Rivers and Groundwater Vulnerability to Accidental Pollutions
Spatial Analysis of Vulnerability Areas

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ABSTRACT

The determination of the water resource vulnerability is a necessary step for the prevention of accidental pollution. When rivers or aquifers are used for water supply, it is very useful to forecast pollutant flow velocity in order to determine travel time between the potential pollution points and the intake.

Usually, water resource vulnerability cartography takes only distance from intakes into account. But others physical factors are involved in pollutant propagation : slope and soil texture.

It is necessary to define a method for automatical cartography of vulnerability zones around the intakes. For this aim, we map spatial distribution of the travel time on the resource catchment (river, lake, or well). This typical problem of propagation requires a specifical spatial analysis : start from the river or the well and extend the zone upstream according to the velocity values. It is an iterative process : for each selected cell, the neighbouring cells which contribute to the inflow are first determined. Then, for these cells, the flow velocity values are used to determine a cumulate travel time to the river or to the well. Eventually, we obtain a travel time map which control a good of the vulnerability.

With the aim of decision support for designing protective zones around the rivers and the wells, this method is integrated in a GIS.

The method is tested on two area in the Massif Central (France).

IMPORTANCE OF WATER RESOURCES FOR DRINKING WATER SUPPLIES

To respect drinking water specifications, natural waters are treated. Water treatment has a cost which depends on natural water quality. Local organizations must :

- reduce the accidental pollution risks which treatment cannot purify,
- keep the water quality at the same level or improve it in order not to increase treatment costs.

If it is possible (presence of alluvial aquifers), groundwater resources must be preferred to surface water resources because they are naturally better protected against pollutions. Expoitable groundwater resource (considering criteria such as flow, quality, pumping costs...) is too short in many regions to supply large cities. In this case, surface waters are used. In France, 37 % of the drinking water supplies come from surface resources (LALLEMAND-BARRES and ROUX, 1989).

Water resources vulnerability may be defined as a physical, chemical and biological fragility of a given water environment to a possible pollution.

Characterizing water resources vulnerability constitutes a very important issue which leads us to identify, in time and space, the areas which can endanger natural water quality in case of accidental or chronical pollution. Solving this problem requires :

- knowledge of involved phenomena : pollutant's velocity, pollution flow decrease by infiltration and then adsorption, filtration or biological degradation in soil or in river.
- geographical reasoning because the involved phenomena use parameters which are distributed in space : slope, soil types, etc.

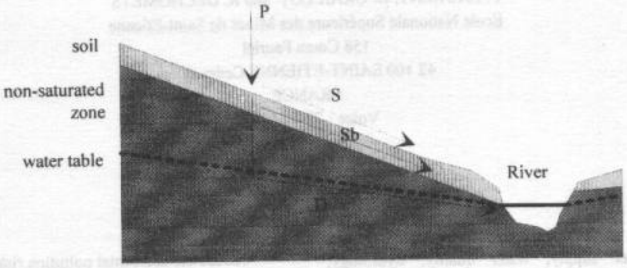
Then, it is necessary to use a method which will integrate these two kinds of knowledge in order to assist to the definition of protective actions. We will restrict ourselves to the physical characterization of vulnerability and we will distinguish the surface waters case from the groundwater case without taking hydraulic interactions between these two kinds of resources into account.

PHYSICAL CHARACTERIZATION OF WATER RESOURCE VULNERABILITY TO AN ACCIDENTAL POLLUTION

Characterization of Surface Water Vulnerability

In order to determine river or lake vulnerability, it is necessary to determine the travel time between any point of catchment and the river or the lake. A river (or a lake) will be all the more vulnerable as a pollution will be able to reach it. If the travel time is long enough, it is possible to intervene in order to stop the pollutant's propagation or to search for an alternate resource.

We can identify three types of runoff in a watershed : a slow flow by permanent groundwater, a quick flow by surface runoff and a quick flow by subsurface runoff in the temporary aquifer (see figure 1).



