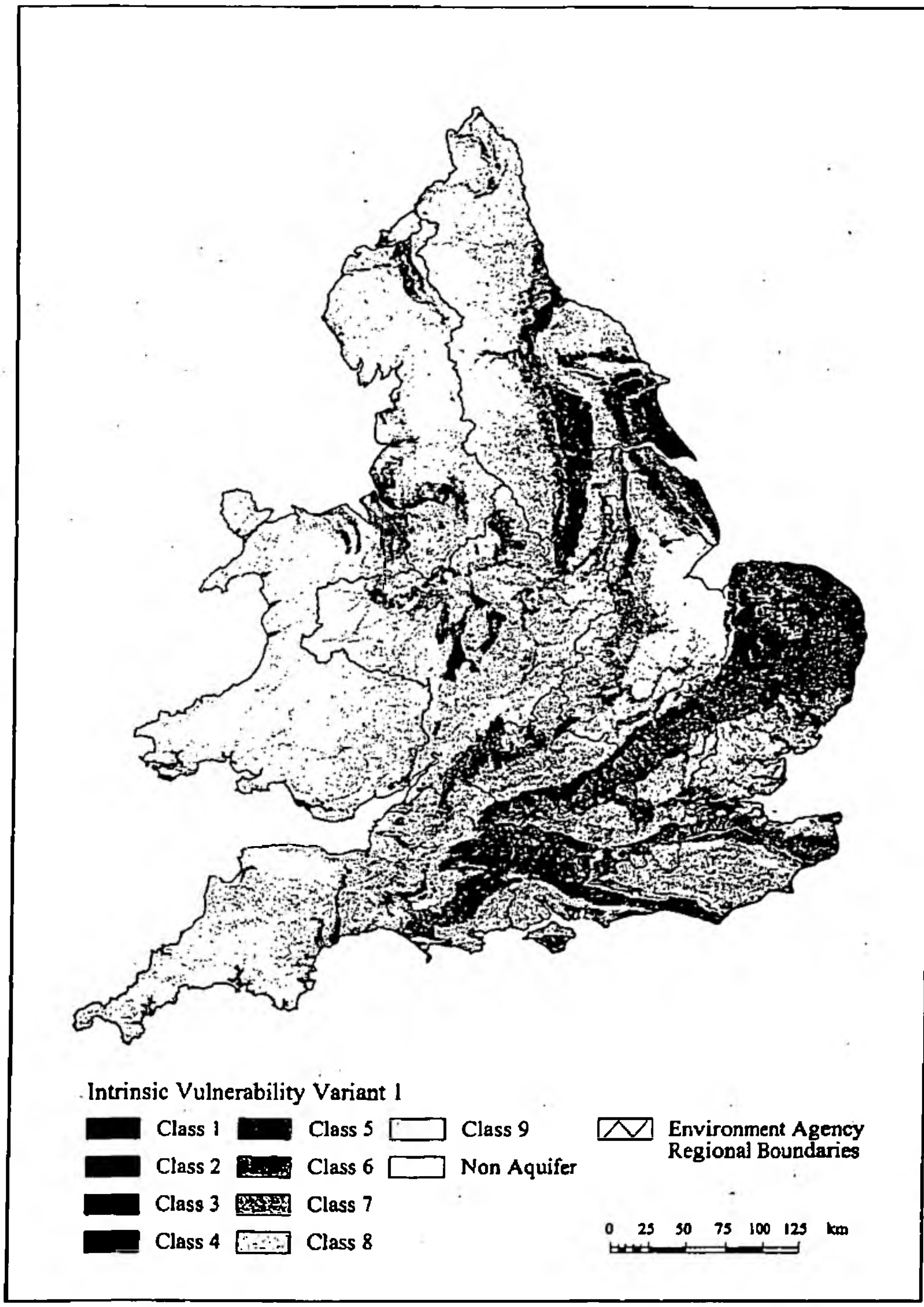


Figure C1: Vulnerability classes for Intrinsic Model, Variant 1.

