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NITRATE IN WATER:
ASSESSING THE EFFECTIVENESS IN TERMS OF WATER QUALITY AND THE IMPACT ON AGRICULTURE OF POLICIES PROPOSED FOR CONTROLLING THE CONCENTRATION OF NITRATE IN WATER

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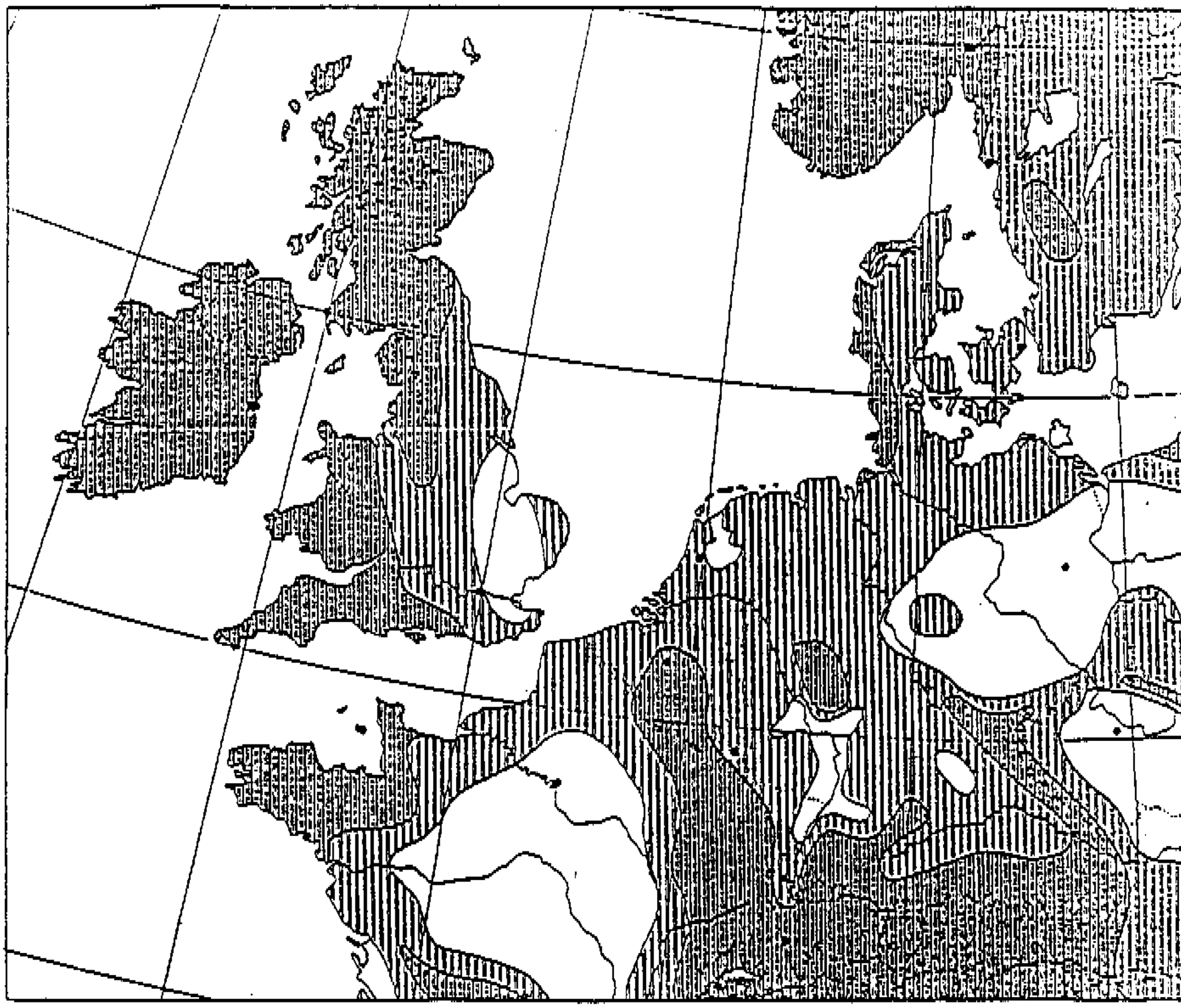
CONTENTS:

Maximum, average nitrate losses (kg N/ha/annum) allowable to meet EC water quality standard (50mg NO_3/l)



1989

SSLRC

Maximum Annual Nitrate Loss (kg N/ha)

to give 50 mg/l in water from rain

33–45

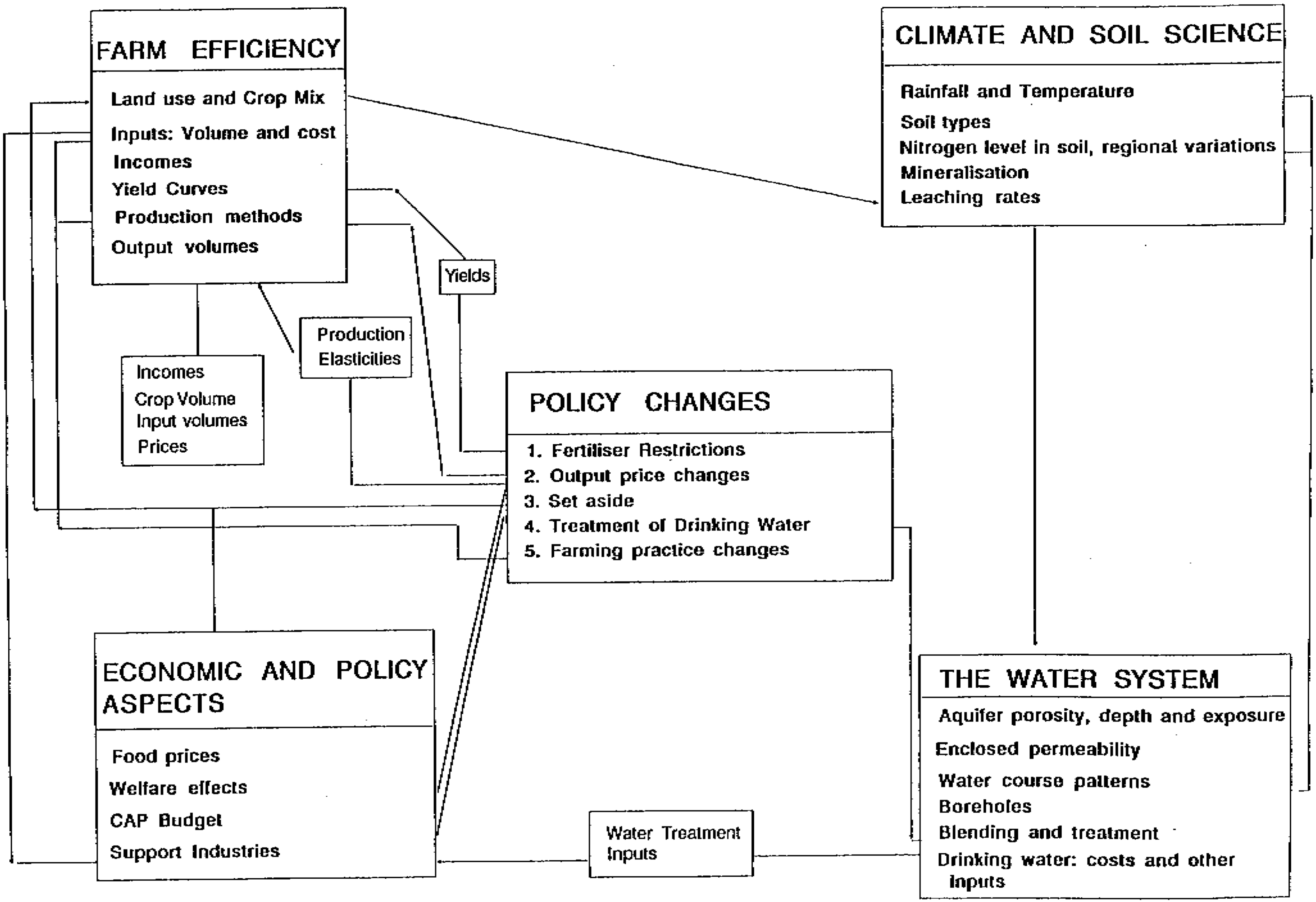
22–33

11–22

Normal UK leaching rates (KgN/ha)
(DoE Report - Nitrate in Water)

