ELSEVIER

Environmental Pollution 118 (2002) 249–258

ENVIRONMENTAL
POLLUTION

www.elsevier.com/locate/envpol

Linkage of a geographical information system with the gleams model to assess nitrate leaching in agricultural areas

José Miguel de Paz[a,*], Carlos Ramos[b]

[a]Centro de Investigaciones sobre la Desertificacion-CIDE, Cami de la Marjal s/n, Apdo, Oficial 46470, Albal-Valencia, Spain
[b]Instituto Valenciano de Investigaciones Agrarias, Spain

Received 10 January 2001; accepted 31 August 2001

"Capsule": *A GLEAMS model was linked with GIS to simulate N leaching of vegetable crops and citrus trees and create pollution risk maps.*

Abstract

The GLEAMS (Groundwater Loading Effects of Agricultural Management Systems, Version 2.10) model was linked with a Geographical Information System (GIS) to evaluate the risk of nitrate pollution in an area of 230 km^2 near Valencia (Spain). Under Mediterranean conditions, GLEAMS was calibrated and validated using results from field experiments on citrus orchards and vegetables grown in that area. A graphical user interface (GUI) was implemented in the GIS-model system to allow a non-specialist to run the model, and to represent simulation results as a thematic map. In order to execute the GLEAMS model, data must be grouped in five basic layers: four layers correspond to the base maps (soils, climate, land use, NO_3 content in irrigation water), and the fifth layer corresponds to agricultural management practices, introduced in the system interacting to the GUI. To illustrate system capabilities, two rotations with crops in the vegetable area (potato/lettuce/onion/cauliflower, and artichoke/artichoke in 2 years' rotation each), and orange trees in the citrus area, were simulated to determine the N leached in the study area. Pollution risk maps show that vegetable crops and areas irrigated with groundwater have the highest potential risk of groundwater nitrate pollution. Further analysis identified potato and artichoke (in the first year) to be the crops with the higher risk. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: GIS; GLEAMS; Nitrate; Leaching; Linkage

1. Introduction

Excessive use of nitrogen fertilizer in agriculture has been associated with groundwater pollution in many parts of the world (Meinardi et al., 1995; Mueller et al., 1995). In Spain, nitrate content of groundwater is higher in those areas with agricultural production (Varela and Navarrete, 1998). In eastern Spain many areas with irrigated crops (citrus trees, fruit trees and vegetables) have high levels of NO_3 in the groundwater and, in some cases, exceed the maximum value of 50 mg l^{-1} for drinking water in the EU (Council of the European Communities, 1980). In the Valencia region more than 750,000 citizens live in areas affected by this problem.

A European directive (CEE 676/91 19 December) proposed a plan to reduce or prevent the nitrogen pollution associated with agricultural activities. In each European country the following steps were implemented:

1. Determine the nitrate pollution sensitive areas.
2. Establish a code of good agricultural practices to apply in the sensitive areas.
3. Establish an active plan in risk areas to prevent and minimise agricultural nitrogen pollution.

To determine the nitrate pollution risk areas, a regional analysis tool was needed. Fortunately, large amounts of data associated with nitrate transport through the soil vadose zone can be managed at a regional scale with the GIS. However, a GIS cannot analyse or predict nitrate leaching with time. Simulation models are the most efficient tool to estimate the risk of N leaching in the soil. A combination of a simulation model with a GIS

---

* Corresponding author. Tel.: +34-9-6122-0450; fax: +34-9-6127-0967.

E-mail addresses: jose.m.depaz@uv.es (J.M. de Paz), carlos.ramos@ivia.es (C. Ramos).

PII: S0269-7491(01)00317-7

however, would permit assessment of N leaching at a regional scale and identification of the nitrate pollution risk areas.

Several authors have combined the GIS with a model for N leaching assessment (Srinivasan et al., 1994; Wylie et al., 1995; Tim, 1996; Liao and Tim, 1997; Navulur and Engel, 1998). When coupling a GIS with a model there are some different degrees of integration, from the most simple link such as 'loose coupling' to a more integrated linkage or 'tight coupling' (Tim and Jolly, 1994; Corwin, 1996). The degree of integration depends mainly on the model's complexity of architecture: simple models (i.e. empirical or logical) usually are more easily integrated to GIS than complex models. One-dimensional deterministic models have been more widely coupled to GIS (Corwin, 1996).

As mentioned previously, simple models have usually been coupled with GIS. Some of these coupled models are: index models like DRASTIC (Halliday and Wolfe, 1991; Navulur and Engel, 1998), empirical models (Jordan et al., 1994), and deterministic models like AGNPS (Liao and Tim, 1997). Some authors have coupled GIS with more complex models such as GLEAMS. Hoogeweg and Hornsby (1995) linked this latter model with Arc/Info GIS to assess pesticide leaching; Garnier et al. (1998) used the GLEAMS and a raster GIS (GRASS and IDRISI) to explore ways of reducing groundwater pollution caused by agricultural disposal of animal waste; and Wu et al. (1996) used a GIS to select different scenarios to apply the GLEAMS model and determine nitrate leaching at a plot scale (10 ha). Linking GLEAMS with a GIS to assess nitrate leaching at a regional scale has not yet been developed.

The purpose of this study was to develop a GIS-N model system to assess leaching at a regional scale in an agricultural area. A graphical user interface (GUI) was developed to simplify the use of the GIS-N model system, to run the model, and to represent of the simulation results as a thematic map. This paper describes the methodology required to link a GIS (PC-ArcCad) to a GLEAMS model and presents an application of this system to show its capabilities.

2. Methods

2.1. Study area

A 230-km^2 area was selected in eastern Spain near Valencia (Fig. 1) to apply the GIS-N model system. This land is used primarily for agriculture (60% of the total area) with many crops (mainly vegetables and citrus) cultivated in soils ranging from sandy-loam to clay which contain high nitrate concentrations in the groundwater (in some cases higher than 300 mg l^{-1}; Varela and Navarrete, 1998). This area is mainly flat with a mean altitude of 60 m, and the aquifer is very shallow (from 2–60 m depth). The climate is semiarid and mesothermic with dry summers and rainy autumns. Many wells are widespread over the zone with different uses, but mainly for irrigation and domestic needs. A total of 1 million people live in this area with a population density of 4300 hab/km^2.

