Using high-resolution electrical resistivity maps in a watershed vulnerability study

Michel Dabas,[1*] Thomas Jubeau,[1] Dominique Rouiller,[2] Jean-Marie Larcher,[2] Séverine Charriere[3] and Thibault Constant[3] **illustrate with a French case study the contribution for agricultural purposes of high-resolution geophysics and specifically apparent electrical resistivity (ER) measurements at three depths of investigation using a specially developed ARP system to determine the intrinsic vulnerability of a water catchment area to pollution hazard.**

The EEC regulation 2000/60/CE lays down ambitious objectives as regards to the re-conquest of the quality of drinking water. Governments must ensure the protection of water catchments areas in order to prevent the deterioration of their quality and to reduce the degree of treatment necessary for the production of drinking water. For this purpose, they must establish protected areas for these water catchments.

In order to better define the action plans and to target and treat on a hierarchical basis the territories of action within the protection zones, it is also necessary to define within the catchment area the most vulnerable zones to pollution hazards. Within the framework of the Grenelle agreements for the environment, 507 water catchments were selected and defined as needing protection in France.

In the case of the catchment area of Ambleville (Oise Valley) and its citation as a priority catchment area according to Grenelle, complementary studies were necessary to refine the understanding of its functioning. Local water catchments use springs of the Lutecian limestone and show a high rate of nitrate and pesticides. The immediate environment is characterized by both dwellings and arable lands. The arable surface is estimated at 382 ha The objective is to carry out agro-pedological mapping and create intrinsic vulnerability maps of the catchment area of Ambleville (450 ha) in order to better understand the hydrogeologic/geological processes linked to the pedology of the basin. The originality of this study was the coupling between three partners: Geocarta for the establishment of the geophysical mapping using the ARP and WebSIG programs, Epis Centre/Axereal in charge of the establishment of the agro-pedological maps, and InVivo AgroSolutions in charge of hydrogeologic interpretations and the establishment of the intrinsic map of vulnerability of the water table.

Figure 1 *ARP in action.*

Geophysical layer: 3 ER Maps

Intrinsic vulnerability is the function of a certain number of parameters such as the presence and thickness of the superficial layers, global pedology of the catchment area (CA), absolute values of the slopes and their lengths, and position of the principal axes of fracturing. Obtaining these data quickly at a reasonable price in order to build models is one of the most challenging issues in trying to obtain accurate vulnerability maps. Spatial resolution of these data is also another question: variations in the subsurface parameters are often at very short wavelengths (a few metres). Consequently the resolution of the input data to any prediction model should be of the same order.

These parameters were acquired indirectly by geophysical measurements using a new system for high resolution mapping of large areas (>100ha) designed primarily for precision farming (PF), namely the ARP (automatic electrical profiling) system (Dabas, 2009). This device was towed all over the free agricultural surfaces (475 ha) within a few days. It makes it possible to bring spatialized information

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(resolution down to 10 m) over the whole catchment area thanks to the mapping of apparent electrical resistivity (ER) with three depths of investigation together with acquisition of the digital elevation model (DEM).

Geoelectrical mapping has proven to be useful in detecting soil spatial variations which can often be related to soil properties relevant for plant growth (Dabas et al., 1989). For instance, soil ER is linked to soil salinity, soil texture, cation exchange capacity, soil moisture, organic carbon, pH, Bulk density, nitrate content, and soil types (Gebbers et al., 2009). Whereas the influence of salinity normally plays a minor role under temperate conditions, clay content and water content are usually the most important factors causing spatial variation in ER.

ER is already used in specific contexts like precision farming (definition of homogenous zones, prediction of yield, management of N input, etc.), soil science (optimized soil survey and guided sampling), and of course in 'standard' geophysics for finding water tables, stratigraphy mapping, detection of voids and buried structures, etc. Its use for watershed studies is not yet developed and the aim of this study was to use the three maps of ER (and DEM) as an additional variable to the other variables needed in the vulnerability model.

In electrical methods, an electrical current is injected in the soil by means of a pair of electrodes. This current is either a DC current or a slow alternating current (several Hertz) to avoid polarization effects and/or eddy currents. The current flow in the whole volume of the soil and subsoil and its spatial distribution is a function of the spatial distribution of the electrical resistivities. As the soil is rarely uniform, geophysicists use the term apparent electrical resistivity to name the 'average' resistivity of the volume where the current is able to flow. This spatial distribution is measured by two or more electrodes on the ground surface, which measure the resulting voltage. The ratio of the voltage to the current, multiplied by a constant (the geometrical factor which takes into account the orientation of the four electrodes) is the apparent electrical resistivity. Because subsurface materials have generally different resistivities, measurements at the surface of the soil can characterize the vertical and horizontal distribution of underlying structures. Typical resistivities span from 2 Ohm.m (clay soils) to several hundreds Ohm.m or even thousand Ohm.m over crystalline or metamorphic areas. Resistivity of subsurface materials is higher than soil resistivities in nearly all cases due, broadly speaking, to a lower amount of water.