Cut grass	10 - 20
Grazed grass	25 - 40
Peas	50
Arable	50 - 60
Ploughed grass	280

THE NITRATES ISSUE: AN OVERALL FRAMEWORK



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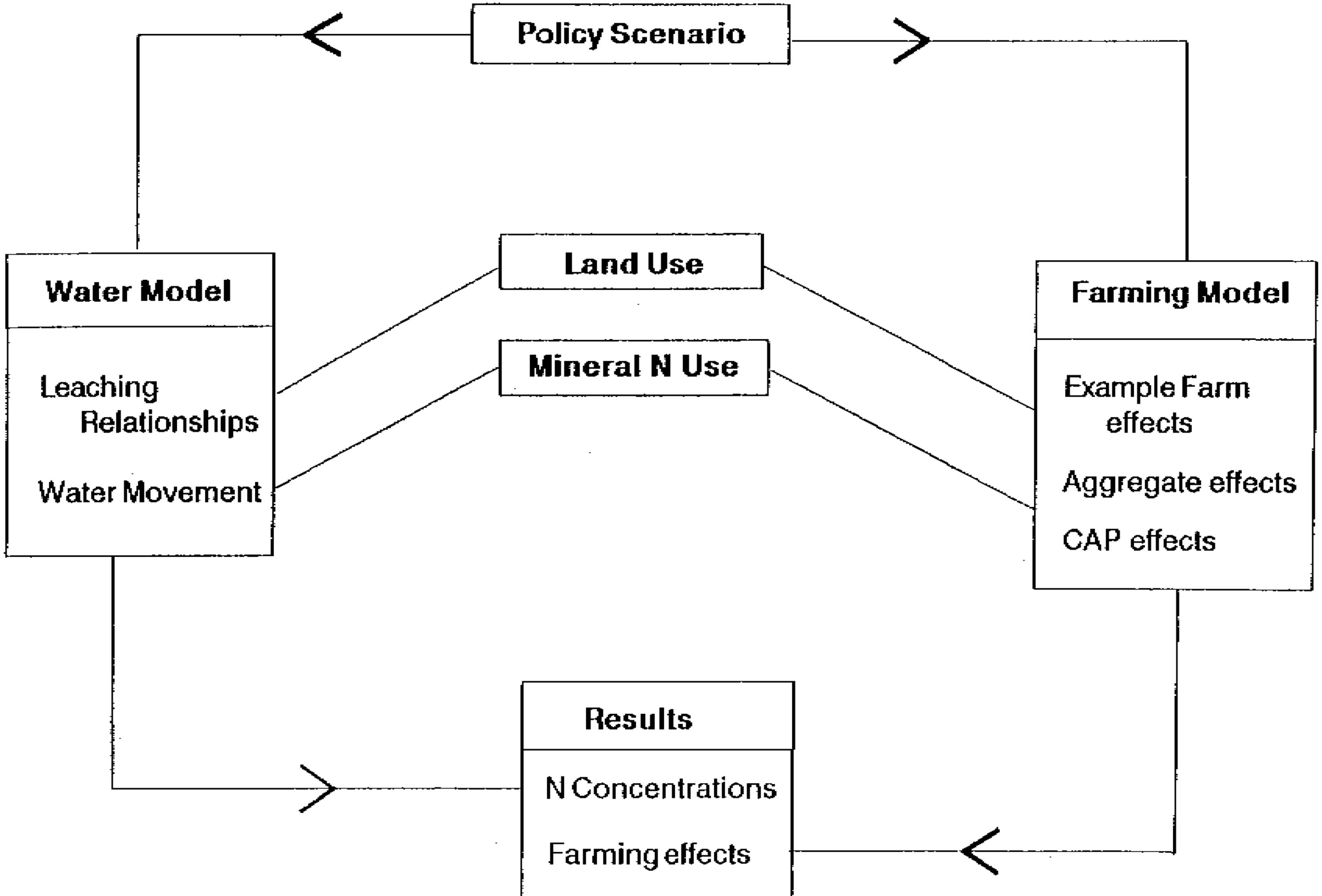
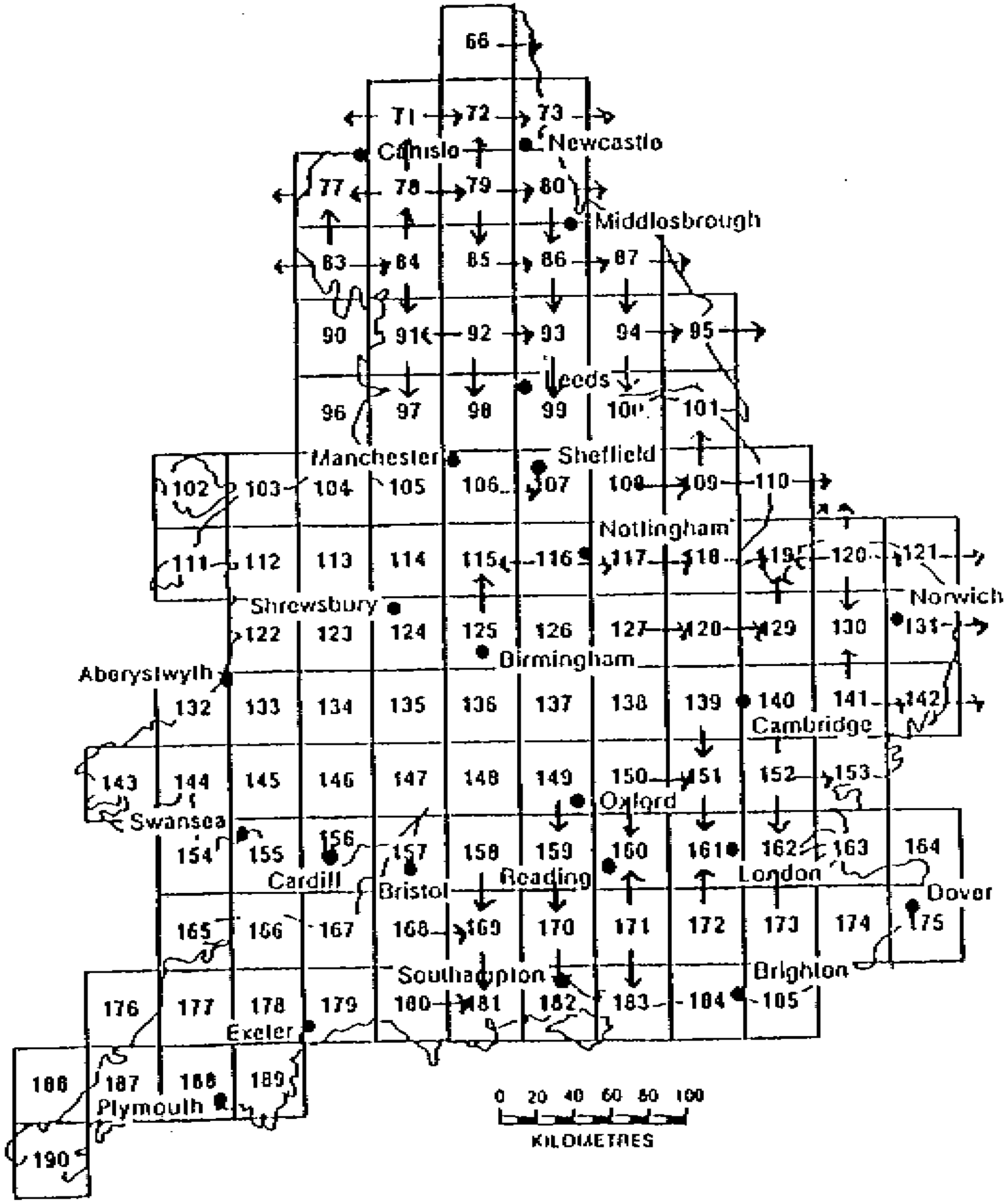
Conceptual Overview of Model





