Integrated Use of GLEAMS and GIS to Prevent Groundwater Pollution Caused by Agricultural Disposal of Animal Waste

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ABSTRACT / In modern intensive animal farming the disposal of a large amount of waste is of great concern, as, if not properly performed, it can cause the pollution of water, mainly because of the high content of nitrate and phosphate. This paper presents the results of a study intended to assess the environmental sustainability of animal waste disposal on agricultural soils in the alluvial plain of the River Chiana (Tuscany, Italy), a particularly sensitive area because of the high vulnerability of the shallow aquifer and of the intensive agricultural and breeding activities. With this aim, a strategy has been employed, that consists of the integrated use of a management model and GISs. The consequences on groundwater of applying animal waste to different kind of soils and crop arrangements have been simulated by means of the management model GLEAMS (Groundwater Loading Effects of Agricultural Management Systems, ver 2.01). As the huge amount of data required by such a sophisticated model does not allow applications at a scale larger than the field size, IDRISI and GRASS GIS packages have been used to divide the study area into land units, with homogeneous environmental characteristics, and then to generalize on these units the outputs of the model. The main conclusions can be synthesized as follows: The amount of animal waste produced in some of the investigated areas (i.e., municipal territory) is greater than that disposable on their own agricultural soil with no risks to the groundwater; consequently a cooperative approach among municipalities is necessary in order to plan waste disposal in a comprehensive and centralized way.

The treatment of waste from animal farming represents a considerable problem, both from environmental and economic points of view. On the other hand, the high nutrient content of this waste makes it particularly suitable for use as fertilizer. In traditional agriculture, animal wastes represent the main source of crop nutrient and, for this reason, in the past, farms were always integrated with animal breeding. The development of modern agriculture and intensive breeding has broken this equilibrium and nowadays the activities are almost always separate. Because of the growing importance of environmental problems, a trend to change this situation can be noted, which consists of singling out well-defined agricultural lands that can be used as the most natural and cheapest destination for animal waste.

KEY WORDS: Land use; Animal waste disposal; Groundwater protection; GIS, Management models

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As a consequence of the separation between cropping and breeding activities, the organization of effective and environmentally compatible animal wastedistribution on agricultural land is becoming important. The planning of agricultural land use plays a key role in this respect; in particular, the most practical action to be undertaken consists of defining land-use planning and management criteria in order to reduce environmental pollution.

Land-use planners have to take into account several environmental and management issues and to evaluate all their possible interactions. The greatest difficulty comes from the number and complexity of the environmental factors involved. Land use (crop patterns), pedology, hydrology, and geomorphology are the main issues to be considered when selecting areas for animal waste disposal. In a typical Italian landscape, the pattern of such environmental characteristics is often so complex that it discourages this approach.

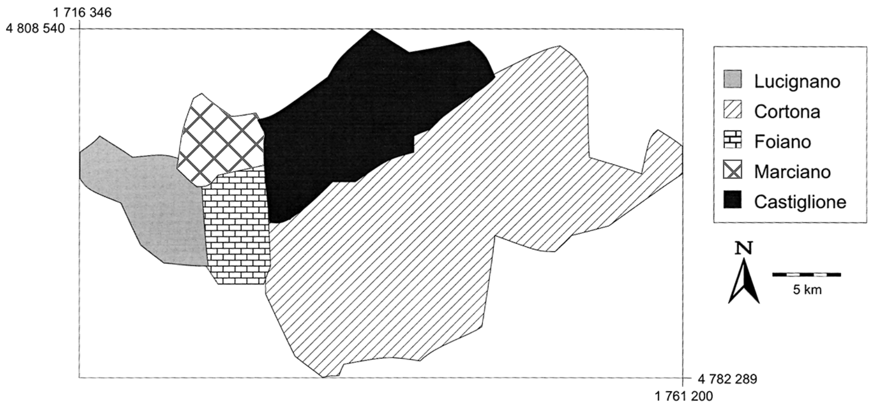

Figure 1. Study area.