2.2. The GLEAMS model

The GLEAMS model (Groundwater Loading Effects of Agricultural Management System) was developed by the USDA-ARS (Knisel, 1993) to predict and evaluate the effect of agricultural management practices on soil erosion, N and pesticide leaching, and runoff. It has been used by several authors to study pesticide leaching (Leonard et al., 1987; Truman and Leonard, 1991), nitrogen losses (Yoon et al., 1994; Wu et al., 1997; Stone et al., 1998; Bakhsh et al., 2000), runoff (Knisel et al., 1991) and, in combination with GIS, to delineate wellhead protection areas (Vieaux et al., 1998) or to simulate nitrate leaching (Wu et al., 1996).

Fig. 1. Study area location.

GLEAMS is a one-dimensional, deterministic and physically based model that simulates percolation, runoff, N and pesticide leaching, and erosion and sedimentation on a daily time step. The model consists of four sub-models, dealing with hydrology, erosion/sedimentation, transport and fate of nutrients and pesticides, respectively. In this study only the hydrology and the nitrogen nutrient sub-models were used. The hydrology sub-model calculates the water balance in the root zone. The water movement through the soil profile is simulated assuming piston-flow, using soil parameters like field capacity and wilting point. The potential evapotranspiration is calculated using either Penman-Monteith (1965) or Priestley-Taylor (1972) equations. GLEAMS uses algorithms to estimate soil evaporation and crop transpiration rates that consider the evolution of leaf area index (LAI), and the soil water content. LAI is also used to simulate root growth.

The nitrogen nutrient sub-model includes the main nitrogen transformations (mineralization, immobilization, nitrification), inputs (mineral and organic fertilizers, N in rainfall and in irrigation water, symbiotic fixation, mineralization from soil organic matter and crop residue) and outputs (volatilization, denitrification, leaching, crop uptake, runoff) in the root zone. GLEAMS is a complex model that requires many data and parameters. These data are organised in three input files:

1. *Hydrology file*. Includes the general parameters such as the initial day, initial and final year, depth of simulation, number of crops by rotation, etc., and hydrology parameters such as soil water field capacity, wilting point, organic matter, porosity, SCS (soil conservation service) curve number, leaf area index, monthly maximum and minimum temperatures, solar radiation, dew point and wind velocity.
2. *Rainfall file*. Daily precipitation data.
3. *Nutrient file*. Management parameters of the crops simulated in the rotation: mineral and organic fertilization, yield, planting and harvest date, tillage and irrigation parameters.

Under irrigation conditions, GLEAMS has been found to predict unrealistic high denitrification values (more than 100 kg N ha^{-1} year^{-1}) (Gowda et al., 1996; Marchetti et al., 1997), for this reason, the original routine to assess the denitrification decay rate (DK):

$$\text{DK}\ \left(\text{mg g}^{-1}\ \text{day}^{-1}\right) = 24 \times (0.0022\ \text{SC} + 0.0042)$$

where SC is the active soil carbon (mg g^{-1}) was changed by the equation proposed by Smith et al. (1980):

$$\text{DK}\ \left(\text{mg g}^{-1}\ \text{day}^{-1}\right) = 24 \times (0.0011\ \text{SC} + 0.0025)$$

The model was tested with data from two experimental plots, one with potatoes (Rodrigo, 1995) and another with citrus trees (Lidón, 1994). A sensibility analysis of the main model parameters was conducted to identify the most important variables determining water percolation and N leaching. In this analysis several selected variables like field capacity, wilting point, root depth, LAI, SCS curve number, uptake parameter, yield, and organic and mineral fertilization were varied within a known interval. The effect of this change on simulated percolation and leaching was used to determine the most influential model variables. After this analysis the leaf area index (LAI) and the uptake parameter (C1) were calibrated, because these were the important and unknown parameters for the crops. In this calibration the LAI parameter was varied to adjust the percolation simulated to those observed in two crops: potato and citrus (Figs. 2 and 3). Once the LAI was calibrated, the crop uptake parameter calibration was conducted by trying to adjust the simulated N uptake to the observed values (Figs. 2 and 3). After these two parameters were calibrated, the model performance was assessed using different data from those used in the calibration, by comparing the simulated water percolation and N leaching with the observed data (Fig. 4) for the two crops.

2.3. Data

Spatial data were obtained from three different sources: (a) published results from specific studies in the zone,

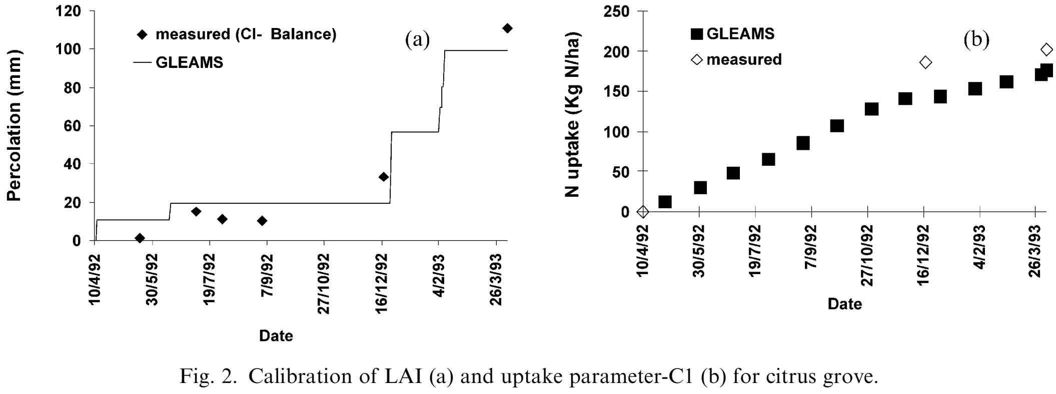


Fig. 2. Calibration of LAI (a) and uptake parameter-C1 (b) for citrus grove.