The MORECS Grid

THE BASIS OF THE WEATHER/WATER DATA FOR THE UK

⟶ Ground Water Flow Directions

⟶ Surface Water Flow Directions

TABLE 1 - IMPACT OF MEASURES TO CURB THE LEVEL OF NITRATE IN WATER

POLICY	REDUCTION IN NITRATE Concentration (mg/l N) in:			IMPACT OF POLICY ON FARMING	EFFECTS ON EUROPEAN BUDGET	OTHER COMMENTS
	Groundwater (Average) (England & Wales)	Surface Water (Average) (England & Wales)	Maximum Reduction in either water type			
Comprehensive change in land use throughout England & Wales	←VARIED→ (less than 11.3 mg/l N target everywhere)			£340M estimate	Not currently available	Some 1.4M ha land's water still fails to meet Directive.
East Anglia: 50% switch from arable crops to extensive livestock	6.6 (East Anglia only)	4.9	12.36	Farm production of arable crops falls significantly. Net farm surplus falls by £173.7M from £144.4M to -£29.3M	Budget reduced by £44.7M	Some areas of East Anglia require up to 80% switch in land use to meet EEC Directive for groundwater. Additional measures required for surface water.
Nitrate Sensitive Areas						
(1) No potatoes	0.23	0.15	1.17	Gross margin reduced by £2039/ha	Minimal	Insufficient for all NSA's to meet 11.3 mg/l
(2) 10% Switch from arable to rough grazing	1.08-3.7	0.6-2.6	Varied	Farm surplus falls by about £30.00 £/ha of all farm land dependent on farm type and location	Minimal (for NSA's alone)	East Midland NSA require switches of 30 to 80% in land use to meet EEC Directive.
Best farm practice: 10% reduction in leaching of arable crops	0.6	0.4	2.7	None - if present labour/ machinery meets requirements	Minimal	Some cost implications and some inconvenience to farmers.
Nitrogen Tax: 40% increase in price	0.47	0.32	1.7	Reduced output. National net farm surplus reduced by £126M	Budget reduced by less than £2M	Raises £142M in taxes. Fertilizer use reduced by approximately 4%.
Nitrogen limit: Fertilizer application restricted to 80% of current levels England & Wales	1.0	0.70	5.7	Farm production falls by typically 9% of base level. Net farm surplus falls by over 9% to £697M	Budget reduced by £17.1M	Each 10% cut in fertilizer reduces sales of fertilizer N by £30M.
Water Treatment	← 1.7 →		18.7	None	None	Solves drinking water position at low cost. Estimated at £65M.

2 BACKGROUND

i The Nature of the Problem

The issue of nitrate concentration in water was first raised as a health issue with concerns over the incidence of gastric cancer and Methaemoglobinaemia. Work by Professor Doll of the Imperial Cancer Research Fund at Oxford and reports from the World Health Organisation have put these into perspective and the maximum admissible concentration of 50 mg/l established by the Quality Drinking Water Directive 80/778 is now regarded as a very prudent level.

The new draft European Community Directive COM (88)708 concerning the protection of fresh, coastal and marine waters against pollution caused by nitrates from diffuse sources has the objectives of avoiding:

a the concentration of nitrate in freshwaters, both surface and ground, reaching a level (50 mg NO_3/l) at which it could interfere with the legitimate uses of these waters.

b the eutrophication of surface, estuarial, coastal and marine waters.

Any area where concentrations exceed these levels will be declared vulnerable zones and subject to controls on agricultural practice. This Directive is subject to debate by the Environment Council and by a Council sub group at both the principle and detail level. Little progress was made at the March 1990 meeting in Dublin and despite the Commission and the Irish Presidency's commitment to reaching the required unanimous decision at the June 1990 meeting this was not achieved. Germany and Denmark seek a substantive Directive, the UK and particularly France a framework Directive. Key issues are:-

- where should samples be taken, at point of extraction for drinking or throughout the catchment area?
- how frequently should samples be taken, and will the maximum limit be an absolute value or determined on some mean or percentage basis?
- will the entire catchment zone be declared a vulnerable zone, or merely that part contributing the most nitrate?
- is the Appendix III which contains all the agricultural measures a legal requirement or a guidance menu for national policy makers?

ii Scale of the Problem

Thomassons work at Silsoe has shown the potential area of Western Europe which will be effected by the draft Directive in the original form. (See Map). This work with iso leachate curves identifies the areas likely to be affected by draft Directive 88/708 but does not assess the effectiveness of policy measures or their impact on agriculture.

iii The Future

Beyond this Directive concern is focusing on the implications for eutrophication and algal blooms of nutrient flows into the North Sea. Environmental Ministers have already agreed a "target of a 50%

reduction", and this implies further farm measures. The underlying concern is with the overall low level of nutrient efficiency in agriculture. This is an issue which will be debated throughout the 1990's with new control measures being introduced.

There are other issues which are receiving the attention of researchers, but which have not yet been formulated as proposals for specific measures. The techniques of "Issue Mapping" and "time tabling" of public concern identify the priority ones, and those where research input can have the greatest influence.

The current modelling work reported in this paper does not address this overall dimension, but concentrates solely on the interaction between farming and water quality. Although specifically addressing the nitrate issue the framework could be adopted for other water quality issues, e.g, pesticide residues, phosphate levels, and other changes in land use and farm practice.

3 OVERVIEW OF THE MODEL

The objectives of the work carried out by ICIF and London Economics were:

- to develop a research methodology which would bring together scientific knowledge in each of the areas which has a bearing on nitrate in water.
- to establish a database and create a computer model which could compare the effect on water quality and the impact on farming and the wider economy of possible policy options for the reduction of nitrate concentrations to below EC limits.
- to use the model, and associated working documents, to assist ICI in developing its strategy and to inform the public debate through the press and other mechanisms.

The work by ICI Fertilizers and London Economics has resulted in a model of the water flows within England and Wales and their interaction with farming. This can be used to assess the impact, on both the agriculture and water industries, of the range of remedial measures currently under discussion for resolution of the nitrate problem on a consistent scientific basis.

The model is best visualised as two parallel units, with interaction between them. On one side is the water model, with its detailed database of water flows and the specification of the nitrate leaching which occurs under varying soil and land use conditions. On the other side is the farming model, which characterises how farmers behave, what crops they grow and their income and asset position. The interface between the two parts is the farmers' use of the land.

