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Nitrate Pollution of Groundwaters in a Small Mediterranean Region

Stéphane Bellon, Patrick Bertuzzi, Joanne Musset, Sophie Vannier, Cécile Mirambeau, Anne-Elisabeth Laques and Pierre Derioz

Abstract

Water resources preservation is a key environmental issue. An increase in the nitrate content of groundwater was observed in a "nitrate vulnerable zone" near Avignon (France). A multidisciplinary research project was then designed to clarify the relationships between agricultural practices and water quality. The approach was first based on separate information layers (crops, soils, groundwater). They accounted both for the main geochemical features likely to explain groundwater quality and for the dynamics of land use, with regional analyses of the landscape and cropping systems. A combined analysis of some of the previous elements (namely landscape and groundwater nitrate content) was performed by using GIS and statistics. The complexity of the local situation did not make it possible to conclude on the influence of specific agricultural practices or activities. Stronger collaborations between workers specialized in different research topics are necessary. Both the combination and the location of cropping systems are a cornerstone for the development of this research project. The analysis will therefore benefit from a renewed land appraisal, namely taking into account soil vertical infiltration capability.

Context and Presentation of the Problem

The study area has been classified as a "nitrate vulnerable zone" since 1993 as part of the European Nitrates Directive of 19/12/1991. It consists of 10 French districts in the Carpentras basin (256 km²) located in the Mediterranean region, north-east of Avignon (France). The area contains about a thousand farms. It is composed of two alluvial plains surrounded by terraces and little hills. It has become strongly urbanized over the last few years. Half of the surface area is devoted to agriculture. Crops are highly diversified, with mainly cash crops (wheat, sunflower), market gardening (melon, strawberry and lettuce), viticulture and arboriculture. This small region has undergone massive changes (Durbiano, 1997) : irrigation systems have evolved, with an increasing number of bore holes and sprinkler irrigation with water from the Carpentras canal. Soil fertility has been decreasing over the last few years. A decrease in the farm population and the appearance of fallow land have also been observed. Traditional markets have been redefined and the competition with other countries or regions has been increasing.

Water analyses in wells and bore holes have shown that groundwaters were locally contaminated by nitrates (OME,1993). The hydrogeology of the Carpentras basin is characterized by the presence of two superposed aquifers:

- an alluvial groundwater whose watertable is located between 1 m and 15 m depth (according to topography). It is the closest to the surface, is mainly fed by infiltration water, i.e. rainfall and irrigation, and is mainly exposed to the consequences of land utilization.
- groundwater in a Miocene aquifer. It is deeper and has a larger volume. The watertable varies but it is often located around 100 m depth. Water can be several thousands years old, with a very slow renewal rate. This groundwater constitutes a protected water resource, which has been much exploited by numerous bore holes for agricultural, household and industrial purposes.

A significant increase in nitrate contents has been observed since 1980 in these two groundwaters. The contents in the alluvial waters often exceed the nitrate limit in drinking water (50 mg/l).

In 1996, we decided to study this phenomenon and attempted to identify the mechanisms leading to this pollution and, in particular, to determine the relationships between agricultural practices and nitrate contents in groundwater. It is commonly assumed that market gardening, which is widespread in the study area and requires a large supply of inputs, mainly contributes to this pollution. We hypothesized that (i) the decrease in water quality cannot only be due to market gardening or a single type of agricultural practice, i.e. fertilisation, and (ii) environmental factors, such as soil and groundwater geochemical features, can decrease or worsen the impact of agricultural practices.

Approach Taken

A multidisciplinary approach was implemented to investigate this complex situation and perform a relevant analysis at the regional scale. It involves several workers from different institutes and specialised in different research topics.

- Hydrogeology and geochemistry make it possible to better understand groundwater depth and physico-chemical characteristics, flow direction, spatial distribution of nitrate contents. These two research topics associated with soil science enabled us to identify phenomena susceptible to explain the nitrate contents and their distribution as observed in the physical environment.
- Geography, which is a more global approach, determines the role of agriculture in land use and the dynamics involved. Indeed the origin of nitrate (agricultural or not) is much debated in numerous vulnerable zones.
- Agronomy contributes to identifying the cropping systems in this territory and determining those presenting the highest risks of nitrate leaching towards groundwater. This research topic combined with the two previous topics makes it possible to determine the effects of cropping systems according to their location. It also participates in the development of practices which better respect groundwater.

The data originating from these different approaches are continuously integrated. This provides partial answers to the main issue of the programme: is there a causal relationship between the land field pattern, in particular agriculture, and the nitrate contents in groundwaters?