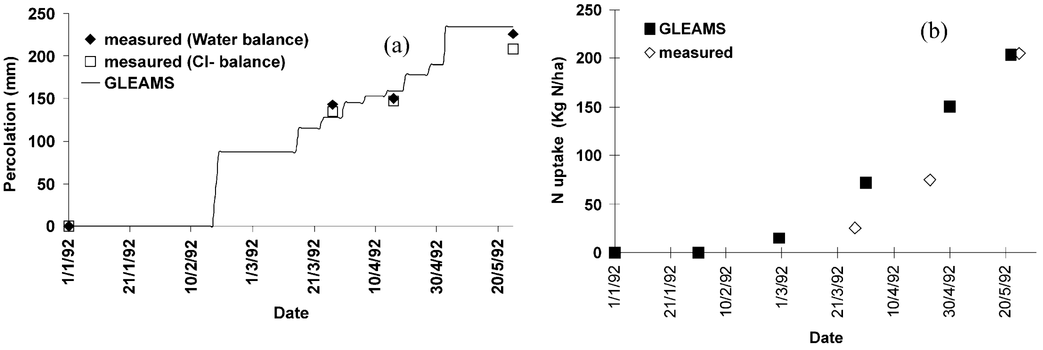


Fig. 3. Calibration of LAI (a) and uptake parameter-C1 (b) for potato.

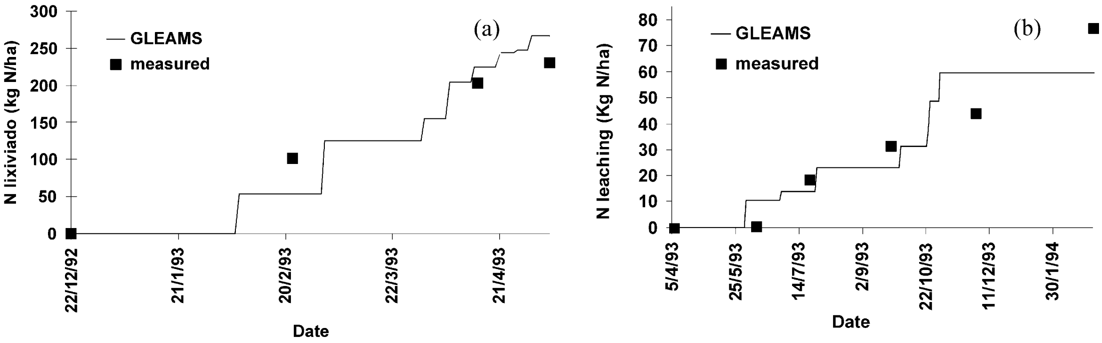


Fig. 4. Validation of N leaching simulated by GLEAMS model for potato (a) and citrus (b).

(b) databases from government agencies, and (c) specific surveys to obtain missing data. The data were organised in four classes:

1. *Soil data*. These were obtained from the LUCDEME project (LUCDEME 1996a,b). In addition, a soil survey was made in which 63 sampling points were taken in the study area resulting in a sampling density of 0.21 points/km^2. At each sampling point, soil samples were taken at 0–30, 30–60 and 60–100 cm depth.
2. *Climate data*. Daily precipitation values were obtained from the nine meteorological stations in the study area, and more general data (monthly mean temperature, dew point, radiation, etc.) were obtained from a general climate database (Pérez, 1994).
3. *Land use data*. Agricultural management practices data were obtained from Maroto (1994) and from agricultural extension personnel.
4. *Nitrate in irrigation water data*. The area studied was divided in two sections. One section was irrigated with groundwater of high nitrate levels, and the other was irrigated with surface water of low nitrate content. Surface irrigation water was sampled twice a year at each main channel to determine its NO_3 content. Nitrate content in irrigation wells was obtained from the ITGE database (Spanish Technological Geomining Institute) and from Sanchis (1991)

2.4. The Geographical Information System

The PC-ArcCad vectorial GIS was used for two main reasons: (1) the large amount of data required by the GLEAMS model is better managed by a vectorial instead of a raster GIS, and (2) programming and implementing a graphical user interface (GUI) can be done relatively easy with the ArcCad GIS.

The required data were organized in five basic layers, of which four were represented by the following base maps: soils, climate, land use and NO_3^- irrigation water content; the fifth layer corresponded to agricultural management data (crop rotation, fertilizer application, irrigation, etc.).

The four base maps were obtained as follows:

1. *Soils*. This layer was digitized from the physiographic map made by Antolin et al. (1998). Each physiograph unit was classified following the FAO soil classification and associated to the soil parameters database (Fig. 5).
2. *Climate*. This area was divided in nine subareas associated to the nine meteorological stations using the Thiessen interpolation technique. Each subarea was associated with the climate parameters database (Fig. 6).
3. *Land use*. The land use map was provided by the regional Ministry of Public Works institution in Arc/Info format. After joining the 696 and 722

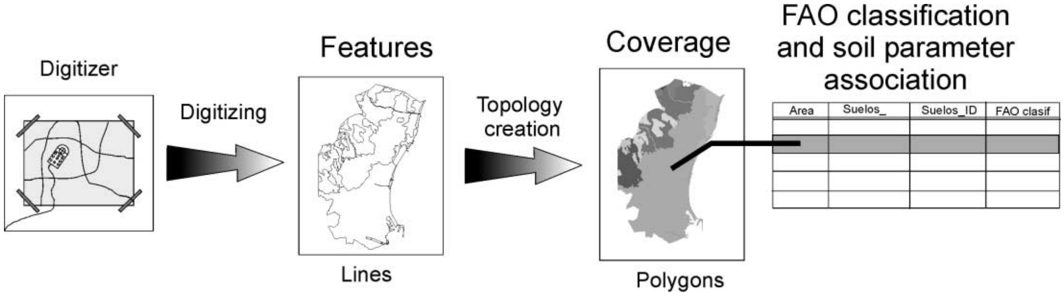


Fig. 5. Soil map elaboration process.