Table 1. Head of animals in the study area (ISTAT 1991)

Municipality	Poultry	Cattle	Swine
Castiglion Fiorentino	50,811	467	6,586
Cortona	112,928	1,600	41,375
Foiano della Chiana	9,590	1,379	3,159
Lucignano	8,406	351	11,387
Marciano della Chiana	16,677	146	1,774
Total	198,412	3,943	64,281

Table 2. Soil types characteristics

Soil type	Description	Soil texture
1	Recent alluvial soils and alluvial fan deposits; noncalcareous, with medium coarse texture	Fine sandy loam
2	Soils on fluvial and lacustrine deposits; calcareous, with fine texture	Clay loam
3	Soils on reclaimed land; siliceous deposits with medium fine texture	Silt loam
4	Soils on fluvial and lacustrine deposits; noncalcareous, with moderately fine texture	Clay loam
5	Soils on fluvial and lacustrine deposits; noncalcareous, with very fine texture	Silty clay loam
6	Soils on alluvial fan and ancient flood deposits; noncalcareous, and at times with a skeletal texture	Clay loam

Background

In order to tackle the problem of animal waste disposal, a strategy is proposed in this paper that consists of the integrated use of the management model GLEAMS (groundwater loading effects of agricultural management systems) and GIS. Among other things, management models such as GLEAMS (Leonard and others 1987), PRZM (Carsel and others 1985), EPIC (Edwards and others 1994), AGNPS (Young and others 1989), and ANSWERS (Beasley and Huggins 1981) allow one to forecast the quantity and quality of leachate and runoff for field-sized areas.

As demonstrated by the many papers issued in recent years, these models are presently gaining approval as effective tools in water resources management, because they have been shown to work very well in the assessment of environmental impacts caused by rural land-use choices. For example, Yoon and others (1994), employed the GLEAMS model to predict nutrient losses in surface and subsurface runoff and their concentration in soil layers, following application of poultry litter, together with commercial fertilizer, on conventionally tilled corn plots in Alabama. Edwards and others (1994) show the results of an application of the EPIC model in Arkansas, which was used to single out the best period for poultry litter disposal on agricultural soils taking into account the spatial variability of the climate and soil pattern.

Unfortunately, the huge amount of input data required by these models is a major obstacle to their application at scales larger than field size. Therefore, particularly in regional or river-basin investigations, it becomes necessary to single out strategies that allow the management models to be applied. The integration of such models with geographic information systems (GIS) is certainly a promising approach. In fact, while models allow one to perform complex and dynamic analyses, spatially coded data deriving from these analyses can be acquired, processed, stored, and visualized in a appropriate and useful shape for planning and management activities using a GIS. The input and output data of distributed models can be considered as cartographic layers and thematic maps (Fedra 1994), to be drawn, modified, and handled with GIS.

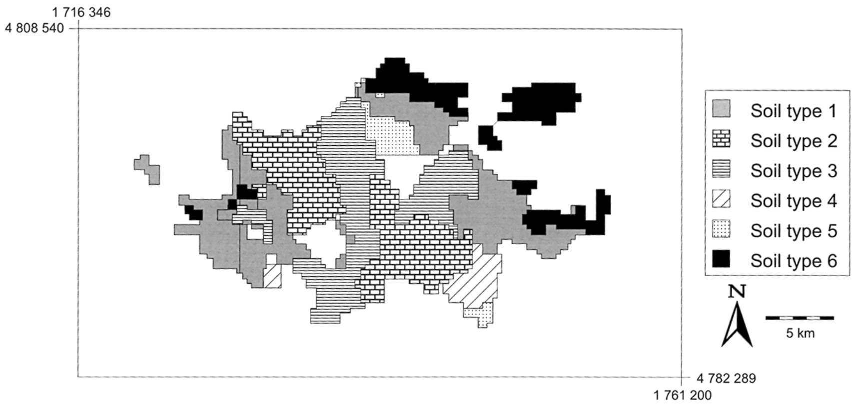

Figure 2. Soil map.