These measurements are slow because operators have to manually insert the four electrodes in the ground. As it is not possible by airborne systems to measure ER correctly within the first 2 m, we had to develop a new towed platform, the ARP system, for measuring the ER continuously. For this purpose, we have to:

- Design a resistivimeter which can cope with high contact resistance, have the best time response, and be easy to operate in the field,
- Design mechanics that can be used as rolling electrodes and be towed by an all-terrain vehicle even in very harsh environments,
- Design hardware and software to drive the instruments, help the operator while driving (auto-guidance), and also makes the real time quality control of ER and positioning parameters.

Thus, the innovation lies in a continuous measurement of ER by a specific device (resistivimeter and spiked wheels acting as electrodes) towed by an all-terrain vehicle (Quad bike, 4x4, farm tractor). Positioning is ensured by GPS (differential or RTK). Measurements are taken every 10 cm along the profiles with three depths of investigation (0 to 50 cm, 1 m and 2 m). The final resolution of the cartography depends on the distance between the two profiles.

ARP (Dabas, 2009) was commercially developed for agriculture by Geocarta, a spin-off from CNRS in 2001, following previous work in CNRS (Dabas et al., 1997, 1998). Several improvements were added like absolute positioning by a dGPS or RTK GPS, possibility to acquire three measurements at the same time corresponding to three depths of investigation (0 to 0.5; 0 to 1 and 0 to 1.7 m) at a speed up to 6m/s with a spatial resolution of 10 cm along the profiles (Figure 1).

In open-field areas, up to 80 ha can be surveyed in a day. In standard conditions, the number of measurements in one hectare is around 30 000 (inter-profile of 10 m, measurement along profile every 10 cm). The average velocity of data acquisition is around 4 m/s (1 ha = five minutes of survey!).

There are now seven generations of ARP systems working in the field. Most of them are built for specific applications. Figure 2 shows the electrical image obtained for channel 2

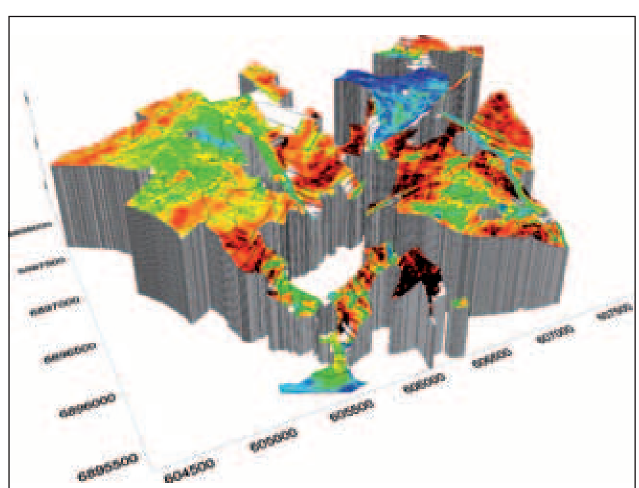

Figure 2 *ER Map superimposed on DEM.*

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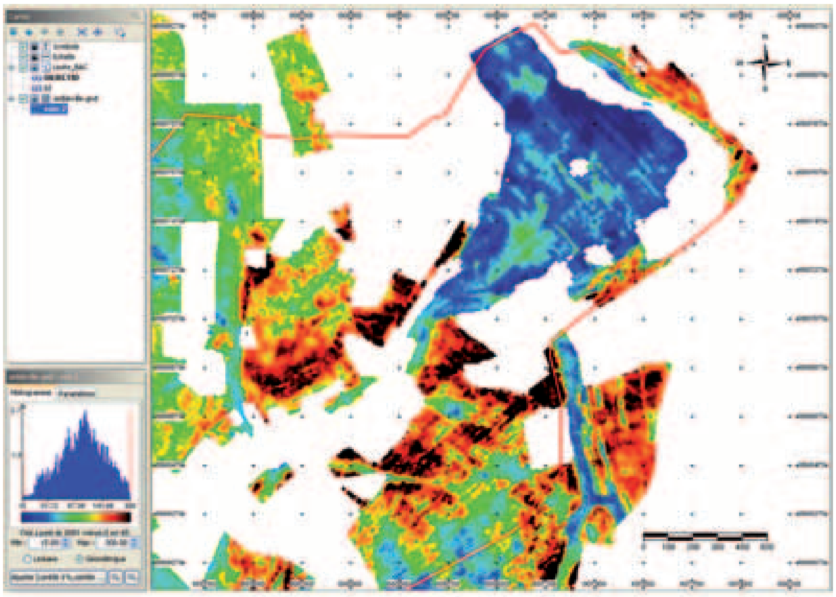