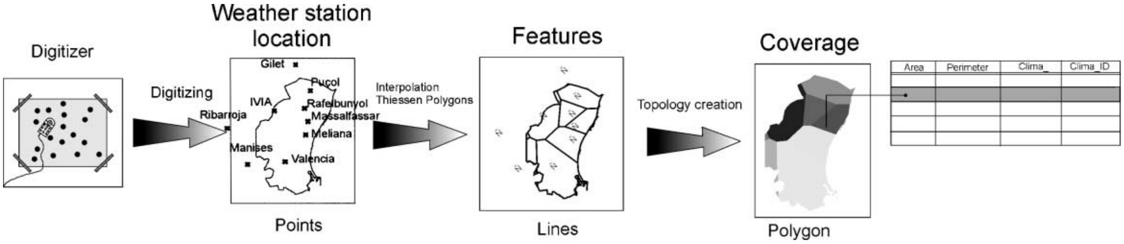


Fig. 6. Climate map elaboration process.

land use coverages, the study area was selected and small polygons were eliminated as showed in Fig. 7. In this map the primary uses were for vegetable, citrus, and urban-industrial efforts.

4. *NO_3^- content in irrigation water*. This map was created by intersecting the surface irrigation map with the groundwater NO_3 content map (Fig. 8), and associating the NO_3 water content to each polygon.

2.5. Coupling the GLEAMS model to the PC-Arc/Cad GIS

Since GLEAMS is a complex model, a full integration was considered inappropriate. Loose coupling was also rejected because the use of this system would be too cumbersome. It was decided to use a close coupling strategy because it was easy to use and appropriate when the model is complex. Several macro routines were programmed in AUTOLISP to facilitate the simulation process, and the implementation of a GUI. A user friendly GUI allows a non-specialist GIS user to simulate different crop managing alternatives, and to show the results as thematic maps (N leaching, percolation, etc.). The coupling scheme is shown in Fig. 9.

2.6. Implementation

To implement the interactive GIS-model system, several menus were created and grouped in three modules (input, execution, visualization) associated to the GUI controls. This interface allowed the user to input data, run the model, and show the simulation results as maps. Detailed functions of these modules are:

1. *Input module*. This module allows the user to input data to simulate crop rotations, agricultural management practices, etc. One of its menus (nutrient parameters input menu) is shown in Fig. 10. This module takes soil, climate and NO_3 content in irrigation water data from the attributes database, and together with the management data creates the input files in ASCII format required by the GLEAMS model. Several AUTOLISP routines were written to manage input data and to create GLEAMS input files.
2. *Execution module*. This module controls the simulation runs, and transforms the output simulation files into a suitable format to be imported by the GIS. Two tables were created for each simulation: one with the monthly percolation, NO_3-N leaching, N uptake, N denitrification, etc., and another with the NO_3-N soil content at different depths, at 15-day intervals.
3. *Visualisation module*. With this module the user can select the variable to be extracted and displayed as a thematic map (i.e. NO_3-N leaching, percolation, etc.), for each simulation year, or as the mean value for a number of years, or as the sum of the selected variable during the total period. The user also has the option to visualize the result maps with the Arc/Cad utilities or with the ArcView GIS.

3. Application of the GIS-model system to the study area

To illustrate the GIS-model system capabilities a simulation in the selected area was conducted. Two traditional

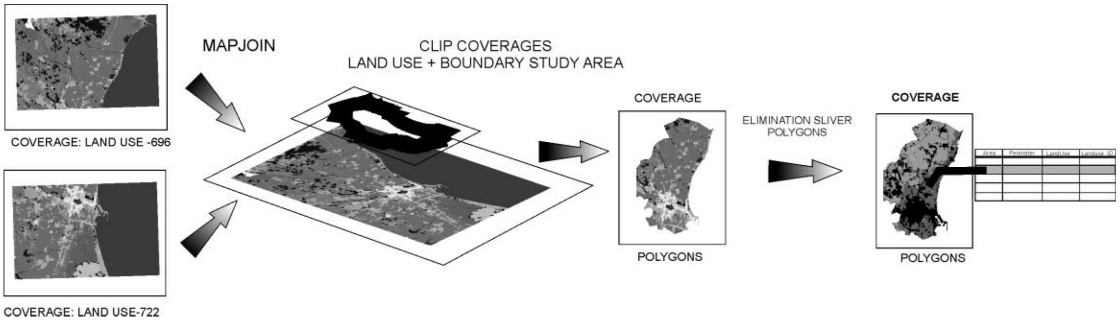


Fig. 7. Land use map elaboration process.

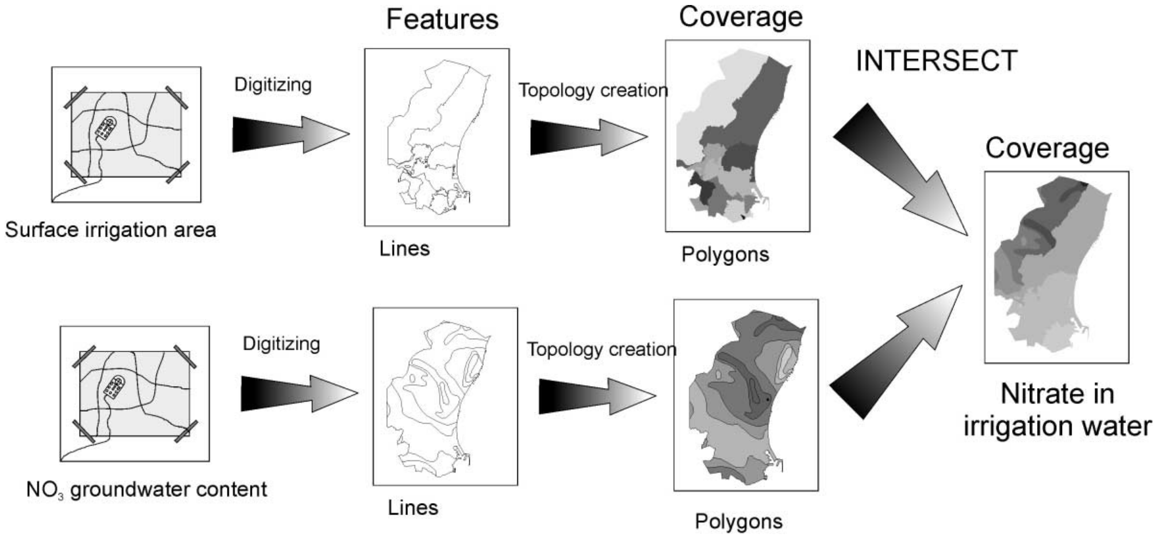


Fig. 8. NO_3 in irrigation water map elaboration process.