Table 3. Fertilization and tillage scheme for crop patterns simulated

Winter Wheat–sunflower–winter wheat						Winter wheat–maize–winter wheat					
			Mineral N application (kg/ha)						Mineral N application (kg/ha)		
Crop	Date	Organic N application (kg/ha)	NO_3^- N	NH_4^+ N	Tillage	Crop	Date	Organic N application (kg/ha)	NO_3^- N	NH_4^+ N	Tillage
Winter wheat	19 Sept	96				Winter wheat	28 Oct	96			Moldboard plow
	20 Sept				Moldboard plow		28 Oct				
	6 Nov				Disk harrow, offset		6 Nov				Disk harrow, offset
	7 Nov				Disk harrow, offset		7 Nov				Disk harrow, offset
	18 Feb		24	12			18 Feb		24	12	
Sun-flower	25 Jul				Moldboard plow	Maize	16 Mar	200			
	25 Feb			60			17 Mar				Moldboard plow
	28 Feb				Disk harrow, offset		8 Apr				Disk-harrow, offset
	2 Mar				Disk harrow, offset		9 Apr				Disk harrow, offset
	28 May		20	20			15 Jun			50	
Winter wheat	19 Sept	96				Winter wheat	28 Oct	96			
	20 Sept				Moldboard plow		28 Oct				
	6 Nov				Disk harrow, offset		6 Nov				Disk harrow, offset
	7 Nov				Disk harrow, offset		7 Nov				Disk harrow, offset
	18 Feb		24	12			18 Feb		24	12	

Integration between models and GIS can be carried out in different ways, from a very simple case in which GIS is used to prepare the model input and analyze its results, to a fully developed way in which the GIS incorporates the model itself among its routines, sometimes completed by a user interface and often by an expert system and a knowledge base (Charnock and others 1996). In the specific field of nonpoint sources of pollution, interfaces are already available, between the GRASS GIS package (USACERL 1993) and various models such as AGNPS and ANSWERS. A GRASS–GLEAMS interface is currently under development. A number of papers have recently demonstrated the growing interest on the subject. For example, Fraisse and others (1994) developed the ‘‘generic interactive dairy model’’ (GIDM), which integrates the GLEAMS model with ARC/INFO GIS software, to help planners and decision makers analyze the effects of alternative dairy waste management practices.

Aim of the Work

One of the main environmental issues in rural areas that are characterized by intensive animal breeding is the correct management of wastes. In this case the use of management models integrated with GIS can contribute to single out the sites most suitable for waste disposal. The Chiana River valley (Tuscany) is a particularly significant area from this point of view because of its great number of breeding farms. Nevertheless the problem is experienced over wide areas of Italy, mainly because of the conversion of an ever larger number of farms to intensive breeding methods. Different animal waste disposal methods and different management criteria have been simulated by means of the GLEAMS model applied to field size areas. Successive model outputs have been compared in terms of groundwater pollution risk (nitrate leaching). The GRASS and IDRISI GIS packages have then both been used to generalize the results of GLEAMS over a large area.

Among the many impacts of the land disposal of animal waste, only groundwater pollution from nitrates has been taken into account here, because it is the most significant in the study area. The present paper presents a methodology that is suited to a wide variety of problems caused by agricultural nonpoint pollution sources, and for this reason it is of little importance which kind of pollution is examined.

Methodology

The study area is located on the alluvial plain of the Chiana, a tributary of Arno River in Tuscany, Italy, an area characterized by a rich and shallow aquifer that is threatened by growing nitrate pollution. The area is mainly flat, with a mean altitude of 200 m asl, except for the northeast part where there are hills up to 1000 m asl.

When manure is utilized on agricultural soil, nitrate can leach out and cause groundwater pollution. The GLEAMS management model has been used to assess this risk. By means of a detailed description of agronomic practices, the model simulates the mobilization of nutrients and pesticides from the soil. GLEAMS only simulates nutrient mobilization within and through the plant root zone, without taking into account the complex interactions that occur between nitrates and the deep rocky layers beneath. For this reason it works adequately, in terms of output reliability, for the shallow aquifer conditions that exist in the study area.

Table 4. Average nutrient concentration in the applied manure

	Percent*			
	Total N	Organic N	NO_3^-	NH_4^+
Swine liquid	0.28	0.04	0.01	0.23
Beef solid	4.8	3.23	0.03	1.54
Poultry solid	6.2	4.12	0.03	2.05

*Percentage of liquid volume in case of liquid manure and of dry weight in case of solid manure.