Figure 3 *ER Map ARP channel 2.*

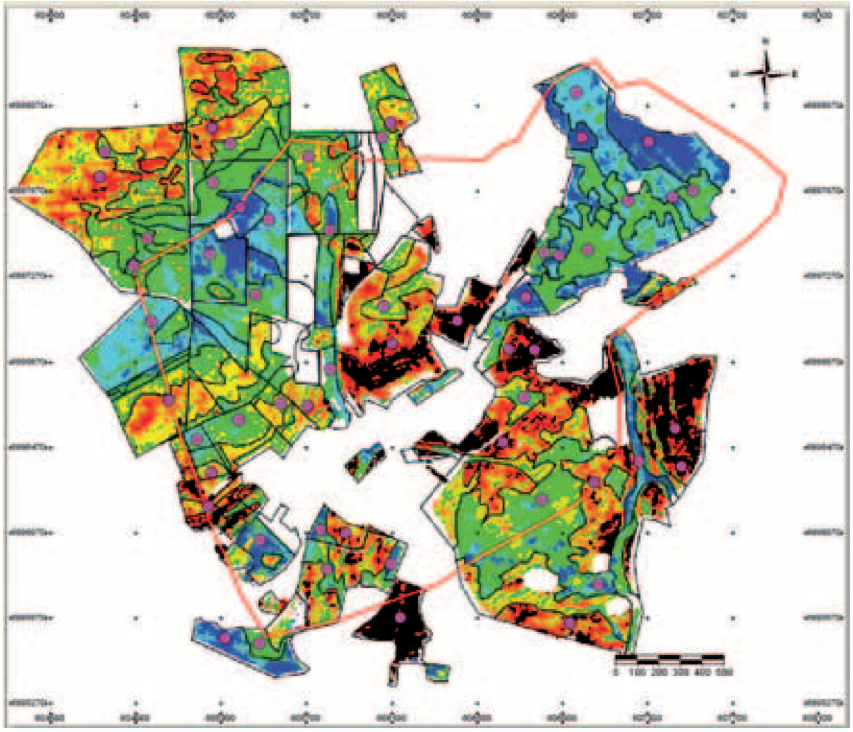

Figure 4 *Sorted resistivity map split into zones (white lines) and location of soil observations (pink dots).*

(depth of investigation of the order of 1 m) superimposed on the DEM acquired at the same time as the resistivity (high resistivities in red correspond to outcrops of limestone and/or very superficial soils and low resistivity zones in blue corresponding to clayey soils).

Figure 3 shows the ER map (5 m grid resolution) output of the GIS with resistivities spanning from 15 to 380 Ohm.m. For example, distinctive anomalies show up clearly like Thalwegs (linear feature in blue), fracturation of the bedrock (direction N44 to the West and N0 to the East of the Thalweg), outcrops of limestone (in black-red), difference in clay content, etc.

The next step is to transform this map into a pedological map.

From ER maps to the composite map and soil map

After the electrical survey, in order to characterize the soil units, a soil survey must be carried out. First the three apparent electrical data corresponding to the three depths of investigation are processed for synthesis onto one single map. Unfortunately three points are not enough to carry a full inversion process in order to get the true ER. Consequently, we have developed a simple algorithm in order to merge the three apparent ER maps: for each depth of electrical measurement, the data are sorted into groups of equal resistivity. For the CA of Ambleville, the data were sorted into four classes for each depth of investigation: low (L), medium (M), high (H) and very high (VH). The resulting composite map has potentially 64 values, however a clustering is carried out between similar classes so that at the end