P : precipitation
S : surface runoff
Sb : subsurface quickflow
D : deep flow in permanent aquifer

figure 1 : flow types on a side

We will not take slow runoff into account because the danger is less urgent.

The surface runoff or saturated overland flow occurs when "on part of the drainage basin, the surface horizon of the soil becomes saturated as a result of either the buildup of a saturated zone above a soil horizon of lower hydraulic conductivity or the rise of a shallow water table to the surface" (PILGRIM and CORDERY, 1992). This phenomenon occurs especially at the bottom of the valley where runoff converges (PILGRIM *et al.*, 1982). So, surface runoff is a rare and space limited phenomenon except when the soil is saturated or impermeable.

The main part of the flow occurs in subsurface. Soil profile usually presents a decrease of hydraulic conductivity with increasing depth because, just beneath the surface, biological activity produces a larger effective porosity than in depth. Often, a temporary groundwater table develops in subsurface and flows out laterally according to a gradient similar to the topographic gradient. It reaches the stream channel quickly and has a large magnitude (PILGRIM and CORDERY, 1992). Then, this process is primordial for rivers or lakes vulnerability characterization, it appears in unfavourable meteorological conditions : wet soils where deep infiltration is limited, and where pollutant adsorption, physical filtration and biological degradation in unsaturated zone are thus difficult.

This characterisation does not take the pollutant's nature into account and assumes that the pollutant is miscible with water. It neglects soil exchange phenomena.

Pollutant travel time depends upon effective velocity u_p which is equivalent to particles velocity in the subsurface saturated zone.

Filtration velocity u_d (in $m.s^{-1}$) is given by Darcy's law which is defined for a porous medium :

$$u_d = Ki$$

where K : hydraulic conductivity (in $m.s^{-1}$)
i : water table gradient (dimensionless)

In order to calculate effective velocity (in $m.s^{-1}$) of any water or pollutant molecule in the porous medium, we can take the effective porosity ω_{eff} (dimensionless) into account. This effective porosity is different from total porosity because it neglects the non-gravitational water which covers the surface of soil particles by capillarity.

$$u_p = \frac{Ki}{\omega_{eff}} \quad (1)$$

We use this law to evaluate groundwater velocity. But in actuality, hydraulic conductivity determination is difficult because a homogeneous medium is an idealized case, which is rare in the field. For this, the real effective velocity has always some uncertainty.

Parameters determination :

- temporary aquifer hydraulic conductivity K is that of the subsurface i.e. that of the first meter of soil,
- water table gradient i : we assimilate it to the topographic gradient,
- effective porosity ω_{eff} : related to the soil texture.

Without field measurments, hydraulic conductivity can be determined by the relationship between this parameter and the soil's texture (RAWLS and BRAKENSIEK, 1983) (see table 1). But, the values given by these authors match those of aquifers. Indeed, with a same texture, the first soil layer (about fifty centimeters beneath the surface) shows higher values on account of vegetal and animal activity or of agricultural modifications (ploughing...). In order to obtain more accurate values, it would be necessary to realize field mesurements, which is impossible in this methodological study. But, BRAKENSIEK *et al.* (1988) reported that ploughing increases soil porosity from 10 to 20 percent depending on soil texture. SKAGGS and KHALEEL (1982) have shown that the infiltration rates are twice as important on a soil under grass as on a bare and crusted soil. From these results, we assume that hydraulic conductivity is twice as important for the soil subsurface as for the bed rock in depth, with a similar texture of course (see Table 1).

Texture	saturated hydraulic conductivity of bed rock K (m.s^{-1})	saturated hydraulic conductivity of soil K (m.s^{-1})
sand	$654 \cdot 10^{-6}$	$1308 \cdot 10^{-6}$
loamy sand	$166 \cdot 10^{-6}$	$332 \cdot 10^{-6}$
sandy loamy	$60.5 \cdot 10^{-6}$	$121 \cdot 10^{-6}$
loam	$36.6 \cdot 10^{-6}$	$73 \cdot 10^{-6}$
silt loam	$18.8 \cdot 10^{-6}$	$38 \cdot 10^{-6}$
sandy clay loam	$8.33 \cdot 10^{-6}$	$17 \cdot 10^{-6}$
clay loam	$5.55 \cdot 10^{-6}$	$11 \cdot 10^{-6}$
silty clay loam	$5.55 \cdot 10^{-6}$	$11 \cdot 10^{-6}$
sandy clay	$3.33 \cdot 10^{-6}$	$7 \cdot 10^{-6}$
silty clay	$2.77 \cdot 10^{-6}$	$6 \cdot 10^{-6}$
clay	$1.66 \cdot 10^{-6}$	$3 \cdot 10^{-6}$