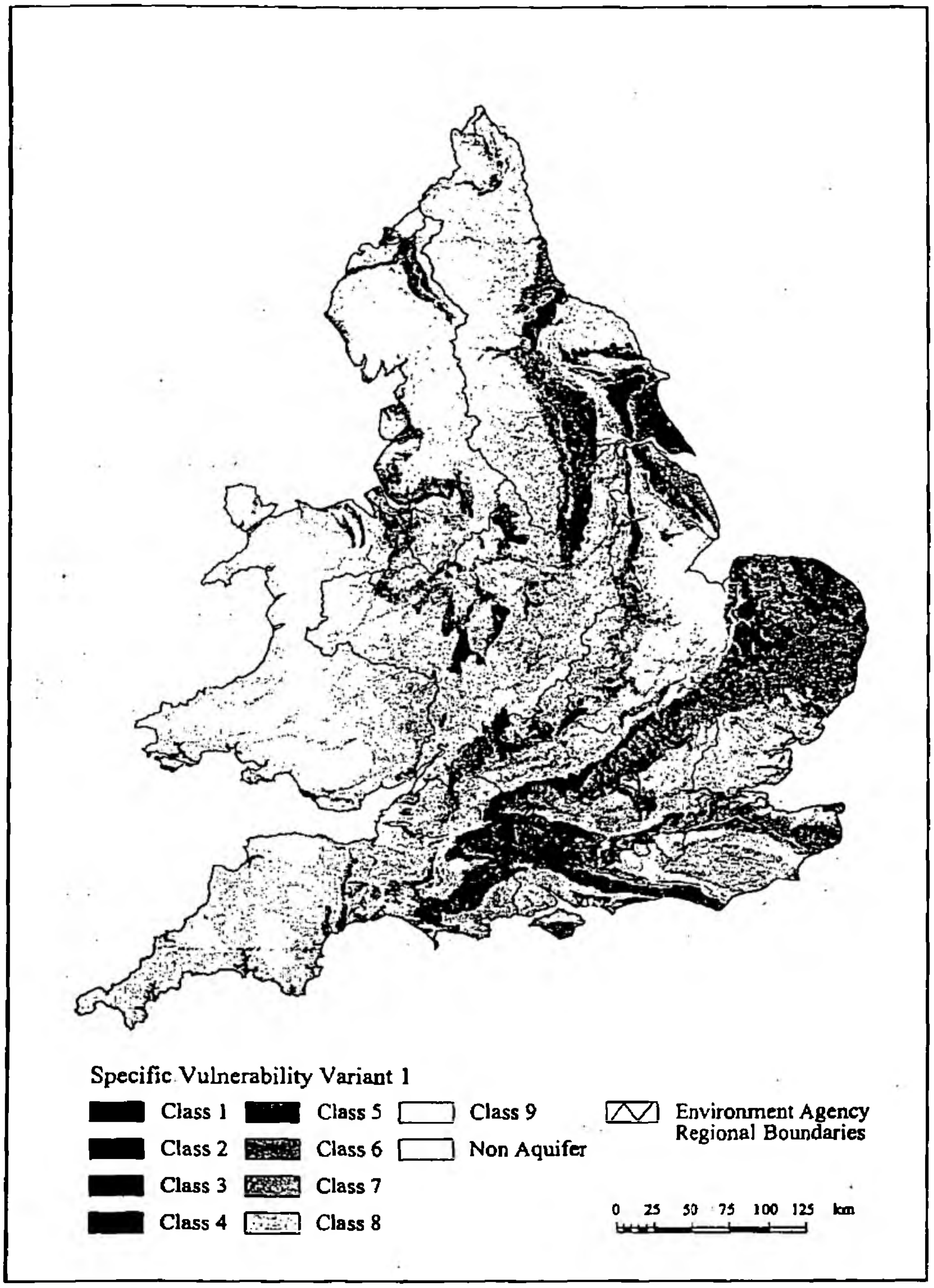


Figure C2: Vulnerability classes for Specific Model, Variant 1.