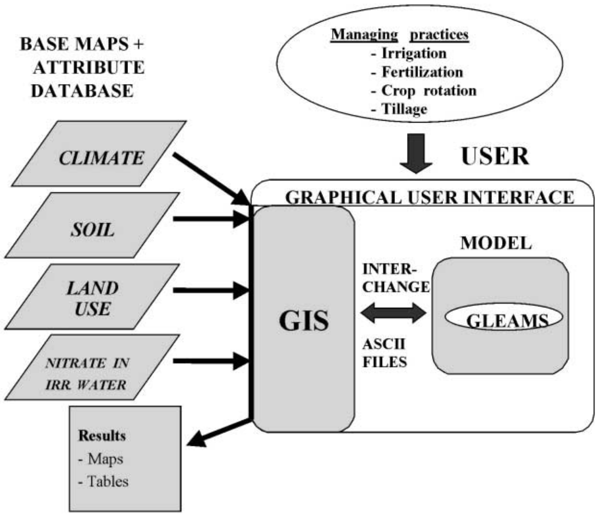
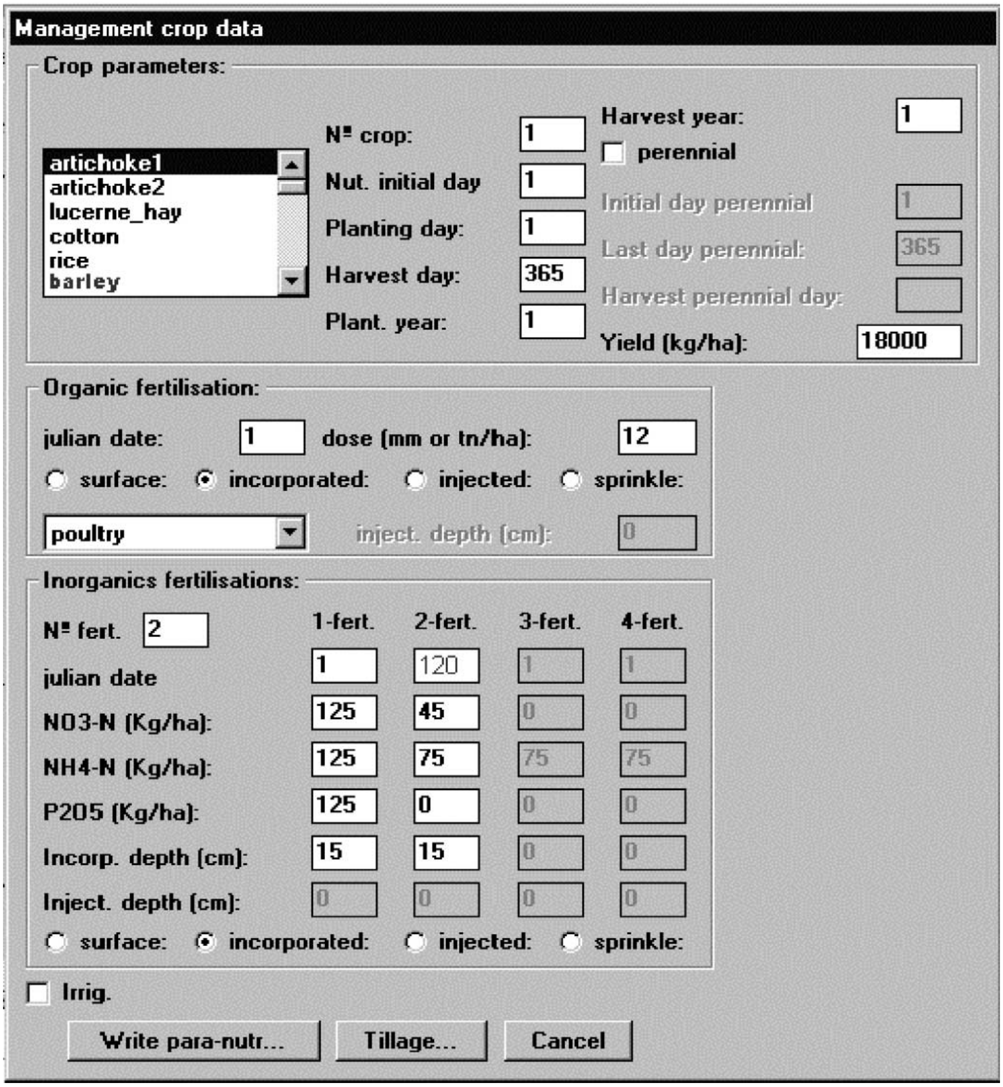


Fig. 9. Scheme for the close coupling of GLEAMS to the GIS.

crop rotations encompassing two years were simulated in the vegetable area (Rotation A: potato/lettuce/onion/cauliflower, and Rotation B: artichoke/artichoke), and an orange crop was assumed for the citrus area. These crop rotations were simulated for a six year period (1980–1986). The usual crop management practices in the zone are shown in Table 1. The average annual rainfall for the period 1960–1990 in the area was between 390 and 580 mm, and the rainiest month was November (85 mm).