The study was restricted to a portion of Val di Chiana that corresponds to the municipalities of Castiglion Fiorentino, Cortona, Foiano della Chiana, Lucignano, and Marciano della Chiana (Figure 1) where, as shown in Table 1, animal farming is a particularly significant activity with regard to the production of waste with a high nitrate content (ISTAT 1991). A spatial data base, issued by the Tuscany Regional Administration, allowed us to identify and locate the crop patterns and the soil typesexisting in the study area (Table 2 and Figure 2). Triennial crop rotations of winter wheat–sunflower–winter wheat (WSW) and winter wheat–maize–winter wheat (WMW) are by far the most widespread in the area, besides being among the most suited to manure disposal.

Model Application

The model was used to assess the environmental compatibility of different schemes of animal waste disposal. To this end, sample areas of 1-ha and farmed with either WSW or WMW crop rotations were analyzed. Simulations were based on the assessment of nitrate leaching into groundwater, assuming a waste application equal to the normal annual NO_3 needs of the crop analyzed. Furthermore, among the existing six types of soil, only two types (soils 1 and 2), with opposite hydrologic and pedologic characteristics (see Table 2), were taken into consideration to highlight different model results.

For the above-mentioned crop rotations nitrate leaching was simulated for a 40-year period. A scheme of the simulated tillages and fertilization is shown in Table 3. Disposal of swine, cattle, and poultry manure was simulated on the assumption that they are the most commonly bred species in the area. The nutrient contents of the animal waste employed in the simulations were calculated by means of average values of the data taken from the literature (Giardini 1991, Knisel 1993) and are displayed in Table 4. Total animal waste

Table 5. Total nitrogen, live weight, and number of animals corresponding to the amount of manure applied*

		Swine		Cattle		Poultry	
	Total N (kg/ha/yr)	Live wt (kg/ha)	Head (number per hectare)	Live wt (kg/ha)	Head (number per hectare)	Live wt (kg/ha)	Head (number per hectare)
Winter wheat	132	550	9.2	710	2.0	300	200.0
Maize	250	1140	19.0	1470	4.2	620	413.3

*Sunflower has been neglected because it needs only mineral fertilization.

amounts supplied to each crop and the corresponding nitrogen content are reported in Table 5. In this respect, it should be stressed that the quantities of animal waste simulated were always calculated taking into account the legal limits in force with respect to both the amount of the manure (expressed as the weight of the animals which produce it: live weight) disposable on each of the crops examined and to the maximum amount of nitrogen allowed. These limits are, respectively: 2000 kg/ha of live wt per year for winter wheat and sunflower, 4000 kg/ha live wt per year for maize, and 250 kg/ha of total nitrogen per year.

Because the model was applied in noncalibrated form, and thus it was not possible to estimate the uncertainty, rather pessimistic assumptions were used in the assignment of values to those parameters that mainly influence nitrate leaching, for example, field capacity (FC). This is also in accord with the sensitivity analysis undertaken in previous papers that deal with a similar environment (Garnier and others 1996). A rather permeable soil, which allows higher nutrient leaching, will cause more groundwater pollution because of its lower water retention capacity, but the dilution effect mitigates an impact that at first glance would seem to be considerable. This confirms the need to employ rather sophisticated models, such as GLEAMS, which allow a global system analysis to be performed.

In order to evaluate the results of the analysis and as a reference point for discussion, the maximum allowed limit of 11.3 mg/liter of nitric nitrogen in drinking water (imposed by Decree of the President of the Republic 1988) was considered. This limit must be regarded as indicative because GLEAMS considers only the agricultural areas, but the aquifer also receives water, with a lower nitrate content, from other areas. This should improve the real situation in comparison to the model results.

GIS Application

To extend GLEAMS model outputs that are related to the 1-ha sample areas to the entire Chiana Valley, elementary land units had to be singled out on which animal waste disposal could be performed. A land unit is defined by uniform environmental (hydrologic, pedologic, and morphologic) and land use (crop pattern) characteristics. With this aim a cartographic database consisting of 400-m-sized squares was built using IDRISI and GRASS raster GIS packages. The procedure included the following steps: (1) derivation of the slope map of the study area from a 1:25,000 digital elevation model (DEM) issued by the Italian National Oil Agency and National Geological Service; (2) rejection of areas steeper than 5%, as animal waste disposal can potentially be responsible for surface water pollution on these because of elevated amounts of runoff; (3) grouping of the six soil types that exist in the study area into three groups which are significantly different from each other in terms of the hydrologic behavior (Table 6); (4) rejection of areas whose land use is different from that of the two crop patterns considered; (5) overlaying of maps ‘‘3’’ and ‘‘4’’ to obtain the land units map (Figure 3); (6)multiplying the number of animals (Table 1) by the average N value produced per capita (Table 7) so as to derive the total N load produced by farming activities in each municipality (Table 8); (7) calculation of ‘‘potentially disposable’’ N (i.e., that is applicable to the soil because it is required by the crops, but without taking into account the risk of groundwater pollution), by multiplying the extension of each land unit by the specific N amount required by each crop pattern (Table 9).