3.1 The Scale of the Model

The choice of the scale at which any model operates reflects a balance between feasibility and utility. Too fine a scale demands a very large amount of detailed information which may not exist, whereas too coarse a scale produces answers which are not meaningful on a localised basis. An early decision was made to work at a level of detail of 40km x 40km, using the "Meteorological Office's Rainfall and Evaporation Calculation System" (MORECS), which provides rainfall and evaporation estimates in Great Britain for each 40 km square. Consequently all parts of the model were brought to this same scale. The model was developed for England and Wales, which account for 114 of the 190 MORECS squares covering the UK.

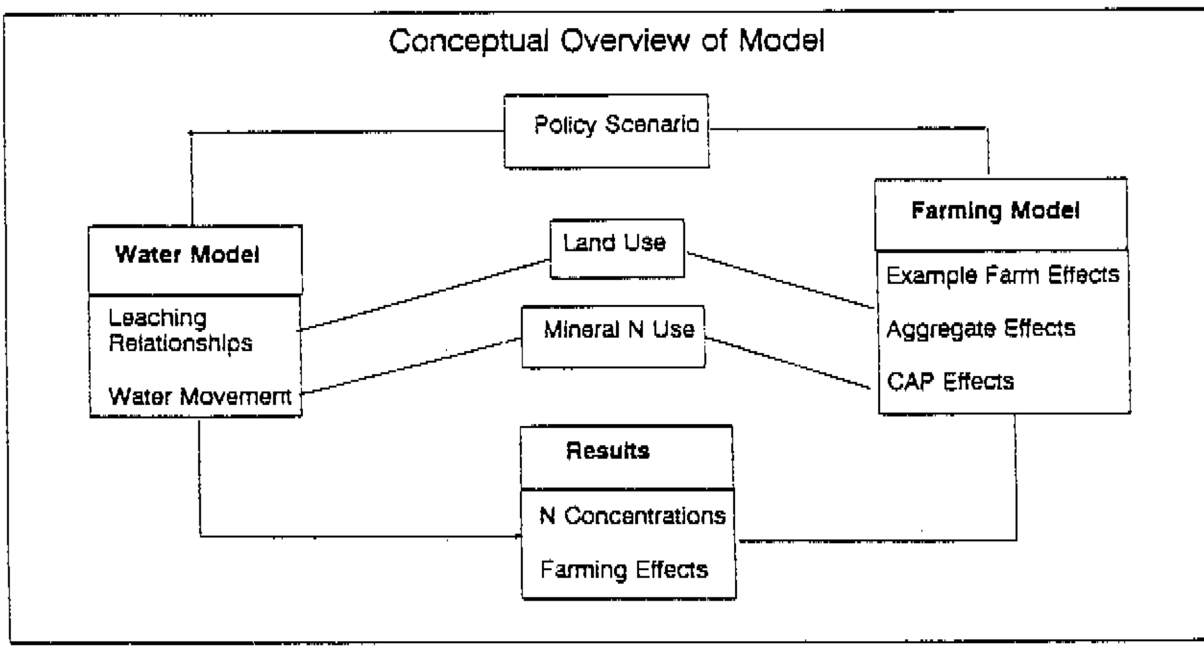
3.2 The Water Model

Data on river flows, hydrological gradients in aquifers, abstraction volumes and surface land use have been mapped to the MORECS basis. Working from this data the gross and net water flows for each MORECS square are calculated, and a consistent overall water balance for England and Wales is generated.

A series of nitrate leaching equations, based upon soil type and land use, together with the rainfall, determine the nitrate concentration of water entering rivers and ground-water supplies.

3.3 The Farm Model

The farming side of the model is based on a series of representative farms. These are derived from the widely recognised national classifications for 7 farm types (specialist cereal, dairy etc). Recognition of farm size, tenancy type and region resulted in 567 representative farm types. Each farm is defined according to its crop mix. On the basis of its crop mix and its inputs changes to current farm income and to the balance sheet data can be calculated. It is then possible to characterise the farming in each 40 km square and to aggregate the results for England and Wales.



The impact on the CAP Expenditure in England and Wales is also determined.

3.4 Interaction of the Water and Farming Models

Introduction of a policy change alters the parameters which drive both parts of the model. Farmers may change their crop mix, fertilizer use or other inputs to the farming process. These changes then feed through to the water model and cause changes in the amount of nitrate leached. The water model predicts changes in concentrations of nitrate in the water supply, i.e. the effectiveness of the policy, while the farm model quantifies the effect on farm income, crop output and economic viability. Conversely for a given nitrate concentration in water the required land use changes can be determined and the impact on farm incomes calculated.

3.5 Hardware and Manuals

The model will run on an IBM compatible pc (eg 3086) with 1Mb of memory and 400 Kb RAM. A hard disc is required for data storage. Typically it takes a minute to run a farm case, 10 minutes for all the farm cases, and a maximum of 30 minutes to produce aggregate UK data.

It is now being made publicly available together with manuals and descriptive material, such as detailed papers investigating particular aspects, including water treatment options, wider effects on the economy and the structure of the water industry. As well as aiding understanding, these allow off-model work such as quantifying the cost of water treatment so that it can be compared with the cost of agricultural solutions. For example, in parts of East Anglia where denitrification of water by the water industry will be inevitable, the relevant cost curves per mg of nitrate removed can be constructed as an aid to determining the balance of a mixed agricultural/water-treatment policy.

Both the various sections and the totality of the model have been validated both by testing against known data, and by exposure to national experts.

4 RESULTS

Given present agricultural practice, the model predicts that the critical concentration of 11.3 mg/l N will be exceeded in some 5.8m ha (39% of the land area) of England and Wales. Over 90% of this total lies in four farming regions - East Anglia, the South East, and the South and East Midlands. These regions account for almost 50% of the total agricultural land, and over 50% of total farm holdings. Output from these farms accounts for over 70% of the country's arable farm income.

For surface water the average nitrate concentration is 8.4 mg NO_3 N/l (range 0.4 - 33) and for ground water 8.5 ms NO_3 N/l. (range 0 - 31.5).[3]

The model has been used to explore the following four farming options which might provide solutions in the nitrate problem:

a Comprehensive changes in land use
b Selective changes in land use
c "Best-Farm Practice"
d Fertilizer Taxes Or Quotas

These options are briefly discussed below and their impacts on the nitrate problem and on net farm surplus are set out in Table 1.

a Comprehensive Changes in Land Use

This is the only agricultural solution which even approaches the draft Directive's requirements. It would entail very significant changes to British farming. Up to 80% of land currently used for arable crops in those areas where the nitrate limit is exceeded (43 squares; 30 both surface and groundwater 8 surface water, 5 groundwater) would need to be put to permanent, unfertilised grass or to woodland. The financial implications would be appreciable, leading to a reduction of some £340m, that is 50%, in the net farm surplus*.

Even this wholesale change in land use would still fail to meet completely the draft Directive's requirements. Some 1.4m ha of land (or more precisely its water), (24% of the total affected) which lies either in close proximity to, or downstream from, urban areas would still fail to meet the targets because they are affected by high dosages of human sewage, (Surface water only is affected).

Such enormous changes to UK farming practice would have a major impact not only on the agricultural industry, but also on rural communities, and are probably politically unacceptable.

The impact of the draft Directive on water in East Anglia has been studied in detail, since it's arable farming produces higher losses of nitrogen from the soil to the water courses than is the case with grassland farming.