Our approach combines several study scales, from the region scale to the plot scale. It is based on bibliographical data (on surface hydrography and hydrogeology, updated agricultural statistics), maps (topography, soil science and piezometry, land-use schemes), aerial pictures (in 1996), interviews with farmers and specialized advisers, transects (the ground is analysed at the landscape scale) and measurements (sampling of groundwater, water and nitrogen balances at the plot scale). Data integration is enhanced by their representation as maps and their combination in a Geographical Information System (GIS).

We present the results obtained with each research topic at the regional scale and then study the results obtained from the combinations of these topics.

Specific Data Obtained with the Different Research Topics

Characterizing the groundwaters and watertables

The first step consisted in performing a diagnosis of groundwater by implementing a dense sampling. 680 samples were taken in spring and summer 1996 in existing wells and bore holes. To understand the composition of groundwater, it is essential to determine its physico-chemical characteristics, i.e. temperature, electric conductivity, oxido-reduction potential, pH, oxygen content, chemical composition (main anions, cations and metal compounds). The chemical composition of water is affected by surface inputs as well as by circulation conditions (flow and aeration) in the soil and geological horizons (Garcia, 1996).

The study revealed a spatial organisation of nitrate contents in the alluvial groundwater : high contents were located in the east in glacis and terraces. They represented about one third of the studied surface area. Low contents were mostly localised in the plains, along a South East - North West axis. Moreover, this study confirmed that the Miocene groundwater was endangered, since nitrate contents were high (although not above the authorized limit). It also made it possible to identify and localize the processes leading to a decrease in nitrate contents. This is particularly due to nitrate reduction through microbial activity following oxygen depletion into soil and/or water table in the plains. It namely occurs in the western part of the area, in relation to top-down water flows (from hills to plains).

The following step of our approach consisted in identifying the mechanisms leading to this spatial distribution as well as its possible relationship with the soil type and land use pattern.

Analysing the landscape

Based on the overall image obtained from landscape physionomy, the objective is to obtain information on the land-use patterns while emphasizing the relationships between the use of soil for agricultural or other purposes.

A land use map is classically established to represent land lay-out. It is difficult and tedious to establish this map for several reasons, i.e. increasing urbanization, parcelled out field pattern, diversified nature and rapidly evolving crops. We favoured an intermediate solution by identifying landscape units. Landscape analysis led us to define spatial units of intermediate size (between the plot and the small region) and to identify the different dynamics, i.e. spatial contraction or extension, simplification or complexification (Bertrand, 1992). It was performed at the scale of the study area (Mirambeau, 1997).

Three major groups of landscapes can be observed in the study area, i.e. relatively homogeneous landscapes, "natural" (wooded hills or hillsides, river banks) or urban, and more heterogeneous landscapes with varying degrees of agricultural dominance. The analysis of these landscapes is based on three notions (Wieber and Brossart, 1980; Dérioz and Laques, 1996): the components, i.e. land-use pattern, landscape objects such as hedges and houses, the frequency of these components and their structure (how components and topographic surfaces are organized, screen and edge effects, water ways). For instance, market gardening bocages are characterized by small plots, a network of dense hedges (which are the main structural element) and an intensive land use almost exclusively devoted to market gardening (main component).

A total of 23 landscape units were identified throughout the area. They can be classified either according to the developments of the study or into major landscape types, according to a hedgerow and field pattern/moisture criterion. For example, agricultural landscapes can be classified as follows:

- The "bocage" type includes the agricultural landscapes whose hedgerow and field pattern is dense and where there are numerous hedges. It includes crops for market gardening and vegetable crops.
- The "wetland " type is characterized by a loose hedgerow and field pattern (open fields) and by a reduced number of hedges. Another major characteristic of the landscape is moisture: there is a large number of drainage and irrigation canals and poplar hedges. It includes cereal plains and meadows.
- The "small wetland " type corresponds to two landscapes with similar structures (plots of mean size) and land-use patterns, one being used for vegetable crops and with very few orchards, the other one combining cereals, vegetable crops and orchards.

This classification makes it possible to highlight the main characteristics of the landscapes and to determine the elements which might play a role in the nitrogen cycle, such as the type of agriculture, the role of the wooded linear structures, the urbanization rate and the presence of water.

Landscape elements can also be used to interpret data on the geochemistry of watertables, i.e. preferential flow directions, transfers and denitrification areas. Marked oxygen depletion occurs in the hollows of the wetland type which have low nitrate contents while more oxygenated conditions are observed in the terraces located upstream due to the more rapid water flow rate in higher areas and the presence of a more aerated soil (coarse deposits).