Table 6. Grouping of soil types

Soil group	Soil types	Leachate (mm)	NO_3 N load in the leachate (mg/liter)
1	1–3	228.4	33.8
2	2	184.6	8.3
3	4–6	210.9	18.4

Results and Discussion

GLEAMS Model Application

As far as the GLEAMS simulations are concerned, and in relation to each type of soil and manure examined, the most significant results are summarized

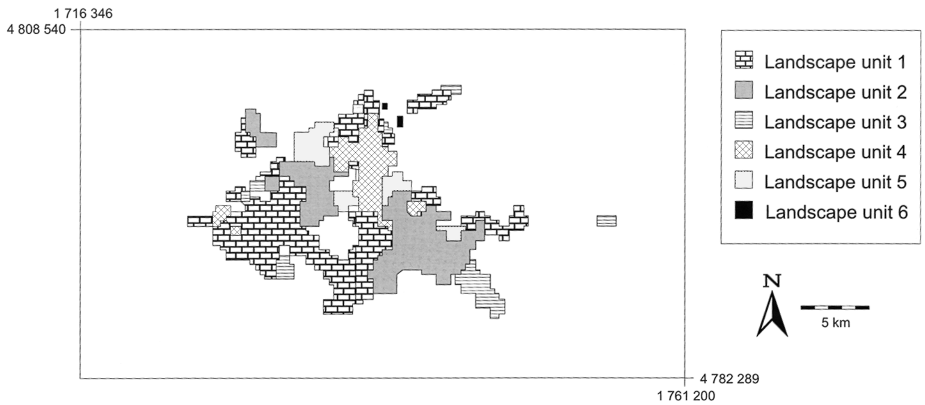

Figure 3. Land units map.

Table 7. N output from farming activity in the study area

Farming activity	Mean weight (kg/head)	N load in manure (kg/tonnes live wt)
Poultry	1.5	325
Cattle	350.0	136
Swine	60.0	175

in Table 10. They refer to the annual average values of leachate and leached nitrate, and the nitrate concentration in the leachate. It should be noted that the results are reliable and conform to theoretical expectations, especially regarding hydrological phenomena. The results show that, in the case of soil 1, the 40-year average values of nitrate concentration are nearly always three times the above-mentioned maximum limit for drinking water and for soil 2 they are very close to this limit, although this is not a reassuring result as the standard deviation is of the same order of magnitude as the average concentration. Annual nitrate concentration in the leachate has been proved to be considerably higher than 11.3 mg/liter in many cases.

It has to be borne in mind that the historical data relative to the 40 years of simulation present some outliers, i.e., values of NO_3 N concentration in the percolate, that are significantly different from those referred to all the other years of the simulation (Figure 4). These outliers occur either when a particularly abundant rain falls just after or in the day of fertilizer application. The first case is realistic because farmers cannot know exactly when it will rain, while the second is unrealistic because farmers do not apply fertilizers on rainy days. Because it uses the same fertilization dates over the whole simulation period, GLEAMS is unable to take account of the difference between these two cases. To overcome this drawback, the causes of these outliers should be checked and, if necessary, fertilization dates should be changed slightly. In this study we did not take into account these adjustments because we considered the mean value of the parameters examined throughout a long time interval (40 years).

GLEAMS' inability to update soil parameters represents another drawback of the model. For instance, the model is not able to consider that animal waste fertilization improves the hydrological performance of soils, as it improves soil structure and consequently causes the progressive decreases of leachate. This drawback can easily be overcome, but it was neglected in this work, as the most pessimistic hypotheses were always used. All these reasons suggest that model outputs have to be considered as a rough evaluation of a behavior. This means, for example, that from the simulations it is possible to deduce that nitrate leaching from soil 1 is approximately four times that from soil 2, but it is not correct to assert that nitrate leaching from soils 1 and 2 are on the average 77 and 18 kg/ha/year, respectively, as calculated from the values of Table 10.