* Net Farm Surplus

As much as 80% of the land would have to be taken out of arable farming in some MORECS Squares, and switched to permanent ungrazed grass or woodland to meet the 11.3 mg/l N target. Even this change is insufficient to ensure that the surface water in four of the fourteen 40 km squares comprising East Anglia meets the target. Water treatment would also be necessary. The impact on the 17,000 farms in the region would be severe, with the net farm surplus falling from £144m to -£27m. In the absence of any compensation payments some 6000 farms are likely to become unviable. UK production of key crops would also be hard hit, as East Anglia provides 15% of the national production of wheat and barley, 50% of the sugar beet and 27% of the oilseed rape.

b Selective Changes In Land Use

Actual nitrate leaching from crops varies with the soil type and farmer's cultivation practices. However, Peas and Beans, Potatoes and Oilseed Rape, together with intensive vegetables, can be regarded as high-risk crops.

Local policies for specific areas with high nitrate concentrations could include limiting the acreage of these crops. The model can be used to study the impact of reductions in the acreage of any crop. For example, if no potatoes were grown in the MORECS squares in which the current nitrate sensitive areas are located, the nitrate concentration of both surface and ground water would be reduced by on average less than 0.5 mg/l N (compared to average values in the range 0 to 30 mg/l N), and in no case is this sufficient to bring an additional MORECS square into compliance. The maximum benefits are 0.8 mg/l for surface water and 1.2 mg/l for ground water.

Since the same study shows the impact on adjusted farm gross margin (that is including labour as a variable cost) the monetary compensation required by farmers to encourage a voluntary move is implied. Adjustments in fixed costs are not covered. In the case of potatoes this sum amounts to <£2000/ha. More importantly, the regional compensation cost can be assessed and weighed against the overall effect in reducing nitrate concentrations.

Various combinations of crop change can also be assessed in this way.

c Best Farm Practice

Although land-use change to the extent necessary is unlikely agriculture must take what steps it can to reduce the losses of nitrate from the soil to water courses. Extensive experimental work by Agricultural Research Centres has shown that reductions in the amount of nitrogen leached from arable crops can be achieved, albeit with some limited cost implications and at some inconvenience to the farmer in comparison to current practice. The improvements require changes to cropping patterns, to sowing and harvesting dates, and careful use of fertilizers and manures to supplement soil nitrogen in an overall balance with the crop nitrogen demand. This rapid adoption by farmers of environmentally effective measures within their cropping systems is referred to as "Best Farm Practice". Those changes which within their crop system enhance farm efficiency may require little more than better education and persuasion of farmers by ADAS and the fertilizer manufacturers and their distributors. Those changes which entail risk, expense or inconvenience, such as earlier planting, will require more effective codes of practice (comparable for example to those used by the Health & Safety Executive), or even direct legislation. Field trial results indicate that Best farm practice seems certain to reduce nitrate leaching by 10%, and some crops probably up to 25% and whilst only 1 and 5 additional squares respectively would then comply with the Draft Diffuse N Pollution Directive there would be an improvement in all squares. Average ground water concentrations fall by 0.6 and 1.5 mg NO_3 N/l, and that of surface water by 0.4 and 1.0 mg NO_3 N/l. (The maximum improvement is 6.6 mg and lies in the East Midlands, to the East of Birmingham).

d Fertilizer Taxes and Quotas

A nitrogen tax has been proposed as a means of limiting the application of fertilizer. A tax of this kind could only be applied nationally. It could not therefore be targeted at those areas which present a nitrate problem. Its other disadvantage is that it would have little effect on farming practice. The relationship between crop yield and fertilizer input is so strongly positive and the price elasticity of demand so low that even a tax as severe as 40% would have little effect on the rate at which fertilizer is applied. The model showed that there was not one of the 43 non-compliant squares in the grid which would comply as a result of such a tax. The overall impact on nitrate concentrations was only 0.3 - 0.6 mg/l N on average, with a maximum of 1.7. The principal effect of a tax would be to redistribute income from farmers to the Exchequer. In so doing, it would reduce the net farm surplus by around £130m, or by 16%.

The application of nitrogen quotas would be more effective in reducing nitrate concentration, and be less burdensome to farmers. For example, the uniform reduction in fertilizer application to 80% of current levels would solve the nitrate problem in five squares, but with a reduction in the net farm surplus for England and Wales by around £70m, or 9%. The percentage decline is much higher in the arable and mixed farming regions. However, such a quota would undoubtedly be difficult to monitor and administer.

The application of a fertilizer quota on the alternative basis of total farm use would have less impact on the water nitrate concentration, and less impact on the farm surplus. Farmers would strive to optimise margins by optimising fertilizer use between crops, and hence fertilizer use on high-leaching, high-margin crops would be maintained.

5 CONCLUSIONS

The modelling framework developed by London Economics and ICI Fertilizers has been shown to be effective in evaluating the effect of differing policy measures on water nitrate concentration and the impact on UK farming. It is a valuable device which enables the impact of the policies to be determined on a consistent basis. In the context of concerns over drinking water quality, taken together with other work on water treatment costs, it provides a means whereby the most cost effective policy solution to the problem may be chosen. As compensation will be claimed where restrictions are enforced, the model also provides a mechanism for estimating the potential size of these payments.

The simulations which have been performed with the model demonstrate that even severe agricultural changes alone will not solve the problem. Further, slow movement through the aquifers which dominate in the main problem areas means that farming changes will take decades to have effect on drinking water concentrations. The economic costs of the farming policies have been shown to be prohibitive. In East Anglia alone, a policy which came close to eventually reducing concentrations to EC limits would cost farming some £174m, and knock-on effects on other industries and on employment could double this cost.

Water treatment and management will therefore need to form the major part of any solution. The estimates suggest that this is also more cost effective in most areas. Overall, the annualised cost is likely to be much lower than achieving a similar long-term outcome using land use changes, and the effects are immediate.

However, the model has provided a ranking of farming changes in terms of cost effectiveness, and isolated those which can make a useful contribution. Although these are not in themselves sufficient to solve the problem, they can reduce the eventual need for water treatment and also assist in reducing nitrate concentrations in water sources. They are:

- improvements in farm practice, including early sowing, drilling and concentration on winter crop varieties.
- selective restrictions on cropping and land use in particularly vulnerable areas.
- reduction in the acreage of high-leaching crops, such as oilseed rape.

6 RECOMMENDATIONS

In developing UK and Community policy in the context of the drinking water Directive, the draft Directive on Diffuse Pollution and longer term concerns over Eutrophication, the following actions are recommended:-

1 A programme of encouraging farms to adopt "Best Farm Practice" methods - so that the contribution of farming to surplus nitrogen in the soil is reduced - should be instituted immediately. Research such as that carried out at the ICIF Arable Centre at Ropsley is currently providing important pointers. It is crucial that this work is extended rapidly.

2 The model and associated information should be used to identify those areas which would be defined as vulnerable zones under a range of parameters. In these areas the specific actions to be taken to curb the amount of nitrogen leached should be investigated. These should include selective changes in land use such as the localised elimination of certain high leaching crops which may include oilseed rape and potatoes.

3 Once the appropriate actions have been identified, the underlying rock strata in each of these problem areas should be identified. In areas where changes in farming practice are likely to solve the problem within, say, ten years, no further action should be taken. Other areas should be classified into those where only a long term solution is likely to occur following the farm practice changes, and those where the problem is too great to be solved by politically acceptable land use changes alone.

4 Part of the problem in certain areas concerns effluent discharges. These should be identified and remedial action taken. The data base of the model provides preliminary guidance in this area, but water industry expertise will need to be sought.

