A METHODOLOGY FOR THE SPATIAL ANALYSIS OF THE IMPACTS OF ROAD DE-ICING SALTS ON SURFACE WATER

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ABSTRACT:

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1. INTRODUCTION

The integration of the concept of sustainable development has become a fundamental concern in the sphere of roads, and research[1] is gradually developing the methodologies and tools that are required to integrate environmental constraints within each phase of the life of a pavement: construction, maintenance and operation.
Considering the environmental impacts of the spreading of road de-icing salts is, of course, only a small part of the whole problem, but this activity is nevertheless responsible for a non-negligible proportion of the diffuse pollution generated by the operation of pavements and has become absolutely necessary after 40 years of systematic spreading of de-icing salts in the winter.

The stakes are considerable, both in France and at a European level, as from a legislative point of view, the European Framework Directive on Water requires all the Member States to achieve “good ecological status” in all their “bodies of water” [2].
In response to this, the winter maintenance resources team at the Regional Laboratory in Nancy has been involved in developing a mapping tool, described in this paper, which will ultimately:

- contribute to research into the impacts of road de-icing salts on the diffuse pollution caused by road networks (interactions between pollutants, identifying the critical pollutant loads with regard to the functioning and quality of ecosystems …),
- provide decision-making assistance to the managers of roads and natural environments for them to develop new spreading strategies in the sectors that will be identified as exhibiting major impacts or high sensitivity to saline pollution,
- meet the need for transversality between local spatial planning managers and those responsible for preserving natural environments in France.
- prevent the irreversible deterioration of ecosystems (in terms of biodiversity and functionality) by ranking the sensitivity of natural environments.

In order to develop this mapping tool, it was necessary to define a methodology for evaluating and spatializing these impacts. This methodology is based on the use of a Pressure-State-Impact model that uses three indicators: a pressure indicator, an environment sensitivity indicator and an impact indicator. These components and the limits of the methodology are described in this paper. Finally, this methodology was applied to a field case in order to test its robustness, highlight the method’s limits and identify the ways in which it could be improved.

2. THE SITUATION AS REGARDS SURFACE WATER

The quantity of road de-icing salts spread in France has varied between 230,000 tonnes and 1,650,000 tonnes in the last thirty years (see Figure 1). It has increased with the size of the road network and is greatly affected by the random severity of winters.
At the same time as an increase in the treatment of roads, we can note a continual but annually variable increase in chloride ion concentrations (the major constituent of road de-icing salts) in both surface water (Figure 2) and groundwater, which gives the impression that these salts accumulate in the soils and aquifers.

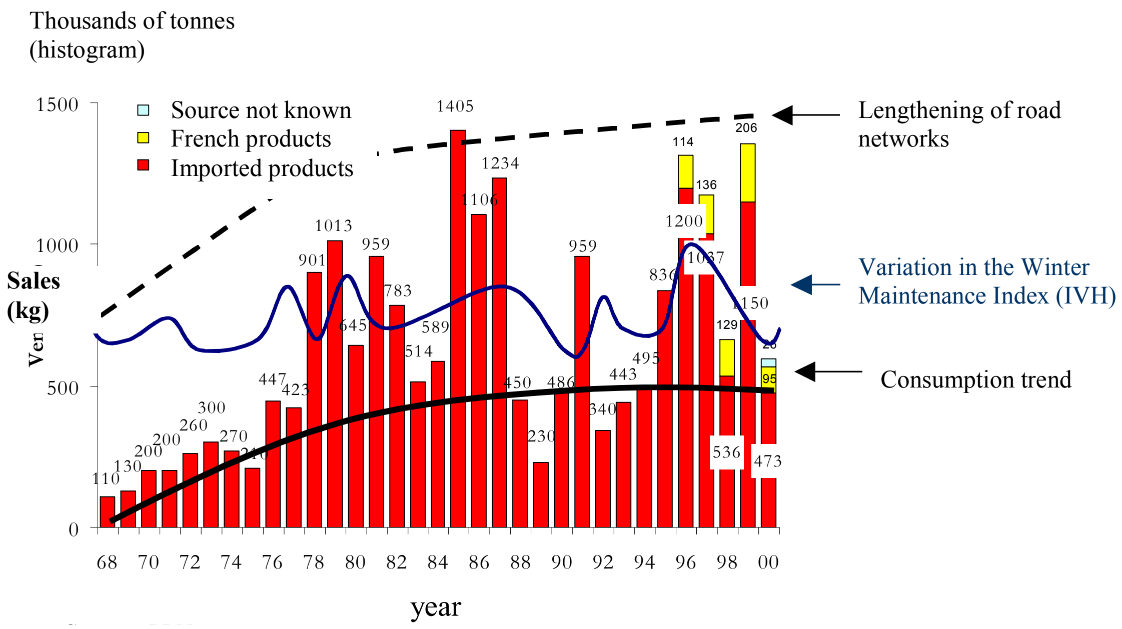

Figure 1 – Amounts of road de-icing salts consumed each winter in France (Data from Rock S.A.) and curves showing the Winter Maintenance Index and the lengthening of the French road network.