The model also reveals the rather chaotic behavior of annual nitrate leaching. While one would expect dilution caused by heavy rains and the consequent increased percolation to reduce the concentration of NO_3 N in the percolate, the low correlation shown by all the graphs in Figure 4 denies this assumption. As heavy rains and percolation are not the main cause of groundwater pollution, a comparative exam was performed between fertilization dates (which were the same every year) and the dates of particularly abundant rains (which were different from year to year). Comparison shows a strong relationship between the two set of dates, thus demonstrating that the causes of groundwater pollution are not the heavy rains and the consequent percolation, but rather the quantity of nutrients in the soil when percolation occurs. The same conclusion was also reached by Line and others (1996).

As far as particular aspects are concerned, it is possible to notice the following: (1) Soils with a fine

Table 8. Total N load from farming activities in the study area

Municipality	C. Fiorentino	Cortona	Foiano C.	Lucignano	Marciano	Total
Total N load (t/yr)	116	566	103	140	34	959

Table 9. Disposable N per land unit

Land unit	Soil group	Crop pattern	Area (ha)	Disposable N carrying capacity (tons/year)
1	1	WSW	7,102	455
2	2	WSW	3,661	234
3	3	WSW	963	62
4	1	WMW	1,594	208
5	2	WMW	1,136	149
6	3	WMW	63	8
Total			14,519	1,116

granulometry imply a lower nitrate pollution risk. (2) Substantial differences among the responses of different crop patterns have not been observed, apart from the response to swine manure, which increases leaching probability as it is liquid and is related to the great quantity of nitrate required by maize. (3) Maize cultivation proves to be responsible for the most significant impacts, notwithstanding this crop is a heavy consumer of nitrate. This can probably be ascribed to the influence of fertilization dates, as described above. Because maize needs a higher quantity of nutrients in a rainy month, the probability of occurrence of important nitrate leaching events increases at such times.

GIS Application

As the model output of the NO_3 N load in the leachate is very close to or greater than the legal limit, it could be argued that the amount of nitrogen contained in the animal waste applied to the whole on each of the simulated crops exceeds the carrying capacity of the area for this element.

Carrying capacity is a concept that is mainly used in ecology, but it also appears in other disciplines. There are a number of definitions of the term, and some are rather different to one another (Landy 1979). The common meaning of all of them, however, is that of a limit which cannot be exceeded without significant changes in some environmental attributes. In this paper the term is used to mean the total amount of N that can be applied on a particular area in one year with acceptable loss of groundwater quality (i.e., not exceeding the legal limit of 11.3 mg/liter of NO_3 N as mentioned above) or, in other words, the corresponding number of animals that can be bred in the area assuming waste application at the site as the unique disposal choice.

On the basis of the organic N applied on the two cropping patterns WSW and WMW (192 and 392 kg/ha respectively, calculated according to the data shown in Table 3) and of their extension to each of the three soil groups (as estimated with GIS), an amount of 3346 tonnes every three years (1116 tonnes/year) of "potentially disposable" organic N was derived (Table 9). Comparing this value with the quantity of nitrogen in the animal waste actually produced (959 tonnes/year, see Table 8), it appears that less N is produced in the study area by animal breeding than the quantity required by the extent of the actual crop rotations of WSW and WMW.

GIS use has enabled quick and precise estimation of the total extent of each crop pattern, and consequently of the amount of organic nitrogen required, in each of the five municipalities of the study area. This has made it possible to compare these values with the corresponding disaggregated values of nitrogen content in the manure produced in each municipality. In this way it has been highlighted that more critical local situations exist, like those of Cortona Lucignano and Marciano della Chiana (Table 11), where the amount of potentially disposable nitrogen is lower than that actually produced.

Table 9 shows that, because of the wider extension of soil group 1 (landscape units 1 and 4), about 3/5 of the organic N needed by the crops, should be applied there. This group is derived by aggregation of soils 1 and 3 (Table 6); it shows the worst hydrological behavior and is responsible for the presence of NO_3 N concentrations in the leachate that are far higher than the legal limit.