Simulation results appear in Figs. 11 and 12. The spatial distribution of water percolation (Fig. 11) in the vegetable zone varied from 200–400 mm depending on soil permeability, and it was greater than in the citrus area (75–150 mm), due mainly to the lower irrigation efficiencies in the vegetable crops (efficiency from 0.5–0.6 dependent on the crop) because of the higher irrigation frequency, and the shallower root depth of vegetable crops (< 60 cm) in comparison to citrus (80 cm depth, and an irrigation efficiency of 0.8).

Fig. 12 shows the calculated nitrate leaching map. The vegetable area leached much more $N\text{-}NO_3^-$ than the citrus area, except where the citrus trees were irrigated with groundwater (with high levels of $N\text{-}NO_3$). In this case, the $N\text{-}NO_3$ applied in the irrigation water (up to 86 kg N ha^{-1}) was not negligible compared to mineral fertilization (370 kg N ha^{-1}), but this N input to the soil is not generally taken into account by farmers.



Nº crop: 1
Nut. initial day 1
Planting day: 1
Harvest day: 365
Plant. year: 1
Harvest year: 1
☐ perennial
Initial day perennial 1
Last day perennial: 365
Harvest perennial day:
Yield (kg/ha): 18000

Organic fertilisation:
julian date: 1 dose (mm or tn/ha): 12
○ surface: ● incorporated: ○ injected: ○ sprinkle:
poultry inject. depth (cm): 0

Inorganics fertilisations:
Nº fert. 2

	1-fert.	2-fert.	3-fert.	4-fert.
julian date	1	120	1	1
NO3-N (Kg/ha):	125	45	0	0
NH4-N (Kg/ha):	125	75	75	75
P205 (Kg/ha):	125	0	0	0
Incorp. depth (cm):	15	15	0	0
Inject. depth (cm):	0	0	0	0

○ surface: ● incorporated: ○ injected: ○ sprinkle:
☐ Irrig.

Fig. 10. GLEAMS nutrient input menu.

Table 1
Management practices

Crop	Rotation A				Rotation B	
	1st year		2nd year		1st/2nd year	
	Potato	Lettuce	Onion	Cauliflower	Artichoke	Citrus
Planting date	6 January	1 August	20 November	15 August	1 August	–
Harvest date	22 May	1 November	20 May	5 November	31 December/30 May	–
Irrigation (mm)	330	120	230	120	400/470	500
Organic manure (t ha^{-1})	26[a]	0	18[a]	0	0/0	0
Mineral fert. (kg N ha^{-1})	445	0	340	200	645/405	370
Yield (t ha^{-1})	46	24	40	35	15/15	46
Simulation depth (cm)	60	60	60	60	60	80

[a] Poultry litter (3.8% N in dry matter, 20% moisture).

Table 2
Main terms of the simulated nitrogen balance for the different crops and N uptake efficiency

Crop	Min. fertilizer (kg N ha^{-1})	N leaching (kg N ha^{-1})	N volatization (kg N ha^{-1})	N uptake (kg N ha^{-1})	N denitrification (kg N ha^{-1})	N uptake efficiency (N upt/Min. fert.)
Potato	445	254	130	207	58	0.47
Lettuce	0	58	0	107	17	–
Onion	340	154	29	201	66	0.59
Cauliflower	200	100	0	158	44	0.79
Artichoke (1st year)	645	198	0	330	63	0.51
Artichoke (2nd year)	405	158	0	371	29	0.91
Citrus	370	138	0	191	44	0.52

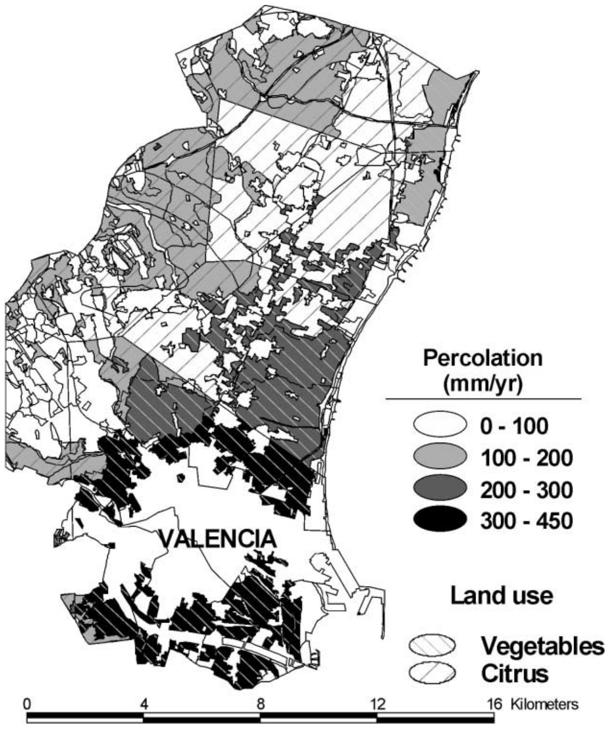


Fig.11. Spatial distribution of percolation.

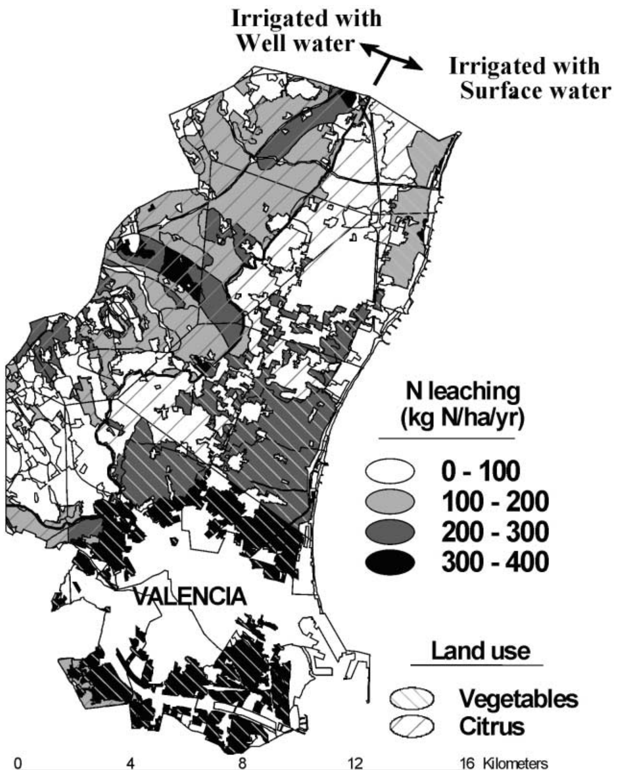


Fig. 12. Spatial distribution of N leaching. The thick line going from northeast to southwest in Fig. 12 divides the area in two parts with different types of irrigation water as indicated by arrows.