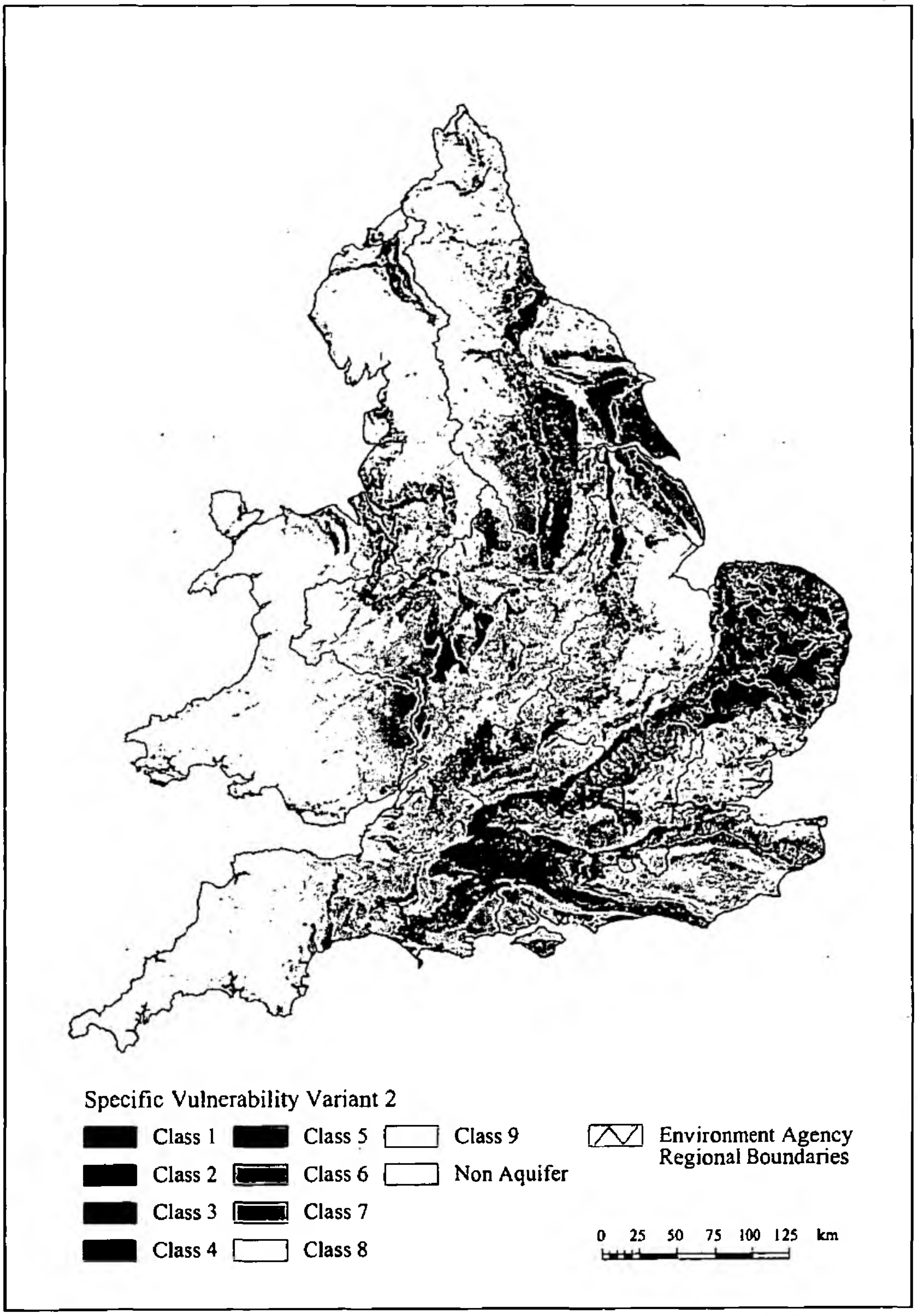


Figure C3: Vulnerability classes for Specific Model, Variant 2.