Conclusions

This study has been designed to assess the environmental sustainability of animal waste disposal on agricultural soil in the alluvial plain of the River Chiana, which is characterized by numerous stock breeding farms. Two agricultural arrangements have been compared in terms of nitrate leaching. Because of the high vulnerability of the shallow aquifer, the environmental system is particularly sensitive to intensive agricultural and animal breeding activities.

Nitrate mobilization from soil has been simulated by means of the management model GLEAMS. The study has confirmed the high variability of GLEAMS outputs

Table 10. Leachate, leached NO_3 N, and NO_3 N concentration related to manure application on examined soils

	Leachate (mm)		Leached NO_3 N (kg/ha/yr)		NO_3 N concentration in leachate (mg/liter)	
	WSW (mean)	WMW (mean)	WSW (mean ± SD)	WMW (mean ± SD)	WSW (mean ± SD)	WMW (mean ± SD)
Soil 1						
Swine liquid	253.9	249.7	80.5 ± 48.0	92.2 ± 53.1	35.9 ± 24.0	41.2 ± 28.6
Cattle solid	253.9	249.7	69.2 ± 42.8	75.4 ± 44.3	30.0 ± 20.3	32.3 ± 20.3
Poultry solid	253.9	249.7	69.3 ± 42.9	75.5 ± 44.5	30.1 ± 20.3	32.5 ± 20.4
Soil 2						
Swine liquid	187.1	184.5	19.7 ± 15.1	27.1 ± 33.1	10.3 ± 6.4	13.3 ± 11.9
Cattle solid	187.1	184.5	15.1 ± 13.6	16.2 ± 17.5	7.7 ± 5.8	8.3 ± 6.7
Poultry solid	187.1	184.5	15.2 ± 13.7	16.8 ± 17.6	7.8 ± 5.8	8.4 ± 6.8