Table 1 : saturated hydraulic conductivity according to texture

In others respects, without measurements of effective porosity, we can use an empirical function defined by ECKIS (cited in DE MARSILY, 1981) which relates effective porosity to soil particles average diameter, i.e. to the texture (Table 2).

particle size (mm)	texture	effective porosity
0.0001	fine clay	0.12
0.001	clay	0.27
0.01	silt	0.33
0.1	fine sand	0.28
1	coarse sand	0.20
10	fine gravel	0.15

Table 2 : effective porosity according to texture

Groundwater Vulnerability Characterization

Involved Factors

Groundwater vulnerability is controlled by the following factors :

- aquifer filtration capacity : weak in porous medium and insignificant in fissurated or karstic rocks ;
- unsaturated zone thickness above aquifer : important natural epuration by adsorption on clay, by mechanical filtration between soil particles or by biological degradation; the main part of adsorption and of biodegradation occurs in the unsaturated zone ;
- groudwater flow velocity : it determines dilution process, pollutant fixation and degradation and pollutant particles effective travel time between pollution point and intake ; ability to give the alert and to intervene depends on this velocity ;
- the type of aquifer : free aquifer or confined aquifer.

Factors Determination

In this study, we are only interested in free aquifers (such as alluvial aquifers) because they are at the same time the most exploited and the most vulnerable.

For the moment, we don't take the self-epuration in the non-saturated zone into account because this phenomena depends largely on pollutant nature and infiltration modelling in non-saturated zones needs different equations and parameters. We assume that the vulnerabilty is only a function of travel time. The pollution danger declines as travel time increases (BARROCU and BIALLO, 1993).

We can use equation (1) in order to determine the particles' effective velocity within the aquifer.

Determination of the equation parameters :

- in the case of a permanent aquifer, the piezometric gradient (given by the water table) does not necessarily match the topographic surface as is the case with a subsurface aquifer.
- the hydraulic conductivity K is that of the aquifer.

VULNERABILITY ZONES AND PROTECTIVE ZONES : « CLASSICAL » DELIMITATION METHODS AND RECENT DEVELOPMENTS

Regulations in force in European countries prescribe the definition of two or three protective zones around groundwater or surface water intake for drinking water supplies. In these areas, certain activities are prohibited or controlled in order to reduce the risks of accidental or chronic pollutions.

In France, hydrogeologists are responsible for the definition of these perimeters. They rely on travel times in accordance with the numerous parameters which we have mentioned before. In alluvial areas, hydrodynamic models exist which can be used to set up these protective zones on a physical basis. But, often, this delimitation is made without modelling (especially for surface water), the expert relies on his knowledge and his experience. Spatial variability of topographical parameters and of hydrogeological phenomena is taken manually and rather subjectively into account. Spatial distribution knowledge and control of these informations at a kilometric scale - between now and the year 2,000, all intakes will be surrounded by protective zones - seem very complex, only decision support computer tools are able to take this complexity into account (storage, consistency control, analysis, vizualisation...). How to determine manually the effects of slope changes, of the covering clay layer distribution or non-saturated zone thickness variation ?

BARROCU and BIALLO (1993) underlined that aquifer vulnerability maps are essential either in the first planning phase of pollution disasters (danger identification, evaluation and zoning) or in later phases (disaster forecast, monitoring system planning, emergency planning, defence planning...).