5 The model should then be used to simulate the remaining problem areas, and classify them into medium term and long-term. Here the most appropriate method of water treatment should be identified and programmes instituted to commission the relevant plant. Where existing Asset Management Plans already commit Water Supply PLC's to certain expenditures, these should be taken into account. The choice of plant will depend on the period for which it is expected to operate; in some areas, the plants may become redundant as other measures slowly reduce nitrate concentrations.

6 In all of the above, a consistent policy evaluation framework should be used which compares the effectiveness of the policy with its overall economic cost. Only then can the EC Directive be met with minimum damage to the UK economy.

7 Further Development of the Model

Although the model provides an unrivalled tool for analysis of effectiveness and of the impact of the policy measures required to meet existing and probable European Community Directives, it could benefit from development. The following would enhance its capability to create cost-effective policy responses:

i Development of water model from a steady-state predictor to one which allows for time-dependency. This should cover both lags in flow through aquifers and in-year fluctuations. The implications have already been investigated and the developments required are reasonably straight-forward.

ii Further development of the summarised output variables and of the overall policy analysis capabilities. This should include incorporation of the off-model work on knock-on effects to the wider economy already completed.

iii Integration of off-model work on water treatment.

iv Development of the water model to incorporate changes in water industry practice.

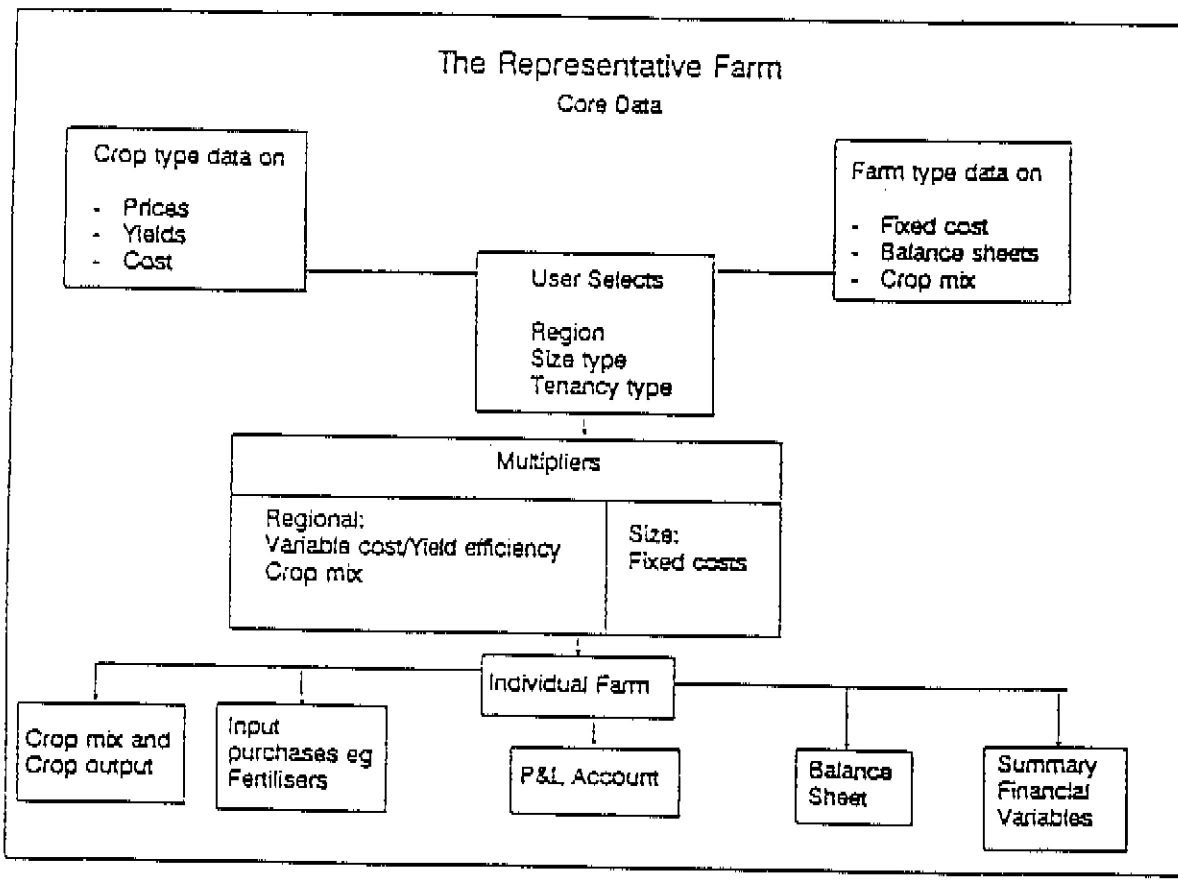
v Development of the model framework so that it is applicable to a range of issues, including determining cost/benefit criteria for assessing farm-based measures considered necessary to reduce Eutrophication.

vi Use by research institutes and universities together with representatives of the water industry, farmers, and environmental groups, at an early stage in the development of new policy issues.

STRUCTURE OF THE MODEL, AND DATA SOURCES **APPENDIX**

The Farm Model

A relatively simple database is used to generate the 567 stylised farms used for aggregation purposes. Data are specified at a national level and converted to a regional level by a set of efficiency multipliers which indicate how a particular data value varies across the regions relative to the national average. There are 8 principal data blocks in the model.



i National Data on Crops

This specifies data on crop prices, yield, fertilizer and other input such as seeds, additional returns (for livestock), labour and machinery expenditure, and calculates data such as fertilizer expenditure, costs per ha of crop and gross margin measures, one of which includes labour and machinery. Twenty five crop types are defined within the model, with equation governing the loss of nitrogen by leaching defined for each crop type.

ii Crop Regional Multipliers

These specify how crop yield, fertilizer usage, seed, spray and other input costs vary across the regions compared with the national average. Nine regions corresponding to those in the Farm Business Survey are recognised by the model.

iii Farm Weights

These define the number of farms in each region by area (small, medium and large), ownership type (owner-occupier, tenant and mixed) and cropping type. Seven types of farm are allowed: cereals, mixed cropping, dairy, arable dairy, pigs and poultry, lowland livestock and LFA livestock. These are a subset of farm types recognised by MAFF and the European Commission. Farm area varies with farm type, as well as with farm size. Tenancy definitions correspond to those used by MAFF.

iv Crop Mixes

The base percentage shares for each crop type are defined.

v National Fixed Costs

Details of fixed costs such as overhead expenditures, depreciation, land and interest charges are defined.

vi National Balance Sheet Data

Asset liability levels are specified.

vii Regional Fixed Cost Multipliers

These specify how fixed costs vary across the regions, compared with the national average.

viii Sized-based Balance Sheet Multipliers

These specify variation of balance sheet structure with farm size. Regional balance sheet multipliers allow for regional variations.

Data Sources

Virtually all data, with the exception of yield curves, have been derived from published sources and refer to the 1987 harvest, the most recent year for which full data sets existed. The principal data sources were:

Agriculture in the UK, MAFF (1988 edition)
Wye College, Pocket Book (1987 edition)
Farm Incomes in the UK, MAFF (1988 edition)
Rothamsted Survey of Fertilizer Practice (1987)
Regional Farm Business Survey Reports
Regional Trends, CSO

Building up the Representative Farm

The Representative Farm is characterised by defining a set of data inputs which are created from the National database via a set of Regional Multipliers.