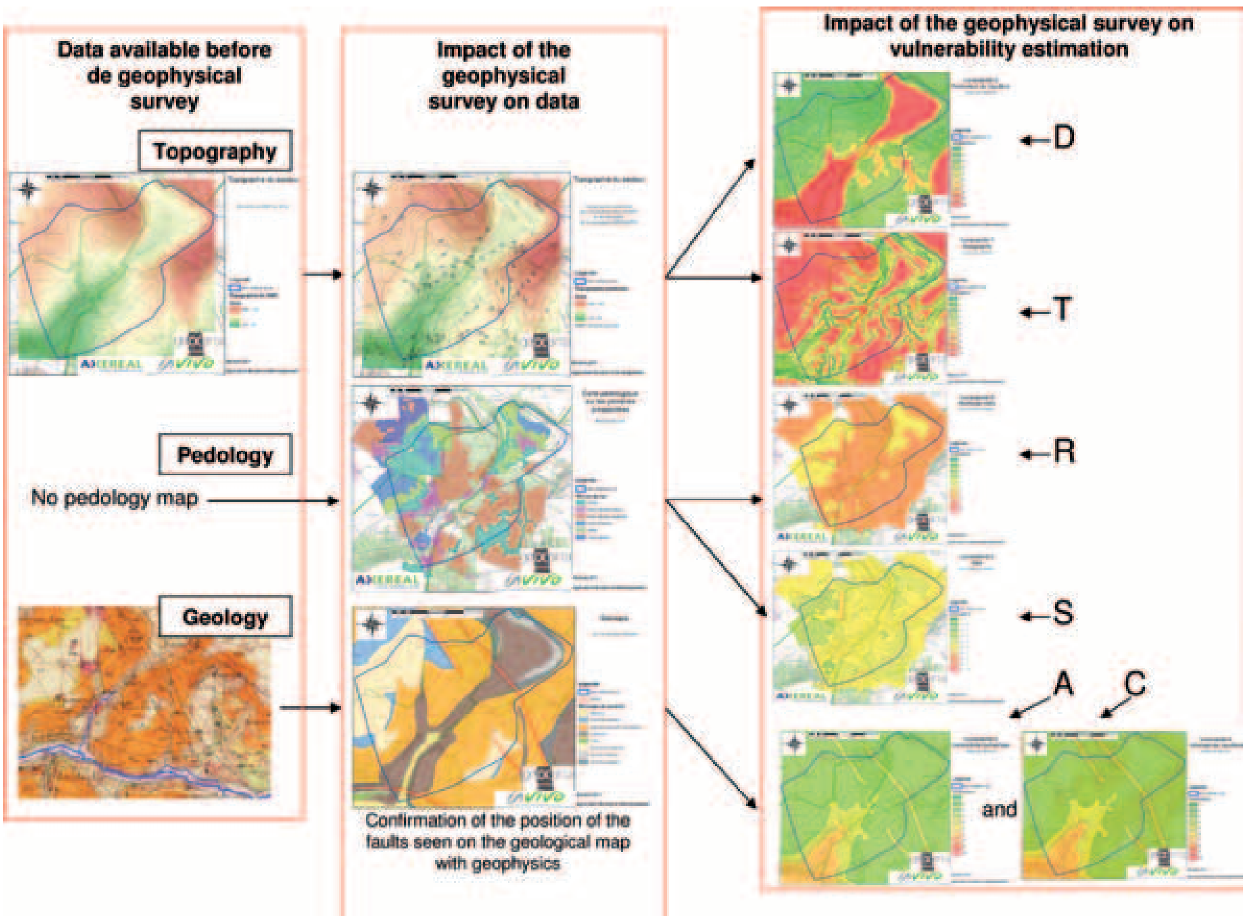

Figure 5 *Scheme showing the improvement of data quality due to geophysics for Ambleville case study vulnerability.*