Geographical Information Systems (GIS) have been used to map groundwater vulnerability to pollution. GIS are able to store flexible information. They are useful to update in a short time the analysis results which are produced by data changes (new well, changes in pumping flow...).

But, as far as we know, GIS is only used in the multicriteria geographical analysis frame. The authors take numerous parameters into account and they overlap different weighted thematic maps (soil, aquifer depth, hydraulic conductivity...) in order to obtain a spatialy distributed index of the vulnerability (ALLER *et al.*, 1987; PEVERIERI *et al.*, 1991; MUNOZ and LANGEVIN, 1991).

But, GIS contribution is not limited to classic map overlapping. Now, several GIS have further developped spatial analysis algorithms (MILLS, 1994).

BARROCU and BIALLO (1993) have already used the groundwater flow directions "to attribute a vulnerability degree of a polygon (area) downstream of a pollutant".

SUGGESTED SPATIAL ANALYSIS METHOD

Representation of Spatial Distribution of Vulnerability Parameters

GIS manage spatial distribution and help to analyse the relationships that exist between certain spatial features.

We use a raster format GIS. The raster format is a regular division of space in square cells organized in a cartesian matrix (called layer) of rows and columns. Each theme is represented by a data layer. Each cell has a value. A raster file (like any layer in a GIS) is georeferenced and has a given resolution which corresponds to the cells size.

Compared with a vector structure, a raster format GIS offers the following benefits :

- better modelling of continuous phenomena (BURROUGH, 1986) : vulnerability is a continuous phenomenon ;
- surface spatial analysis is more advanced because pollution spread modelling is easier with the constant size and shape of spatial units, the parameter value of a localisation is controled by the values of this parameter in surrounding localisations (ESRI, 1991) ;
- overlays are easier (BURROUGH, 1986).

Raster geographical databases are bigger than vectors, but we did not suffer from processing time because our database is limited : our surface water catchment has an area of 67 km² and is treated with a cell resolution of 50 meters ; our surveyed aquifer has an area of 15 km² and is treated with a cell resolution of 50 meters.

Parameters Integration in a Geographical Database

Our geographical database is made of several vector and raster layers. The vector layers are transformed into raster layers for the processing.

We use the following layers :

- for surface water :
  - elevation : raster from the Digital Elevation Model of the Institut de Géographie Nationale (IGN), resolution of 50 m
  - hydrography : vector, accuracy of 25 m
  - soil types : vector, accuracy of 50 m
- for groundwater :
  - elevation : raster from the Digital Elevation Model of the IGN, resolution of 50 m
  - piezometric level : vector, accuracy of 25 m
  - hydraulic conductivity : vector, accuracy of 25 m

Developing an Algorithm for the Representation of Travel Times

We use the GIS functions which relate the cell's value to the neighbouring cells values, since the pollutant propagation is a phenomenon which may be calculated using a continuous map to determine spreading pathways (BURROUGH, 1986).

The vulnerability of a river or a well depends on the travel time t (in seconds) between an upstream point of the aquifer and a well or a river :

$$t = d / u_p$$

where d : path distance (in meters)

u_p : effective velocity (in $m.s^{-1}$)

We want to map spatial distribution of this travel time on the resource catchment (river, lake, or well). We know $1/u_p$ values at each point of catchment after calculation of parameters values of hydraulic conductivity K, effective porosity ω_{eff} and hydraulic gradient i (derived from elevation). We cannot take d as a simple distance to the river or to the well because d is a flow path distance on a relief (topographic or water table).

We suggest the following iterative method (see figure 2) :

a) build a raster layer of $1/u_p$ values

b) assign zero to river or well cells for travel time and take these cells like processing cells

c) select neighbouring cells "flowing" into river or well cells

d) calculate travel time t_{ij} (in seconds) between processing cell i and each neighbouring cell j using the following formula (if a neighbouring cell "flows" into 2 processing cells, keep only the shortest time) :

$$t_{ij} = \frac{d_{ij}}{(U_p)_{ij}}$$

with : d_{ij} distance between the cell i and the cell j (in m)

$(u_p)_{ij}$ mean velocity between the cell i and the cell j (in $m.s^{-1}$) like :