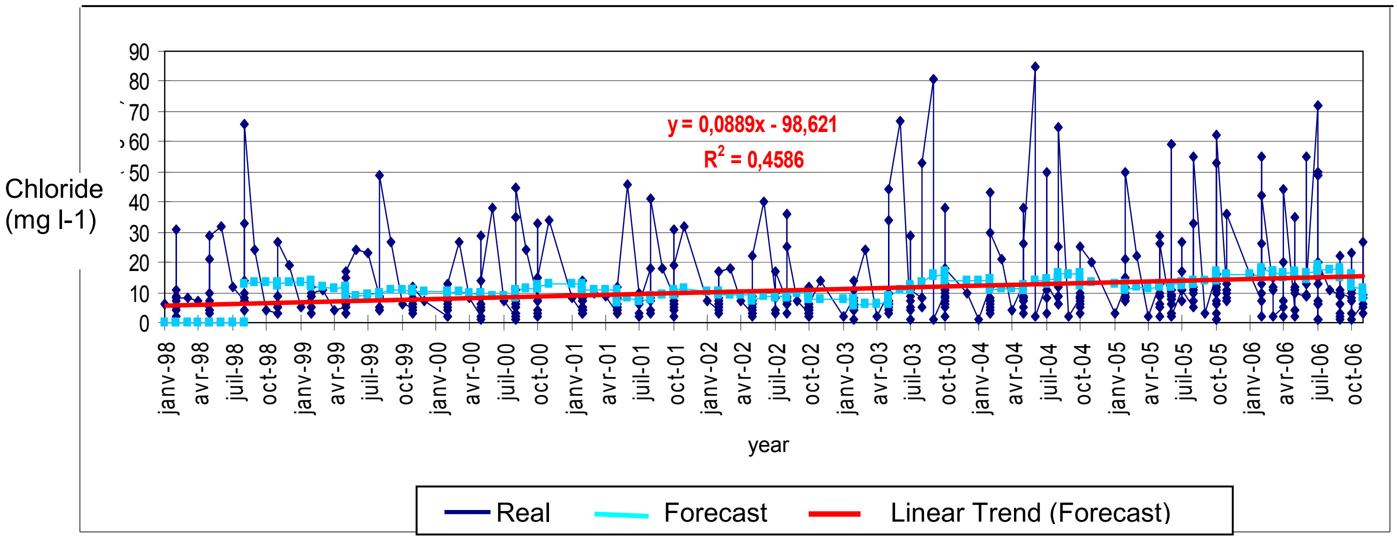

Figure 2 – Surface water chloride ion content (mg.l^{-1}) versus time – “Upper Rhine” hydrographic sector (Source : AERM)

In addition, a large number of scientific publications have shown that spreading de-icing salts increases the mobilization of toxic elements in the pavement foundations and their transport into the natural environment [3][4][5][6], as well as on colloid dispersion and exchangeable base cation leaching (affecting water and soil pH) [7] and disrupts the nitrogen cycle [8].

3. THE METHODOLOGY FOR THE SPATIAL ANALYSIS OF THE IMPACTS OF ROAD DE-ICING SALTS ON HYDROSYSTEMS

3.1. Premises and principle of the model

The study sets out to answer the following question: “What methodology should we apply in order to spatialize and evaluate the variability of the levels of impacts caused by spreading road de-icing salts on continental hydrosystems?"
To do this, an explanatory model for “pressure – state – impact” relationships was selected on the basis of research work conducted by a number of French research teams [9][10][11][12] [13][14][15]. The model’s components were identified and organized in the form of a Geographic Information System which facilitated data cross referencing and display of the results on a map.
Three indicators were proposed, one corresponding to each of the model's three components. They were defined on the basis of the following premise: “The variable pressure on hydrosystems that results from the spreading of de-icing salts and the specific sensitivity of these systems are responsible for the variability of the observed impacts.”
Where the impact is defined as the outcome of a pressure that is applied to a state of the hydrosystem,
the sensitivity of the hydrosystem is defined as the “ease with which a given hydrosystem can be damaged due to the arrival of pollutants within it” [16]
and the **pressure** applied to hydrosytems is expressed in terms of the average (and/or maximum) quantity of road de-icing salts that are spread per winter and per hydrographic unit (or catchment area).