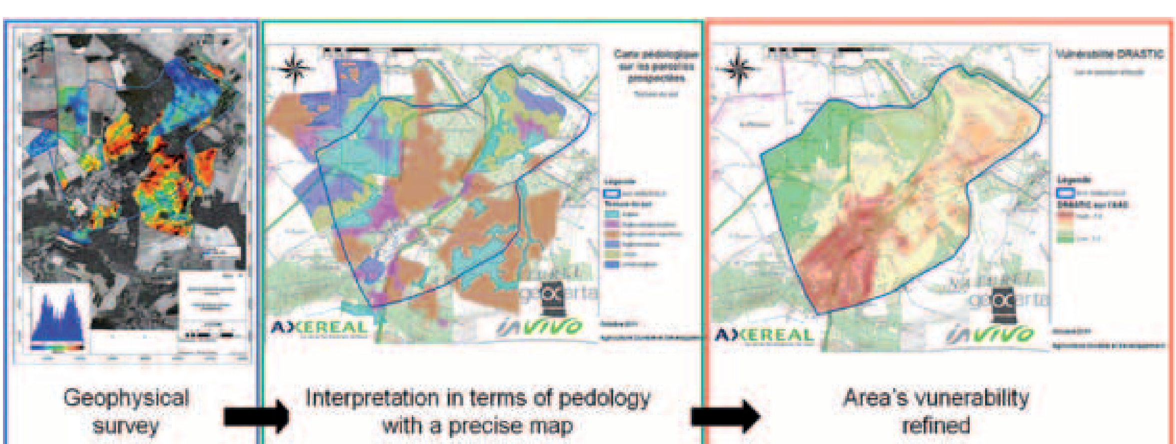

Figure 6 *Interpretative scheme of the method used on the CA of Ambleville.*

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Symbol	Parameters	Properties	Weight
D	Depth of the water table	Over this depth, the higher the contaminant takes a long time to reach the water table	5
R	Net recharge	Primary vehicle for the transport of the contaminant. Plus this refill, the greater the risk of contamination is high.	4
A	Lithology of the aquifer	Characterized by the size of the saturated soils or their degree of cracking. Il is involved in the trapping of the contaminant that may escape the absorption capacity of the soil.	3
S	Soil	The more the soil is rich in clay and organic matter, the greater the absorption of metals and cations is important an therefore the groundwater contamination is low.	2
T	Topography	The steeper the terrain, the greater the runoff, and therefore the groundwater contamination is low.	1
I	Unsaturated zone	The impact is determined from the texture of the land within it. The percolation of the contaminant to the water table is all the greater that is favorable texture (gravel, coarse sand...)	5
C	Permeability	The more this parameter is big, the greater the transfer of the pollutant is fast.	3

***Table 1** Parameters of DRASTIC method for the estimation of groundwater vulnerability.*

only six main classes remain. By aggregation of the three depths of investigation, this composite map shows the area characterised with equivalent vertical electrical profiles. The result is shown in Figure 4.

The colour code is as follows:

- Blue: L,L,L
- Sky blue: M,M,L
- Green: M,M,M
- Yellow: M,H,H
- Red: H,H,H
- Black: VH,VH,VH

The aim of the soil survey is now to convert these electrical profiles into soil profiles. Unfortunately, we have to describe the soils, in situ, with auger observations. For the 475 ha, it required a three-day survey with 59 auger borings carried out. Some of the borings proved unnecessary, but prudent to check the validity of the composite map, and to be certain that the same colour (class) in different areas corresponded to the same soil unit. The first analysis of the soil observations shows that 30 auger borings were sufficient to describe the CA, thus reducing the length of the survey to one day and a half.

Finally, three main soil units were observed: deep clayey soils (low resistivity/blue), deep silty loam soils (medium and low resistivity after 40 cm/sky blue), and shallow depth calcareous soils (high resistivity/yellow, red and black). The green colour also corresponds to silty loam soils but the parent material (limestone bedrock), in this case, is never deeper than 80 cm.

Therefore, for each soil area, we were able to provide DRASTIC method with all the data required to establish computerized vulnerability maps, such as soil layer texture and thickness, the range of stoniness (limestone flags), potential implanting depth, and soil water potential.

Interpretation in terms of vulnerability of groundwater to pollution

The methodology used in the estimation of the vulnerability of the CA of Ambleville is DRASTIC, which incorporates seven parameters of vulnerability (Aller et al., 1987). Studies for similar agricultural environments have already been carried out (Barber et al., 1994).

Each of these seven parameters (see Table 1) is spatialized and represented under a GIS (geographical information system), then weighted and assembled into a final map with a vulnerability scale from 1 (low vulnerability) to 10 (high vulnerability). We show here only the final results.

The contribution of the geophysical surveys, soil interpretation and implementation of the DEM has provided:

- Increase of the accuracy of maps related to pedology (R, S) and geology (A, C)
- Increase of the accuracy of the topographical map of the area (T) and consequently the map of the depth of the aquifer (D), with the finest DEM

Finally, maps of parameters D, R, A, S, T, and C are refined and we have computed that about 78% of the final result of the vulnerability map was refined (with the weights chosen).

Conclusion

We have shown in a practical example over an agricultural area of 450 ha that it was possible to better predict the vulnerability to various agricultural pollution hazards. The method used was the DRASTIC model. The data of this model were refined through the use of an extensive geophysical survey with a very high spatial resolution of 12 m. This electrical survey was carried out by an ARP towed system within a week and a pedological survey in two days. These two surveys have brought information used by the DRASTIC model mainly DEM and soil units. The definition of the vulnerability zones is now done with a spatial resolution of the order of 10 m and the increase of accuracy has been estimated of the order of 80%. The management of pollution in agricultural areas can be associated to the direction given by precision agriculture (PAG) in the management of fertilizers and phyto-sanitory products. Clearly the low cost acquisition of ER data developed for agriculture in the context of PAG can benefit studies related to the hydrologic processes.

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