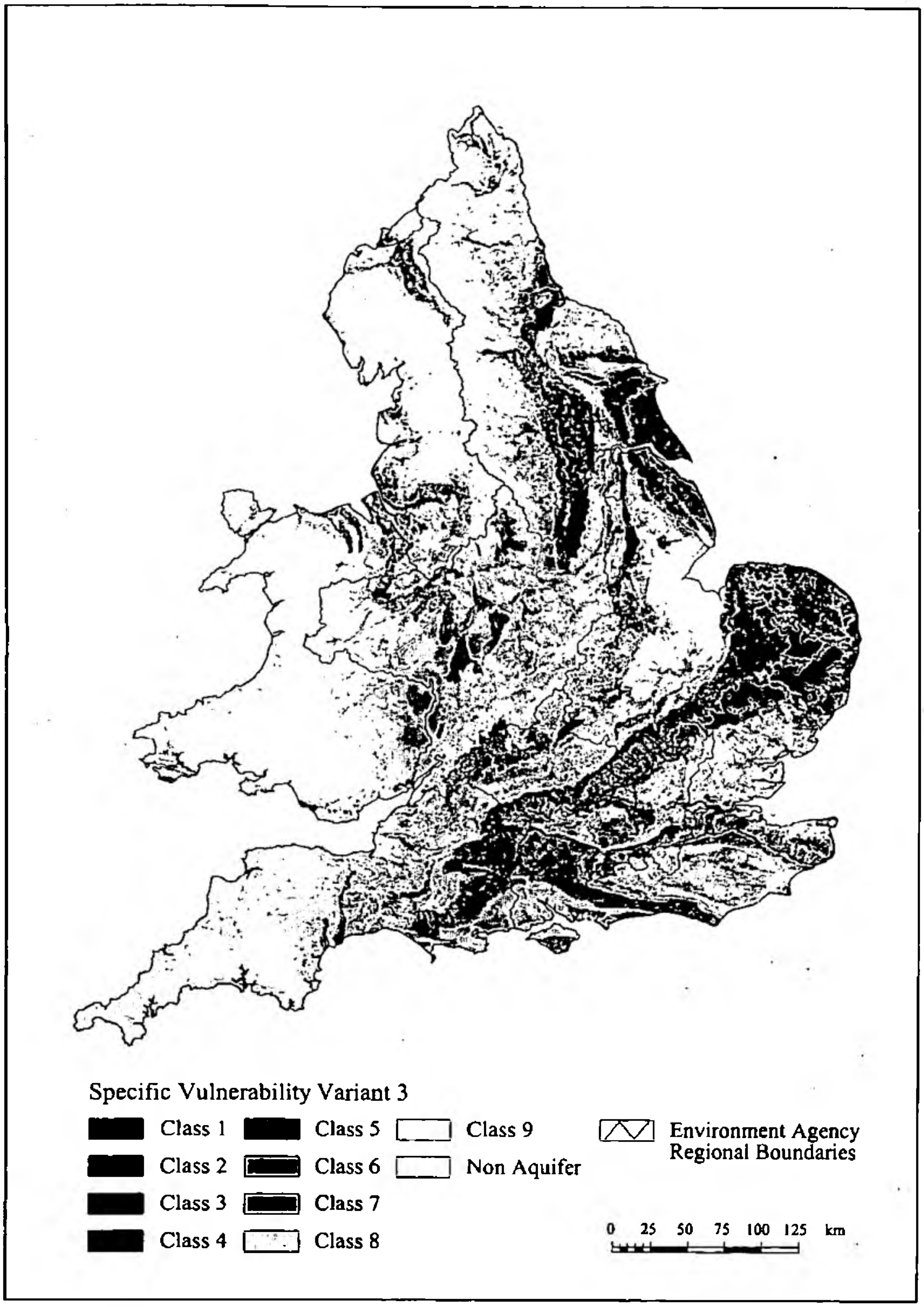


Figure C4: Vulnerability classes for Specific Model, Variant 3.

Figure C5: Vulnerability classes for Risk Model, Variant 1.