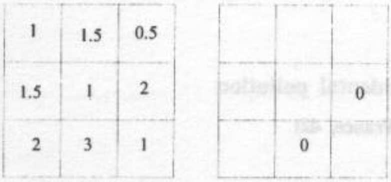
$$(U_p)_{ij} = \frac{(U_p)_i + (U_p)_j}{2}$$

e) consider the previous cells like processing cells and select the neighbouring cells which "flow" into them, give them a cumulate travel time (own travel time + travel time of cells into which they flow)

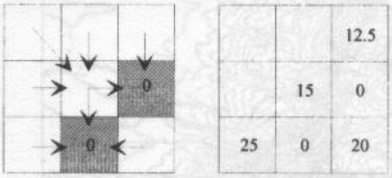
f) repeat this process for each cell which flows into resource cells directly or indirectly, until the whole catchment is covered.

This algorithm is similar to the one which would be used to describe a path cost on a surface with a unit cost distributed in space (this "cost", here, is equal to a travel time : the steeper the slope or the higher the hydraulic conductivity, the shorter the travel time). But, a runoff on a relief is more complex because it is controled by slope direction : we must only consider cells which flow into processing cells and eliminate the others. If we considered only slope amplitude without knowing flow direction, we would give for example a low travel time (or a high vulnerability) to a zone with a high slope, near a water resource but on another catchment.

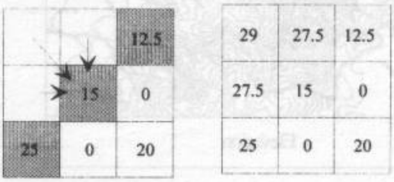
Then, we use the following criteria in the process : distance between a potential pollution source and the resource, hydraulic conductivity and slope amplitude and direction.



a) (1/Up) values b) river or well cells



c) cells contributing to the inflow d) time values for contributing cells



e) cells contributing to the inflow f) time values for contributing cells

figure 2 : cost-distance spatial analysis

Operators and functions of spatial analysis have been integrated in some GIS, they are based on formal modelling language : map algebra (TOMLIN, 1990). This language is implemented in two popular software packages on the market : ARC/INFO and MGE (Intergraph) (MILLS, 1994). We use ARC/INFO.

The ARC/INFO function being used ("pathdistance") is an algorithm which permits the representation of cells as nodes and links. Each cell center is considered as a node and is connected to the adjacent nodes by links. To each link is affected a "cost" equal to an average "cost" per unit of distance of each cell multiplied by the distance between these cells. If two values of cost-distance are affected to the same cell, then the algorithm keeps the weakest.

The unit's cost is equal to the spatial parameter ($1/u_p$), i.e. it is equal to : $\omega_j / (K_j * i_j)$ (see equation (1)).

This function also permits to consider the flow direction by a vertical factor VF (see equation (2)). In order to take flow direction into account, we must measure the slope between the processing cell and each of the neighbouring cells : if the slope is positive then flow into the processing cell is possible, otherwise there is no flow coming from this direction. In the algorithm, when the slope is positive or null, we assign a "1" value to VF and when the slope is negative (which is the case when the process meets a topographic divide) we give VF a high value (100 for example).

In order to correct the effects of relief projection on a plane, the algorithm is able to give the real distance.

So, the cost-distance, corresponding to the inverse of the vulnerability, is achieved using the following formula :

cost-distance = real distance * VF * cost (2)

Application for Surface Water Vulnerability

We apply the method on a catchment in the north-east of the Massif Central (France) : the Renaison catchment. On this catchment, two dam reservoirs are fed by numerous streams and supply drinking water for the city of Roanne, a town of 50,000 inhabitants.

In order to determine surface water vulnerability, in our application, we use all the river and lake cells as processing cells. The travel times for all their catchments can be calculated.

This catchment of 67 km² is very contrasted : the top is near a 1,300 meter elevation and the lowest point is near 350 meter elevation, soil types are quite different (loamy sand soils on granite in the west mountains, clay or alluvial sand in the east plain).