Identification and organization of crops at the basin scale

The high diversity of the crops in the Carpentras basin is due to the size of the study area, its topography (plains and hills are represented), soil variability and the history of the basin, especially regarding the field pattern, crops and water management.[13] Figure 1 shows how crops and their managements, i.e. in fields or in greenhouses, can be classified.

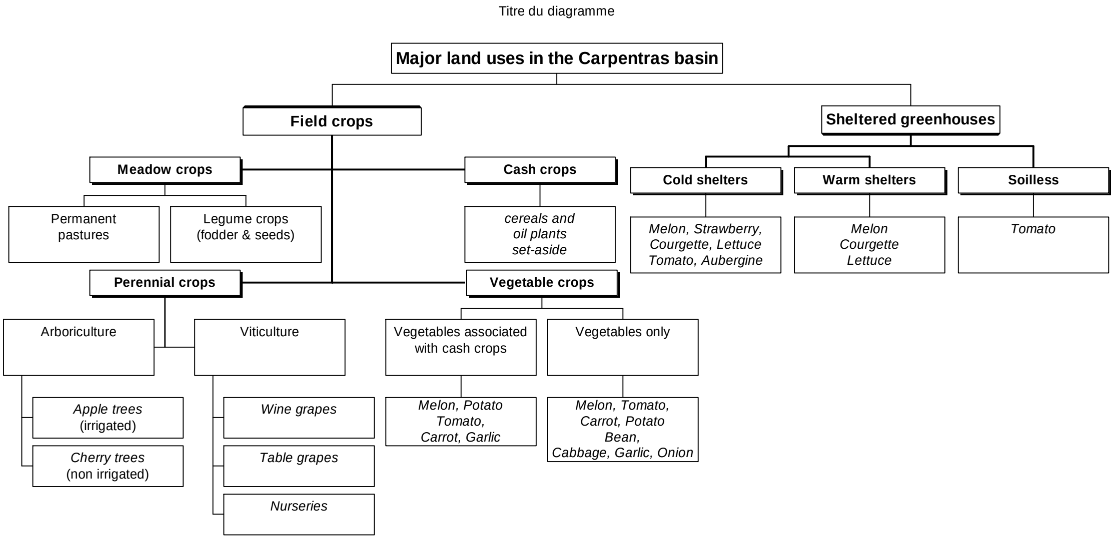

Figure 1. Major land uses in the Carpentras basin

A first spatial representation of the land-use pattern is based on the identification of « sub-basins » at the scale of the study area (Caussanel, 1996). Sub-basins are defined by a major production, e.g. cash crops corresponding to several cropping systems, and a particular location, e.g. rearing of ruminants on a hydromorphic plain. Their limits are validated by surveys, ground observations and expertise of specialized advisers.

Complementary studies have been carried out on the mode of production, for example for market gardening in greenhouses by Faidix (1995) and rearing[14] by Talon (1997). We hypothesized that the diversity of crops and their combinations can be classified into a few typical situations. The first objective is to define typical cropping systems (TCS). After having defined all the crop sequences and management practices, the nitrate losses of each cropping system were characterized and TCS were organized into a hierarchy. This implies defining indicators (Caussanel, 1996), in particular crop successions (nature of the crops, number of crops per year, the time before a crop is grown again, rooting depth), assessment of intervals between crops (period, duration, management of the residues and intercropping), management of nitrogen fertilization (periods, amounts and possible fractionation) and management of irrigation (system, period, amount).

This approach, which is illustrated by cropping systems under cold shelters (see Box 1), will be applied to other situations.

[13] The small mean size of plots is related to how land is inherited as well as to traces of technical structuration: windbreak hedges approximately every 30 m in an east-west direction and gravitational irrigation limited to a distance of 100 m.

[14] Rearing ruminants occupies almost one thousand hectares of meadows, cereals and fallow land.

Once cropping systems are characterized, they can be organised into a hierarchy and their risks of nitrate losses into the groundwater are weighted according to their localization (Lanquetuit and Sebillotte, 1997).

Box 1. main cropping systems with strawberries under cold shelters

The types of crops and their sequences were analyzed for market gardening under cold shelters. Seven to nine-meter-wide plastic tunnels are mainly observed in the central-eastern area of the Carpentras basin characterized by soils with high permeability. Nitrate contents are relatively high in the groundwaters. The number of crops present is limited. Melon, strawberry, lettuce and courgette (spring and autumn) are the main crops, with melon being the major crop. Eggplant and pepper are started to be developed. After analyzing the results of surveys with market gardeners, two types of crop sequences were identified depending on whether they contained strawberry or not. Indeed, this crop presents specificities, in particular regarding the duration of the cycle (11 months), which involves different sequences on a given plot. We only present the results regarding gardening crop sequences with strawberries. It should be noted that one-crop systems are not represented in the sample studied. Analyzing the different situations observed led to the following statements:

- Strawberries are grown again every 2.5 years on average.
- Strawberries are most often preceded and followed by a spring crop, usually melon.
- An autumn crop, most often lettuce, can be included in the sequence.