Appendix D

Variations in Nitrate Levels Across Vulnerability Classes for the 9 Revised Model Variants

Key to Variable Names

The variables included in the tables are as follows:

% Area	Percentage of aquifer area in the vulnerability class
Sc. Min	Minimum vulnerability score in the class
Sc. Max	Maximum vulnerability score in the class
Sites	Number of boreholes in class
% Sites	Percentage of all boreholes on aquifer areas
Mean NO_3	Mean nitrate value (mg/l NO_3) in class
Std. Dev.	Standard deviation of nitrate values in class
Sites ≥ 50mg/l	Number of boreholes in class with 'high' NO_3 levels.
% ≥ 50mg/l	% of boreholes in class with 'high' NO_3 levels

Intrinsic Model Variant 1

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	1.083	2.083	285	8.65	33.96	22.39	98	34.39
2	2.5-5	2.167	2.583	297	9.01	39.07	20.21	113	38.05
3	5-10	2.667	3.333	421	12.78	41.98	24.22	185	43.94
4	10-20	3.417	4.750	638	19.36	35.39	21.16	201	31.50
5	20-30	4.833	7.250	516	15.66	31.62	21.63	119	23.06
6	30-40	7.333	8.750	337	10.23	26.09	30.27	81	24.04
7	40-50	8.833	10.333	327	9.92	23.18	22.52	63	19.27
8	50-75	10.417	14.250	366	11.11	25.28	24.57	77	21.04
9	75-100	14.333	21.000	108	3.28	17.28	20.31	13	12.04
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=33.00	r = -0.867	1016	27.36

Intrinsic Model Variant 2

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	1.583	3.333	223	6.77	37.34	22.11	81	36.32
2	2.5-5	3.583	4.167	241	7.31	38.77	27.66	101	41.91
3	5-10	4.333	5.333	577	17.51	37.98	21.32	223	38.65
4	10-20	5.500	7.500	693	21.03	35.12	22.02	221	31.89
5	20-30	7.583	9.500	472	14.32	30.91	23.09	112	23.73
6	30-40	9.583	11.250	412	12.50	26.24	27.62	86	20.87
7	40-50	11.333	13.083	253	7.68	24.44	22.39	51	20.16
8	50-75	13.167	18.667	331	10.05	25.10	23.85	66	19.94
9	75-100	18.750	28.000	93	2.82	16.38	19.75	9	9.68
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=25.48	r = -0.933	1016	27.36

Intrinsic Model Variant 3

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	2.583	6.083	237	7.19	36.69	22.40	85	35.86
2	2.5-5	6.333	6.667	214	6.49	34.16	23.06	77	35.98
3	5-10	6.917	8.583	521	15.81	38.09	23.55	200	38.39
4	10-20	8.667	11.750	707	21.46	33.36	24.15	233	32.96
5	20-30	11.833	13.750	552	16.75	30.75	24.93	154	27.90
6	30-40	13.833	16.500	425	12.90	30.45	26.42	85	20.00
7	40-50	16.583	19.083	235	7.13	30.73	22.54	66	28.09
8	50-75	19.167	27.583	312	9.47	24.21	19.61	46	14.74
9	75-100	27.667	42.000	92	2.79	13.18	17.07	4	4.35
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=18.04	r = -0.933	1016	27.36

Specific Model Variant 1

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	3.125	3.125	355	10.77	43.16	22.34	172	48.45
2	2.5-5	3.625	3.625	198	6.01	41.91	20.92	94	47.47
3	5-10	4.125	4.125	377	11.44	41.58	21.92	169	44.83
4	10-20	4.625	5.125	920	27.92	31.65	20.39	207	22.50
5	20-30	5.625	9.750	295	8.95	32.19	26.42	77	26.10
6	30-40	9.875	14.000	462	14.02	27.20	26.36	107	23.16
7	40-50	14.125	15.125	284	8.62	22.91	24.88	63	22.18
8	50-75	15.375	18.125	281	8.53	23.01	23.66	49	17.44
9	75-100	18.250	30.500	123	3.73	15.37	18.86	12	9.76
Aquifer Total				3295	100.00	3[illegible].97	24 12	9[illegible]0	28.[illegible]3
Non Aquifer				419				66	15.51
Total				3714		F=45.02	r = -0.967	1016	27.36