On the map (see figure 3), we can see the analysis results. We have created zones of equal travel time interval. The zones of low travel time, thus of high vulnerability, are larger in the west where the relief is more broken and the soils have a higher hydraulic conductivity whereas, in the east, the high vulnerable strips are very thin around rivers and lakes.

We must underline the fact that some parameters values have not been measured on the field, they are theoretical values obtained using general tables (see above).

In other respects, cells' spatial resolution of the Digital Elevation Model (elevation map) have produced some errors in the mapping. Low vulnerability isolated cells rise in the middle of high vulnerability cells sometimes near the streams because slopes calculated from data of the DEM are lower, so the cell's velocity is lower and its vulnerability is almost null. Another processing would be necessary in order to clean the data.

Last but not least, we must make it clear that these results are based on assumptions of a porous medium (see above).

Application for Groundwater Vulnerability

Aquifers are exploited by wells. Therefore, this method will be applied for the determination of intakes' vulnerability regarding a potential aquifer pollution.

The vulnerability of an intake depends on the travel time in the aquifer without considering the unsaturated zone.

Such a spatial analysis is similar to the case of surface waters but the hydraulic gradient corresponds to the slope of the water table. We consider the aquifer's permeability.

On figure 4, we can see the travel times on a well's groundwater catchment expressed in days. The well is in an alluvial aquifer near the Loire river in the north east of the Massif Central (France). 25 m^3 per hour are pumped from this well, it causes a deformation of water table which contour lines

Figure 3

River vulnerability to accidental pollution

Renaison catchment (France, 42)