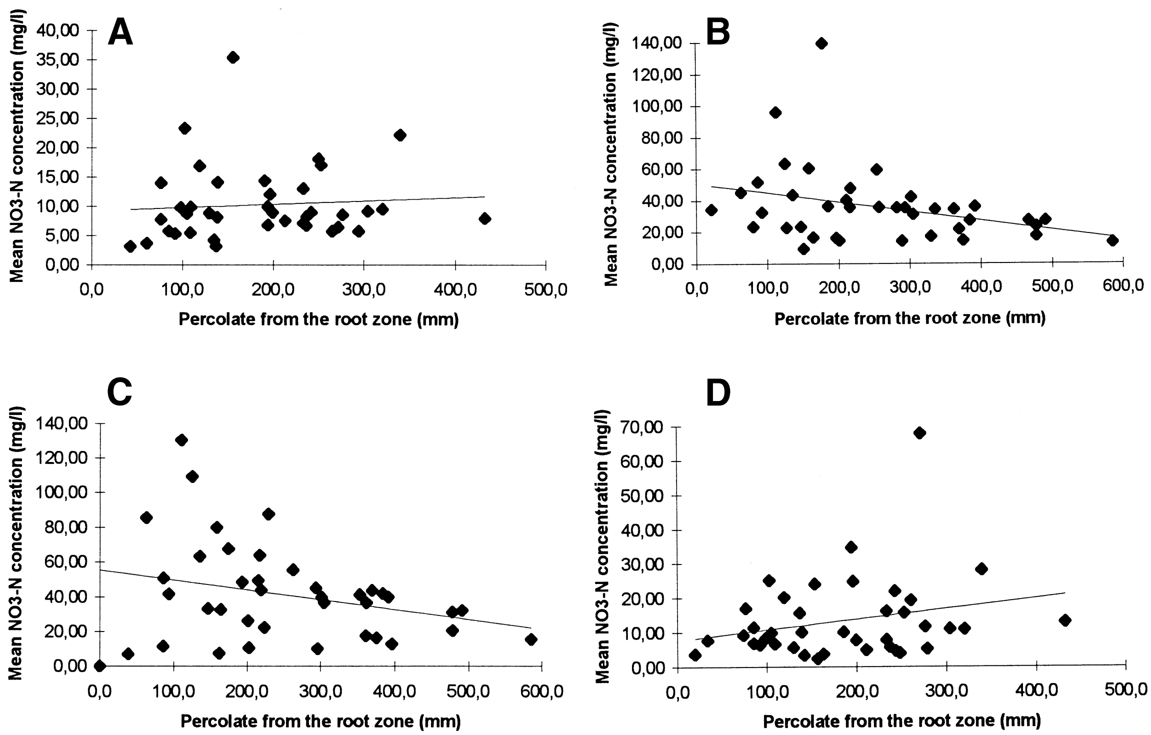

Figure 4. Annual values of nitrate in percolate vs percolate quantity for swine manure application (a) crop rotation WSW on soil 1 ($R^2 = 0.11$); (b) crop rotation WSW on soil 2 ($R^2 = 0.01$); (c) crop rotation WMW on soil 1 ($R^2 = 0.08$); (d) crop rotation WMW on soil 2 ($R^2 = 0.06$).

with field capacity (FC) variation. Nevertheless, a clear stability exists in terms of comparisons: for instance, NO_3 N concentration in the leachate originating from soil 1 is always higher than that from soil 2, and that from the crop pattern WMW is always higher than that from WSW, independent of the value of FC considered. This shows that the model is not intended for the absolute prediction of nutrients in time and space, as its authors would confirm. It is rather a tool for comparative analyses and can thus be used to compare different soils, different management schemes, and other variables (Leonard and others 1990).

The analysis of model simulation results suggests the following conclusions: (1) The amount of animal waste that can safely be applied to agricultural soil without risk to groundwater resources is lower than the limit specified by present local regulations, particularly in the case of liquid manure. (2) The cropping pattern based

Table 11. Comparison between produced and disposable N on a "per municipality" basis

	Castiglion F.	Cortona	Foiano C.	Lucignano	Marciano C.	Total
Disposable N (t/yr)	322	519	160	58	57	1116
N Produced (t/yr)	116	566	103	140	34	959
Balance	206	−47	57	−82	−23	157

on maize proves to be responsible for the most significant impact. This shows that choice of land use is of critical importance to pollution prevention.

Taking into account the fact that total nitrogen application rates correspond to those of typical intensive agricultural systems and that quantities of nitrate leaving the soil surface are in practice the same for the application of either organic or synthetic nutrients, simulation results indicate a significant impact of agriculture on groundwater, whichever crop rotation, animal waste, or kind of soil is considered.

In the second part of this work, GLEAMS results were extended to a larger area using the IDRISI and GRASS GIS packages to generalize the results. In the context of the land disposal of animal waste, the concept of land units appears to be quite promising. Thus the integration of a management model and a GIS has proved to be very useful in land-use planning and in the assessment of the consequences of different land management practices. It allows one to map the risk of NPS pollution in large areas with an accuracy and a level of detail that are far greater than those obtainable with other methods. Moreover, the maps are clear enough to allow easy understanding of model outputs and they also provide a convenient interface for spatial data.

In this paper the model has been integrated with the GIS at a rather low level, as the latter was only used to extend the output of a model formulated for use at the field size to larger areas and to locate and visualize such outputs. A higher integration level might involve the use of customized programs to transfer spatial data from the GIS to the model and then to display and analyze the results of the model using the of GIS.

Notwithstanding the poor level of integration, the joint use of a model and GIS technology allowed an important conclusion to be drawn: under the hydrogeological and land-use conditions that exist in the study area, the land disposal of animal wastes is not a completely environmentally sustainable choice. In particular, similar amounts of produced and disposable N, the uncertainty inherent in model outputs, and the particularly critical situation of the most widely represented landscape units are aspects that the integrated use of the model and GIS have highlighted. This suggests the following land management strategy:

1. The land disposal of the bulk of the animal waste should be combined with treatment of the excess material.
2. The problem of animal waste treatment and disposal should be tackled by a cooperative approach among municipalities so as to prevent situations in which the local excess of waste production, if disposed in situ, could cause a significant risk to groundwater.
3. A lower water quality level should be accepted, thus restricting the problem of possible improvements in water quality to supplies destined for human consumption only.

In conclusion the proposed approach also shows promise for future studies designed to suggest management practices that are most suited to the study area (such as optimization of fertilizer application dates and changes in cultivation practices).

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