Specific Model Variant 2

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	3.625	3.625	355	10.77	43.16	22.34	172	48.45
2	2.5-5	4.625	4.625	198	6.01	41.91	20.92	94	47.47
3	5-10	5.625	6.250	382	11.59	41.50	21.94	171	44.76
4	10-20	6.625	7.625	920	27.92	31.65	20.39	207	22.50
5	20-30	8.250	11.625	290	8.80	32.09	26.52	75	25.86
6	30-40	11.875	15.125	485	14.72	27.33	26.31	118	24.33
7	40-50	15.250	17.125	259	7.86	22.40	24.79	52	20.08
8	50-75	17.250	21.500	297	9.01	22.39	23.30	49	16.50
9	75-100	21.750	40.000	109	3.31	15.92	19.63	12	11.01
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=44.78	r = -0.983	1016	27.36

Specific Model Variant 3

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	4.625	4.625	355	10.77	43.16	22.34	172	48.45
2	2.5-5	6.625	7.250	203	6.16	41.75	20.98	96	47.29
3	5-10	8.625	9.875	430	13.05	40.95	22.22	186	43.26
4	10-20	10.625	12.500	509	15.45	32.82	23.72	150	29.47
5	20-30	12.625	15.250	687	20.85	30.85	20.90	132	19.21
6	30-40	15.875	18.625	434	13.17	26.61	26.11	99	22.81
7	40-50	19.125	21.125	273	8.29	22.69	24.67	56	20.51
8	50-75	21.250	27.250	295	8.95	22.38	23.35	48	16.27
9	75-100	27.750	59.000	109	3.31	15.45	19.08	11	10.09
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=45.93	r = -1.000	1016	27.36

Risk Model Variant 1

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	3.125	5.125	171	5.19	42.32	21.08	84	49.12
2	2.5-5	5.625	6.125	318	9.65	46.26	25.37	178	55.97
3	5-10	6.250	7.750	338	10.26	38.89	23.57	138	40.83
4	10-20	8.125	10.250	759	23.03	32.46	19.76	186	24.51
5	20-30	10.375	13.250	610	18.51	32.74	24.61	151	24.75
6	30-40	13.375	16.750	411	12.47	26.16	24.45	99	24.09
7	40-50	16.875	19.500	272	8.25	20.47	21.18	48	17.65
8	50-75	19.625	23.125	308	9.35	24.56	24.30	53	17.21
9	75-100	23.250	31.500	108	3.28	16.26	20.03	13	12.04
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=46.13	r = -0.950	1016	27.36

Risk Model Variant 2

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	3.625	8.250	172	5.22	42.09	21.23	84	48.84
2	2.5-5	8.625	9.625	318	9.65	46.26	25.37	178	55.97
3	5-10	9.875	12.875	390	11.84	38.29	24.09	155	39.74
4	10-20	13.250	16.500	606	18.39	32.38	25.02	161	26.57
5	20-30	16.625	19.125	625	18.97	32.09	22.00	162	25.92
6	30-40	19.250	22.500	492	14.93	26.23	20.13	89	18.09
7	40-50	22.625	26.125	293	8.89	25.86	22.65	69	23.55
8	50-75	26.250	32.000	280	8.50	22.98	24.20	47	16.79
9	75-100	32.125	42.000	119	3.61	15.66	17.62	5	4.20
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=42.50	r = -0.983	1016	27.36

Risk Model Variant 3

Class	% Area	Sc. Min	Sc. Max	Sites	% Sites	Mean NO_3	Std. Dev.	Sites ≥ 50mg/l	% ≥ 50mg/l
1	0-2.5	4.625	14.500	174	5.28	42.06	21.54	85	48.85
2	2.5-5	14.625	16.500	273	8.29	45.14	25.77	145	53.11
3	5-10	16.625	20.625	384	11.65	39.31	27.63	157	40.89
4	10-20	21.125	26.625	673	20.42	32.85	24.91	223	33.14
5	20-30	27.000	31.125	482	14.63	28.05	20.79	92	19.09
6	30-40	31.250	35.750	431	13.08	31.02	21.77	104	24.13
7	40-50	35.875	40.375	413	12.53	27.61	21.94	86	20.82
8	50-75	40.500	49.125	354	10.74	24.12	20.32	54	15.25
9	75-100	49.750	63.000	111	3.37	15.00	17.54	4	3.60
Aquifer Total				3295	100.00	31.97	24.12	950	28.83
Non Aquifer				419				66	15.51
Total				3714		F=36.35	r = -0.967	1016	27.36