The data that need to be specified to create a representative farm are:

- a cropping mix that indicates how a farm allocates its available land amongst the crop/livestock categories allowed in the model;
- a farm size that gives the total acreage of the farm;
- a fixed cost structure describing the spend in £ per ha on costs such as rent, depreciation, interest and overheads.
- a Balance Sheet recording levels of assets and liabilities; and
- a Farm Weight, used in aggregation, being the number of that particular type of farm in given region of a given size and tenancy type, e.g. the number of medium sized East Anglian Cereal Farms.

Describing the Representative Farm

As output the model records the following:

Profit and Loss Account

Revenue from Livestock and Arable Enterprises
Income from Set-Aside and other sources
Grants and subsidies
Total Variable Costs - including Labour and Machinery
Expenditure on Rent, Interest, Depreciation and Overheads
Net Surplus: equal to Total Revenue minus the sum of all the costs listed above.

Balance Sheet

Net Current Assets
Long-term loans
Net Assets

Summary Financial Information

Net surplus from P&L Account
Gearing
Interest Cover
Networth
Expenditure on Seed, Sprays, N and P/K Fertilizer

Production Information

Total output (in tonnes) for:

Dairy	Beef	Pigs	Poultry
Sheep	Barley	Wheat	Oilseed
Sugar Beet	Potatoes	Veg.Mkt Gardening	Other Arable
Orchards			

These results are aggregated using the Farm Weight.

The Treatment of Livestock in the Farm Model

Six types of livestock are currently permitted in the Farm Model. These are: Dairy, Beef, Sheep, Pigs, Poultry and Extensive Livestocking. The treatment of these land uses is different from - and more complex than - the treatment of arable land uses.

The model requires that all productive activities of a farm are put on a per ha basis; this is to tie in with the leaching model. This means that for each of the livestock categories, in order to calculate a return per ha, the model needs:

- an area of farm land allocated to each livestock type;
- a yield curve, input usage, and price per ha.

Yield Curves

Data for response curves were supplied predominantly by ICI and are best for winter cereals. For arable crops (peas and beans excluded) the response curve is quadratic, with the yield rising and then falling as fertilizer use increases. For livestock, the level of nitrogen applied affects the stocking rate, (the yield per animal being assumed to be unaffected by the nitrogen application).

Fertilizer Use

The level of fertilizer use per crop can alter in response to changes in the price of either fertilizer or the crop.

a Fertilizer Price Elasticity

This describes the proportional change in nitrogen use for each crop for a given proportional change in the price of fertilizer.

Although it may be altered by the programme user, it is normally set at 0.3 - a level which best reflects empirical results. This means that if the fertilizer price doubles, fertilizer usage falls by 30%.

b Marginal use Derived from Yield Curves

Fertilizer is applied to the point at which the marginal benefit from applying a unit of fertilizer is equal to the cost of so doing.

An increase in the price of the crop increases fertilizer usage, since this increases the value of the marginal benefit, at any level of fertilizer usage.

Land Reallocation

Land use is changed subsequent to output price changes in a two-stage mechanism. Certain crop types are unaffected; those on a quota, such as milk and sugar beet, and those for which planning permission is likely to be needed, such as non-agricultural uses and woodland. Land use is split into two categories, arable and livestock. The first part of the mechanism calculates average price indices for the arable and livestock categories. Land is then reallocated in total between arable and livestock on the basis of the price change and on input elasticity, which is generally set at 0.6, to represent the difficulties and costs associated with switching between farm types.

The second part of the mechanism reallocates land within the arable and livestock categories on the basis of price movements of each crop type relative to the average price change and an output elasticity, which is generally set at 1.

Input Use

The model reflects the fact that marginal benefits from input usage increase with output price. A yield multiplier calculates the amount by which output has to increase for a given increase in output price. After allowing for the increased fertilizer use, the residual is allocated pro-rata amongst all the inputs used by a crop in proportion to the share of that input in total crop marginal costs. The yield per ha is then increased in line with the residual multiplier on yield, as are crop inputs.

The MORECS Squares Grid

Data on the water supply system of England and Wales is largely available in the public domain but the sources are diverse. They include:

- Meteorological data, including rainfall
- Physical data on soil types, rock strata and catchments
- Abstraction points and volumes
- River flows
- Hydrological pressure in aquifers
- Validation data on direct measurement of nitrate concentrations.

The data is organised on a variety of different geographical bases, ADAS regions, Water Company boundaries, map references and a meteorological grid known as the MORECS grid. This last grid was chosen as the basis for the water model database because it is the system on which the largest single body of data existed and also because it formed a uniform pattern, with 40 km squares covering the whole of England and Wales. By mapping the different data sources to this one grid each square could be treated as a mini-model with complete nitrate leaching and water supply definitions. Parts of England and Wales were analysed in depth using groups of squares before the complete system was combined for all regions.

It is possible, to assemble a complete set of information for each MORECS square, to enable the dynamics of its water system to be understood. The next task was to assemble a model of the national system from these local systems, taking account of their effects on each other. The procedure which was used identifies those squares which receive no external flows from other squares, since concentrations in such squares depend only on local characteristics. Squares containing river mouths and large groundwater flows to the sea were analysed last. In this way it was possible to construct the cascade, running from the high points in England and Wales towards the coast, which carries the nitrogen through the country's water system.

Groups of MORECS squares can be analysed separately from the complete water model to analyse particular problems in different areas. This approach was used to investigate the particular nitrate problems in the East Anglian surface and groundwater catchments.

The Water System in the MORECS Square

Rain falls on the surface of the earth soaks into the soil. Some of this water will evaporate directly from the soil and some will be absorbed by plants and will subsequently evaporate from the plant leaves in the process called "transpiration". The sum of these evaporative processes is called "evapotranspiration". In the UK, annual rainfall tends to exceed annual evapotranspiration. Consequently there is a net excess of rainfall which drains from the soil and is known as "hydrologically effective rainfall". "Water" in this study refers to this concept. Once the water is present in the soil it will dissolve some of the soluble soil constituents such as nitrate, so that the drainage water will contain such constituents. As the water drains it ultimately meets the top of the underlying rock.

If the rock is porous it is known as an aquifer and will absorb the water soaking through from the soil. If not, the water flows over the rock to meet surface water courses such as drains and rivers. In places where the soil cover is thin and overlays non porous rock, the soil can become soaked, resulting in surface water run-off; water then runs directly over the surface into water courses.

For every MORECS square the water is now divided into two recharge volumes - surface water and groundwater. In the model these are calculated respectively as the proportion of rainfall that falls on non-porous rock and on outcropping aquifer.

The groundwater recharge moves down slowly through the aquifer in the MORECS square until it reaches the water table. At the "base" of the square the water moves horizontally under the influence of hydraulic gradients into other squares or into the sea.

Surface water recharge collects in individual catchments and then moves along water courses into other squares and eventually into the sea.

There is one additional flow which contributes to surface water. This is a groundwater flow to surface water which occurs throughout the year, supplying water to rivers in dry periods. These flows are modelled from measurements of river water flows in drought conditions.

The model calculates a complete mass balance of the water flows through all MORECS squares, from the initial rainfall volumes. A proportional relationship between the various flows is then applied, in order to preserve the physical relationship between ground and surface water in periods of high and low rainfall.

In each square there are five predominant water movements

- rainwater recharges water moving downwards through the aquifer towards the water table.

- water moving horizontally below the water table and mixing with water from other squares.

- surface water collecting in water courses within a square.

- surface water flowing downstream into other squares and into the sea.

- groundwater seeping into river beds.