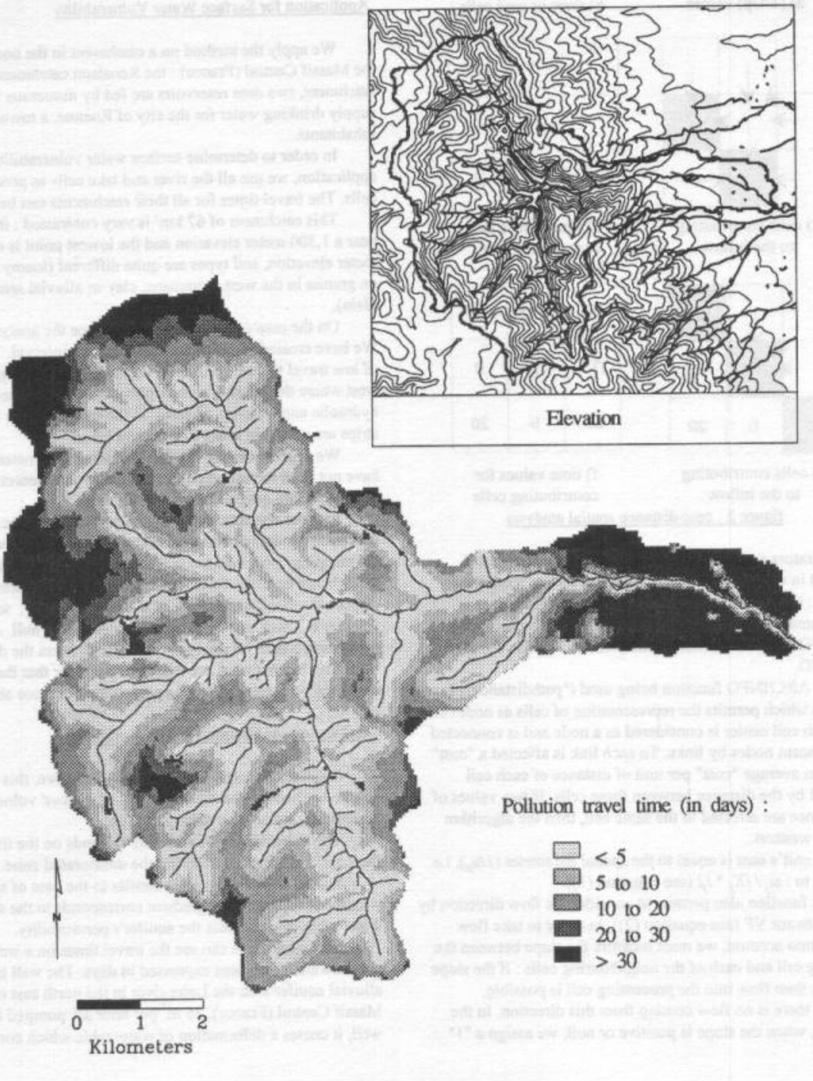
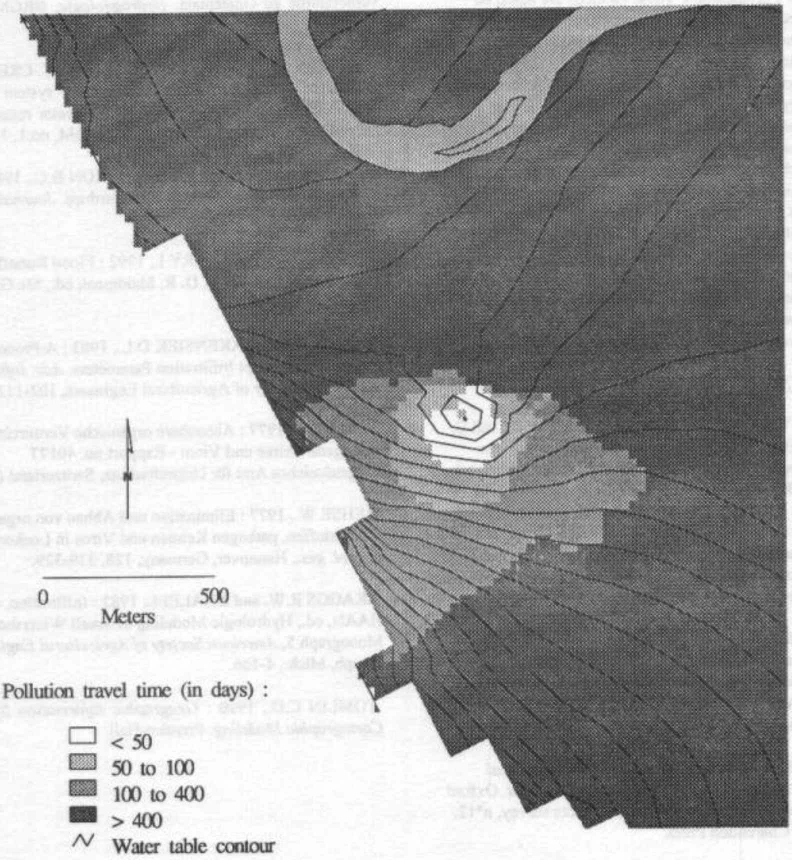


Figure 4

Well vulnerability to pollution

Balbigny aquifer (France, 42)



are represented on the map. The results show some isolated high travel time cells surrounded by cells with a low travel time. They are produced by the same causes as in the case of surface water : insufficient slope knowledge which produces flat cells. This type of error is even more frequent when the hydraulic gradient is weak. Thus, we must underline the fact that the analysis is limited by data resolution.

SPATIAL ANALYSIS AND NUMERICAL MODELLING

The type of transfer considered in our approach is purely convective. Under no circumstances, this spatial analysis should be a substitute for traditional numerical modelling methods of the pollution's propagation. These methods are based on differential equations which are built on the equation of continuity and Darcy's law and which take dispersion and diffusion (Fick's law) into account.

Our approach consists rather in a complementary means in order to analyze and visualize the spatial variability of hydrologic parameters involved in the determination of protective zones.

For such a determination hydrodispersive or hydrodynamical models are not always ready to operate (lack of data, unfitted parameters, calculation time...). But when they are available, pollutants' propagation models are more efficient for a better understanding of hydrodynamical behaviour in order to foresee the impacts of a pollution.

As a conclusion, spatial analysis of hydrological parameters provides a complementary means of numerical and stochastic modelling for groundwater transfer processes.

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