The surface area with vegetable fields is about 37% of the total cultivated surface area, but its NO_3^--N leaching represents up to 54% of the total. Fig. 13 shows the main terms of the N balance for the whole study area. The main outputs were: crop uptake and leaching (82% of the N output). Gaseous losses were about half the amount of leaching. Altogether, the N input in the irrigation water was about 10% of that added as mineral fertilizer (Fig. 13).

The N input in the balance showed in Fig. 13 is less than 50%, because it does not consider the N mineralized from the manure application and soil organic matter.

The GIS-model can easily summarize the N balance terms for the different crops (Table 2). Crops with high nitrate leaching were: potato (254 kg N ha^{-1}) and artichoke (198 kg N ha^{-1}), probably due to the high N application rate in these crops and their low N use efficiency (Table 2). These N use efficiencies were similar to the ranges reported by Greenwood et al. (1989). Ammonia volatilization occurred only in potato and onion crops because they received a manure application, but GLEAMS just considered volatilization from organic fertilization.

4. Conclusions and recommendations

The GIS-model system developed permitted assessment of nitrate leaching and other nitrogen balance terms

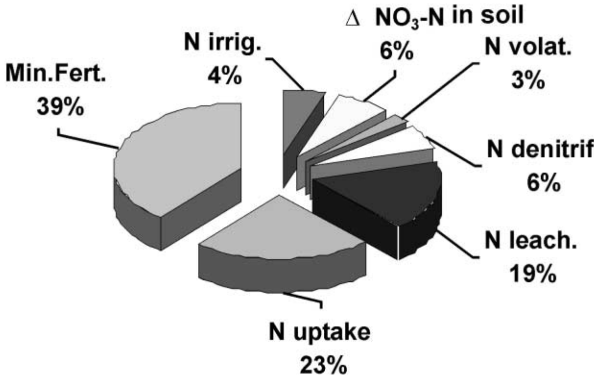


Fig. 13. Comparison of the relative main terms of the N balance for the study area.

in agricultural soils at a regional scale, and representation of this data as thematic maps. GIS utilities made it possible to determine the areas and crops with the highest risks of nitrate leaching.

In the study area vegetables represented less than 40% of the cultivated area and less than 45% of the total applied mineral N fertilizer, but they contributed by 55% to the total nitrate leaching. Vegetable crops showed a high risk of nitrate groundwater pollution because of the high fertilizer rate and organic manures applied by farmers, their shallow root depth, and the low irrigation and nitrogen uptake efficiencies. Potato and artichoke (1st year) were the crops with the higher nitrate leaching risk because each received the highest N mineral dose and their uptake efficiency was the lowest.

The citrus zone irrigated with groundwater, with a high nitrate concentration, increased nitrate leaching because the nitrate applied in this water (86 kg N ha^{-1}) was not negligible with respect to the mineral fertilizer application (370 kg N ha^{-1}). In the citrus orchards, 50% of the nitrate leaching occurred in autumn when rainfall was important, the N mineral content in soil was high, and the N uptake capacity by the trees was low.

In order to decrease nitrate pollution risk: (1) the nitrogen applied in irrigation water should be taken into account when planning the crop fertilizer management, (2) fertilizer rates applied to vegetables should be reduced and (3) nitrogen fertilizer should not be applied in citrus orchards near autumn.

Acknowledgements

This work was funded by the Instituto Nacional de Investigaciones Agrarias (Ministerio de Agricultura Pesca y Alimentacion of Spain) and developed in the Instituto Valenciano de Investigaciones Agrarias. We express our gratitude to A. Lidón and A. Rodrigo for providing information in the model evaluation process.

References

Bakhsh, A., Kanwar, D., Jaynes, D.B., Colvin, T.S., Ahuja, L.R., 2000. Prediction of NO_3-N losses with subsurface drainage water from manure and UAN-fertilized plots using GLEAMS. Trans. ASAE 43, 69–77.

Corwin, D.L. (Ed.), 1996. GIS applications of deterministic solute transport models for regional-scale assessment of non-point source pollutants in the vadose zone. In: Proc. of Int. Conf. on Applications of GIS to the Modeling of Non-point Source Pollutants in the Vadose Zone (Special Publication No. 48). ASA-CSSA-SSSA, Madison, WI, pp. 69–100.

Council of European Communities, 1980. Directive Relating to the Quality of Water for Human Consumption (Directive 80/778/EEC). Brussels, Belgium.

Garnier, M., Lo Porto, A., Marini, R., Leone, A., 1998. Integrated use of GLEAMS and GIS to prevent groundwater pollution caused by agricultural disposal animal waste. Environ. Management 22, 747–756.

Gowda, P.H., Ward, A.D., White, D.A., 1996. Using GIS with Field Scale Model to Describe Agricultural Impacts on Rock Creek Watershed (ASAE Paper 96-3090). American Society of Agricultural Engineers, St. Joseph, MI.

Greenwood, D.J., Kubo, K., Burns, I.G., Draycott, A., 1989. Apparent recovery of fertilizer N by vegetable crops. Soil Sci. Plant Nutr. 35, 369–381.

Halliday, S.L., Wolfe, M.L., 1991. Assessing ground water pollution potential from nitrogen fertilizer using geographic information system. Water Res. Bull. 27, 237–245.