The most frequent sequence is as follows:

spring crop - strawberry - (lettuce) - spring crop - (lettuce)

where spring crop = melon or courgette or pepper or eggplant and (lettuce) can be replaced by sorghum or radish.

This model accounts for the two and a half years between strawberry crops.

Examples : melon - strawberry - pepper - lettuce *or* melon - lettuce - strawberry.

Two variants of the previous model are possible depending on how often strawberries reappear in the sequence, i.e. every 2 or 4 years.

The cropping practices identified for strawberry can be compared to these three typical sequences in order to define risk indicators for each cropping system.

It first appeared that soil is disinfected with methyl bromide before planting almost systematically. Only long periods between two strawberry crops and the alternation of crops in the sequence make it possible to do away with this disinfection, which is combined with large supplies of water which cause the deep migration of bromide ions. Possible nitrogen residues from the crop preceding strawberry are probably leached. Organo-mineral fertilizers are almost systematically applied before strawberry planting (90% of the cases).

Irrigation corresponds to two distinct periods: from planting to growth cessation (the stage when the crop becomes established) and from regrowth (mid-January) up to harvesting. This second irrigation period is often combined with fertilization. Fertirrigation varies from farm to farm. It seems to be monitored from reference stages specific to the crop with a general increase of fertilization from flowering to fruit setting. The consequences of these practices were assessed by measuring nitrogen residues.

Combining Research Topics

Combinations of parallel approaches

During the project, in particular during landscape analysis, it appeared that interdisciplinary debates were necessary to define landscape units, to classify them and to discuss the limits and the types of contacts between units.

The landscape analysis performed at the scale of the study area enabled us to specify the relationships between agriculture and other land use patterns. It revealed the existence of land use dynamics likely to modify the general distribution of agricultural waste in water tables, especially where residential urbanization is expanding and where derelict land is developing. This analysis can lead to landscape planning, such as the planting of hedges and grass strips (Merot and Reyne, 1996). Nevertheless, it did not account for the structuring of agricultural space regarding the interweaving and sequence of crops. This is why it was necessary to work with agronomists in order to better understand the dynamics of the agricultural land use pattern and the organization of crops.

The localization of cropping systems combined with biophysical sciences makes it possible to diagnose the water quality of water tables and to study water and particle transfers. The combination of the geochemical analysis and the analysis of the cropping systems showed that soil maps were not appropriate for studying groundwaters. Maps are established from pedogenetic criteria or land cropping suitability criteria which do not account for the risks of nitrate leaching (role of convective flows?, possible presence of almost impermeable horizons?).

This study showed that it was necessary to define a new map database. We contemplate establishing a soil map according to soil vertical infiltration capability. The results continue to be integrated by using information combinations and GIS.

Combinations based on the use of statistical treatments and a GIS

Geographical information systems (GIS) aim at producing thematic maps and carry out a number of spatial and statistical treatments. Their use should make it possible to better understand the pollution mechanisms in the study area by comparing maps and performing treatments from the database of the GIS.

Preliminary treatments with the use of a GIS:

The first step is based on mapping of different information layers (nitrate contents, soils, landscapes, topography and hydrography). Their comparison and combination made it possible to build new maps on several topics, such as the localization of nitrate contents in relation to the landscape (in order to define "sensitive" landscapes) and the types of soil (to better understand the type of exchanges with the water table), the definition of preferential flow directions, the comparison of soil types and landscapes in test areas and the possible relationship with the pollution levels observed.

Combination currently concern three information layers considered as having priority: soils/landscapes, soils/nitrates, landscapes/nitrates. They are then subjected to a statistical analysis around two topics : relationships between nitrate contents/soils/landscapes and the calculation of the surface areas occupied by each type of soil and landscape.

Statistical treatment from GIS data

The statistical treatment was only used with the soils/nitrates and landscapes/nitrates combinations to which a chi-square test was applied in order to determine whether there is a relationship between variables and assess the intensity of this relationship if it exists. This test is thus supposed to answer questions, such as "is market gardening a privileged source of nitrate leaching?", "can cereal crops be considered as less polluting?". It is thus possible to distinguish the behaviour of the two types of landscapes, i.e. market gardening bocage and cereal plains, which represent 13% and 15% of the territory, respectively, in relation to nitrogen pollution (Figure 2).