In addition to these major physical effects there are a number of artificial systems which affect water movements within individual MORECS squares:

The water abstracted for public supply can be either surface or groundwater and in both cases the model returns the water to surface supplies after use. For groundwater this is equivalent to assuming abstracted water is additional to the groundwater flow to river beds.

Pipelines are used extensively in some regions to transfer water over long distances. These flows are modelled as normal water movements between squares. Squares do not have to be adjacent to exchange water.

Nitrate Movements in the MORECS Square

The nitrogen movements are intimately connected with each of these water movements. The nitrogen already in the soil contributes significantly to the total quantity that is available for leaching. Additional nitrogen is applied from various sources principal among which are:

- nitrogen fertilizer
- animal manures
- wet and dry deposition from the atmosphere and from rainfall

A set of "leaching" equations estimates from these inputs the quantity of nitrogen that is released into the water system. The rainfall quantity, the soil type, the crop grown, the time of planting, and the crop rotation all condition the exact quantity that is washed from the soil into the recharge water.

The recharge concentration can then be calculated from the quantity of nitrogen leached per volume of recharge water. The dissolved nitrate is then carried in the water through aquifers and into streams and rivers. Where squares meet they interchange both water and dissolved nitrate and the mix of the two determines the changing nitrate concentrations. The model calculates the nitrate interchange as a function of the water volumes and nitrate concentrations affecting individual squares.

Once dissolved in water, nitrate concentrations can be affected by a variety of natural and artificial chemical and biological processes:

In some aquifers nitrate reduction through denitrification can occur due to a lack of oxygen. However, denitrification is most important for surface water. Reductions in the nitrogen content vary according to the climatic and biological regime but can be substantial, particularly in summer months when temperatures are high. Natural denitrification is modelled at the MORECS square level to take account of seasonal patterns across England and Wales.

Artificial denitrification - treating the water - has been proposed in a number of regions to solve the short term high nitrate levels.

This process is modelled for both water supplied to public households and for surface water within a MORECS square. The downstream effect of denitrified water when it is returned to surface water supplies can be influential in determining the number of plants required to achieve the EEC nitrate standard of 11.3 mg N/l.

An additional input of N to the water system is due to human effluent. Different levels of effluent treatment can be modelled to observe the effect on river water concentrations and the degree to which effluent is responsible for high nitrate levels in estuaries and at sea.

Using the MORECS Square

The MORECS square serves as an elemental building block for the modelling of water and nitrate movements though England and Wales. Sets of these building blocks are important for analysing particular regions of Britain. The definition of all the influences bearing on a single grid system makes geographical areas immediately comparable and simplifies the integration of different aquifers and geographical regions. In addition, individual MORECS squares can be analysed in greater depth.

Data Sources in the Water Model

Each square within the grid covers an area of 1600km². For each crop grown the average fertilizer use in the region was known, however every square had other characteristic features which influenced the nitrogen-water cycle. The complete list is:

- land use. 23 crops and other use.
- fertilizer use
  by crop, by compound/straight, by region
- mix of soils. 5 types
  sand, sandy loam, silty loam, clays, drained heavy soils
- the rainfall
- the number of intensive Pig and Poultry farms
- the average wet/dry deposition of nitrogen from the atmosphere
- the natural denitrification rate
- the quantity of effluent disposed of into surface waters
- the water movements
- the volume of water abstracted for use in public supply.
- the degree of artificial nitrate treatment.

A method was developed for calculating the water flows across the boundaries between grid square, for both surface water and groundwater. A total mass balance was produced from the quantity of rainfall to the calculation of flows to the sea ie the mass of water entering any square had to be accounted for by the flow of water leaving it.

Surface Water Data

Maps of rivers, the position of gauging stations, and a simple indication of surface water catchments are published by the Institute of Hydrology. By superimposing our grid and interpolating between river, catchment size and nearest gauging station measurement, we could obtain a value for mean surface water flows across grid boundaries. In addition we recorded the base flow, which is the summer river flow after some months of drought, and which is typically presented at a percentage of the mean flow. This is a measurement of the flows rising into the surface water system from groundwater sources.

Ground Water Data

No measured flows can be taken directly for groundwater as it moves through the aquifer as a whole, as distinct from the individual fissures in it. There are, however, maps of groundwater contours which show the height of the saturated zone above sea level for all the aquifers in Britain. All other things being equal, the closer the contours the greater the water flow. The other aquifer characteristic of major importance is the permeability - a measurement of the resistance of the rock to water movement. Chalk, for example, with very small pores, is much more resistant that sandstone.

The England and Wales grid was first superimposed on the map of groundwater contours and permeabilities. An average value for the difference in contour spacing was deduced for the edge of every square together with a value for the permeability. From these we calculated the volumes of groundwater crossing the edge of each square.

The Total Water Balance

The complete water system has then four distinct components:

rainfall
surface water movements
groundwater movements
groundwater to surface water movements

Each is deduced from different data sources. We combined these systems and expressed the flow movements as a percentage of the rainfall within each square. For example, of the rainfall that falls on outcropping aquifer in square 141, 40% flows underground to square 142, 40% to square 130, 10% rises to the surface as base flow, and 10% evaporates.

The Calculations of Nitrate Concentrations

The first stage of the model uses the leaching equations to calculate the quantity of nitrate leached for every combination of crop, rainfall, wet/dry deposition, soil type, fertilizer use and intensive farming that occurs within the England and Wales grid. An average quantity is then calculated for each square.

This nitrogen is dissolved in the rainwater as it seeps through the soil; the concentration is called the "recharge concentration" . The rainwater then carries the nitrogen into the surface water or groundwater system depending on whether it falls on exposed aquifer or impermeable rock. The flows between squares and between the surface and the ground then determine the distribution of the nitrate through the water system and into the sea.

Finally, we needed to understand and measure the factors other than the leaching of fertilizer, which affect nitrate concentration levels.

Natural denitrification occurs in every square, especially in surface water. Where good data is lacking, 15% of nitrate in surface water is assumed to be denitrified.

Abstraction volumes do not interfere with the measured flow values used in calculating the water movement grid. Surface water that is abstracted is returned to surface water after passing through the domestic supply system. Abstracted groundwater that is returned to surface water is only another element of the contribution to base flow. However, abstracted water if high in nitrate will need to be treated. In addition low nitrate abstracted water can be piped to high nitrate regions for blending.

Artificial denitrification has been proposed as a solution to high nitrate water in many regions. Within the model experiments can be made with levels of denitrification and the effect on the abstraction and surface water concentrations.

Effluent tonnages are taken from the Royal Society report on the nitrogen cycle. Roughly a third is dumped at sea and the remainder is distributed into surface water, the quantity depending on population density within a MOREC square. The quality of sewage treatment can be input to the model. Only two possibilities are considered - completely treated or untreated. The nitrate from effluent is added onto the concentrations in the abstracted water before it is returned to the surface water system.

Data Sources

Soil Types	Soil Map of England and Wales. Soil Survey of England and Wales, Harpenden. 1975.
Wet/dry Deposition	United Kingdom Atomic Energy Authority. Harwell
Pig & Poultry Density	MAFF June 1987 Census
Surface Water	Institute of Hydrology, 1986 yearbook
Rainfall	The Meteorological Office
Groundwater	1982 EEC Groundwater maps for the UK, supplemented by more local British Geographical Survey Maps.

Effluent	The Nitrogen Cycle of the United Kingdom. The Royal Society. 1983
Denitrification	Unwin, ADAS
Abstraction	1982 EEC groundwater data. Water authority figures for surface water.