Hoogeweg, C.G., Hornsby, A.G., 1995. In: Corwin, D.L. (Ed.), Proceedings of the 1995 Boyoucos Conference. US Salinity Laboratory Riverside, CA, pp. 326–340.

Jordan, C., Mihalyfalvy, M.K., Garret, M.K., Smith, R.V., 1994. Modelling of nitrate leaching on a regional scale using a GIS. J. Environ. Management 24, 279–298.

Knisel, W.G., 1993. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems, V.2.10. University of Georgia, Coastal Plain Experiment Station, Biological and Agricultural Engineering Department (Publication No. 5).

Knisel, W.G., Leonard, R.A., Davis, F.M., Sheridan, J.M., 1991. Water balance components in Georgia Coastal Plain: a GLEAMS model validation and simulation. J. Soil & Water Conservation 46, 450–456.

Leonard, R.A., Knisel, W.G., Still, D.A., 1987. GLEAMS: groundwater loading effects of agriculture management systems. Trans. ASAE 30, 1403–1417.

Liao, H., Tim, U.S., 1997. An interactive modeling environment for non-point source pollution control. J. Am. Water Res. Assoc. 33, 591–603.

Lidón, A.L., 1994. Lixiviación de nitrato en huertos de citricos bajo diferentes tratamientos de abonado nitrogenado. PhD thesis, Universidad Politécnica de Valencia (Spain).

LUCDEME, 1996a. Mapa de suelos de la Comunidad Valenciana, Burjassot (696). Generalitat Valenciana, Conselleria d'Agricultura i Mig ambient Valencia, Spain.

LUCDEME, 1996b. Mapa de suelos de la Comunidad Valenciana, Valencia (722). Generalitat Valenciana, Conselleria d'Agricultura i Mig ambient Valencia, Spain.

Marchetti, R., Donatelli, M., Spallacci, P., 1997. Testing denitrification functions of dynamic crop models. J. Environ. Qual. 26, 394–401.

Maroto, J.V., 1994. Potencialidades y expectativas de la produccion horticola de primor en la huerta de la ciudad de Valencia. Seminario

Internacional sobre la Huerta de Valencia. Ayuntamiento de Valencia (ed.), Valencia, Spain, pp. 177–292.

Meinardi, C.R., Beusen, A.H.W., Bollen, M.J.S., Klepper, O., 1995. Vulnerability to diffuse pollution and average nitrate contamination of European soils and groundwater. Water Sci. Tech. 31, 159–165.

Mueller, D.K., Hamilton, P.A., Helsel, D.R., Hitt, K.J., Ruddy, B.C., 1995. Nutrients in Groundwater and Surface Water of the United States. An Analysis of Data Through 1992 (Water Resources Investigations Report 95-4031). US Geological Survey, Reston, Virginia, USA.

Navulur, K.C.S., Engel, B.A., 1998. Groundwater vulnerability assessment to non-point source nitrate pollution on a regional scale using GIS. Trans. ASAE 41, 1671–1678.

Pérez, A.J., 1994. Atlas climático de la Comunidad Valenciana. Generalitat Valenciana, Conselleria d'Obres Públiques, Urbanisme i Transport, Valencia, Spain.

Priestley, C.H., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100, 81–92.

Rodrigo, A., 1995. Efecto del abonado nitrogenado en la lixiviación de nitrato en el cultivo de la patata. PhD thesis, Universidad Politécnica de Valencia (Spain).

Sanchis, E.J., 1991. Estudio de la contaminación por nitratos de las aguas subterraneas de la provincia de Valencia. Origen, balance y evolucion espacial y temporal. PhD thesis, Diputación Provincial de Valencia, Valencia, Spain.

Smith, S.J., Kissel, D.E., Williams, J.R., 1980. Nitrate production, uptake and leaching. In: Kissel, D.E. (Ed.), CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems (Conservation Research Report). USDA, pp. 493–508.

Stone, K.C., Hunt, P.G., Johnson, M.H., Coffey, S.W., 1998. GLEAMS simulation of groundwater nitrate-N from row crop and swine wastewater spray fields in the eastern coastal plain. Trans. ASAE 41, 51–57.

Tim, U.S., Jolly, R., 1994. Evaluating agricultural nonpoint-source pollution using integrated geographic information systems and hydrologic/water quality model. J. Environ. Qual. 23, 25–35.

Tim, U.S., 1996. Emerging technologies for hydrologic and water quality modeling research. Trans. ASAE 39, 456–476.

Truman, C.C., Leonard, R.A., 1991. Effects of pesticide, soil and rainfall characteristics on potential pesticide loss by percolation—a GLEAMS simulation. Trans. ASAE 34, 2461–2468.

Vieaux, B.E., Mubaraki, M.A., Brown, D., 1998. Wellhead protection area delineation using a coupled GIS and groundwater model. J. Environ. Management 54, 205–214.

Varela, M., Navarrete, P., 1998. Estado de la calidad química y contaminación de las aguas subterráneas. In: Calidad y Contaminación de las Aguas Subterráneas en España: Propuestas de Protección. Ministerio de Medio Ambiente, Secretaria de Estado de Aguas y Costas, Madrid, Spain, pp. 17–103.

Wu, Q.J., Ward, A.D., Workman, S.R., 1996. Using GIS in nitrate leaching from heterogeneous unsaturated soils. J. Environ. Qual. 25, 526–534.

Wu, Q.J., Ward, A.D., Workman, S.R., Salchow, E.M., 1997. Applying stochastic simulation techniques to a deterministic vadose zone solute transport. J. Hydrol. 197, 88–110.

Wylie, B.K., Shaffer, M.J., Hall, B.M., 1995. Regional assessment of NLEAP NO_3-N leaching indices. Water Resour. Bull. 31, 399–408.

Yoon, K.S., Yoo, K.H., Wood, C.W., Hall, B.M., 1994. Application of GLEAMS to predict nutrient losses from land application of poultry litter. Trans. ASAE 37, 453–459.