Figure 2 shows a relationship of dependence between the nitrate contents observed in the alluvial groundwater and the landscape. The interpretation is made difficult by the existence of a "spatial bias". The nitrate contents tend to be high in market gardening bocages. The results of the test are not necessarily reliable as the landscape is rather continuous. Therefore, other causalities have to be studied.

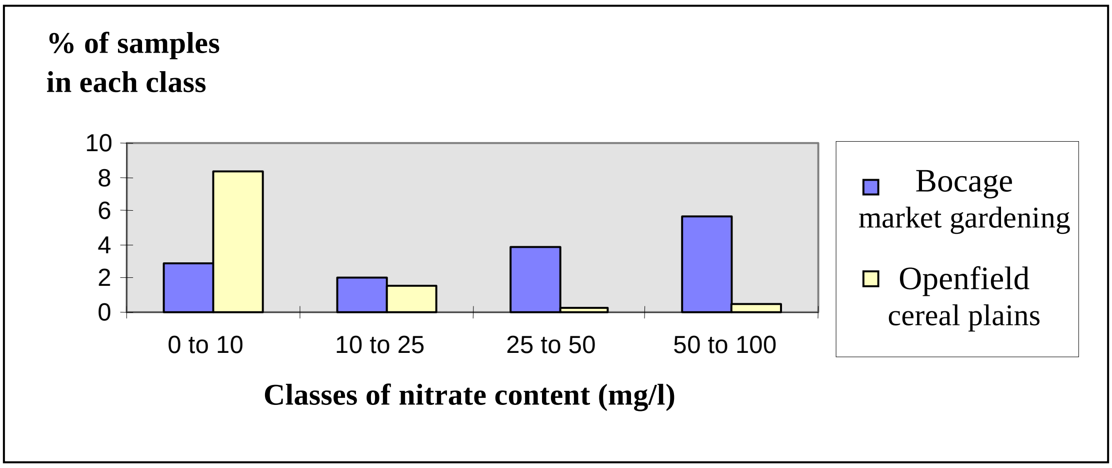

Figure 2. Frequencies of the nitrate contents in two landscape units

It is necessary to add other types of information into the GIS?

The treatments performed made it possible to partly explain certain hypotheses, e.g. the role of the verticality of convective fluxes in the transfer of nitrates or other polluting elements. To obtain more precise answers regarding such a complex situation, it is necessary to add other information layers, in particular regarding urbanization (land-use scheme and reclamation). These data should make it possible to assess and map the "risks", while introducing notions of spatial and temporal dynamics. It might be necessary to collect information in the marginal zones of the study area, e.g. for viticulture in the northern hills and for hydrography.

Conclusion and Perspectives

Segmentation into information layers, i.e. land use, soil and water table, first appeared necessary to study the relationships between agricultural practices and the nitrate content of groundwater. Diagnosing the nitrate contents and their spatial distribution in the water tables made it possible to obtain an initial organization of the Carpentras basin by revealing areas with varying degrees of pollution and a gradual nitrate depletion from the hills to the plains. Another structuration appeared at the end of the landscape analysis which made it possible to identify five major types of landscapes and determine the role of agriculture in land use. The correspondence between the entities defined, e.g. between the landscape units of the geographer and the sub-basins of the agronomist, remains to be specified.

Land use was more precisely studied through the analysis of typical cropping systems. The cropping systems classified as presenting the highest riks of infiltration losses and located in the most sensitive areas were studied in priority (risks were classified according to the « cropping system x soil » pair). This supposed transforming the current soil map into thematic maps: vertical infiltration capability, soil behavior towards nitrogen. Analysing cropping systems led to changes in the assessment of agricultural practices (compensation effects are possible at the scale of the crop sequence, such as the introduction of an only slightly fertilized cereal in a vegetable sequence), the modifications of practices (type and supply periods of fertilizers) and the relocalization of crops in order to develop a type of agriculture to better exploit the soil and respect groundwater. The use of soil-plant-atmosphere models for crop sequences known to be at risk constitutes a complementary tool to test the effect of modifications in practices on the environment. The interest of this tool is to better take into account the influence of climatic variability.

The transversal analysis using a GIS makes it possible to compare sectorial results with the hypothesis of dominating vertical fluxes. The soil-landscape-nitrate combination shows that this hypothesis is limited given the complexity of the phenomena involved, such as groundwater run-off, technical changes and landscape and agricultural changes.

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