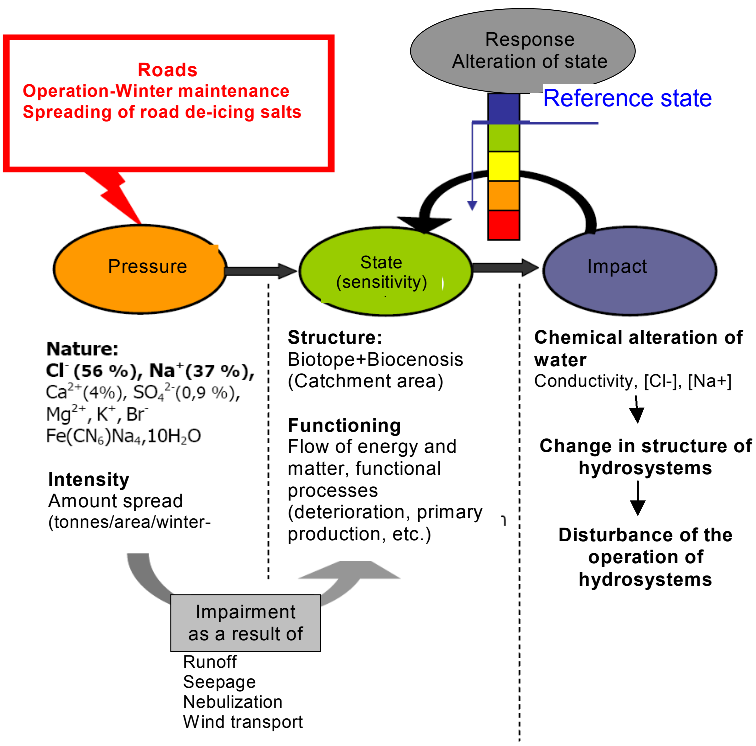

Figure 3 – The “Pressure-State-Impact model” for road de-icing salts

The model considers the road system and its winter operation as the generator of the pollution pressure. As this pressure is exerted on hydrosystems with differing sensitivities, the resulting impacts are characterized by the response of these hydrosystems that results in a variable alteration in their state.
As this variability in impact is the outcome of an interaction between the pressure (nature and intensity) and the sensitivity of the environment (its physical structure and functioning), we should make no assumptions about a given influence factor (does the pressure provide a better explanation of the variability of the observed impacts?).
We thus attempt, before trying to develop an approximate typology of the environments, to build an explanatory model for these relationships, at two geographical scales, the so-called “hydroecoregion” [14] and the hydrographic zone.

3.2. Selecting geographical scales for analysis

In order to apply a spatial analysis model it is necessary to decide on a desired level of spatial resolution. As this level depends directly on the geographical scale at which the data will be applied and at which it is available, working scales have been identified that are appropriate for the issues dealt with by the method.

Two geographical scales for analysis have thus been defined:
- a regional scale that provides an overview of the impact trends for decision-makers in order to inform road policy,
- a local scale that provides more detailed diagnosis of impacts and the sensitivities of the affected ecosystems. In more concrete terms, the value of this scale is that it provides an appropriate framework for cross-referencing the Pressure data (which are linked to the road network and the variation in the applied spread rates); the State of sensitivity of the ecosystem (linked to the configuration and hydrographic nature of the site the road passes through), and the Impact (linked to the chemical and hydrobiological measurement station and the surface area of the catchment area it covers).

These data representation scales each correspond to a nationally available geographical demarcation:
- The level 2 Hydroecoregion defines the regional scale of analysis. This demarcation is based on a combination of relief, climate and geological variables and allows us to link the components of the environment to road treatment policy. It therefore provides an appropriate framework for analyzing the major trends as regards de-icing salt damage to hydrosystems.
- the Hydrographic Zone, defined by the French Geographical Institute (Institut Géographique National) defines the local scale of application of the model. This demarcation corresponds to the smallest homogeneous unit with regard to the hydrological functioning of an area. As water is the principal medium and final receptor for de-icing salts, this unit provides an appropriate framework for analyzing the behaviour of de-icing salts in the environment, and hence “Pessure-State-Impact” relationships.

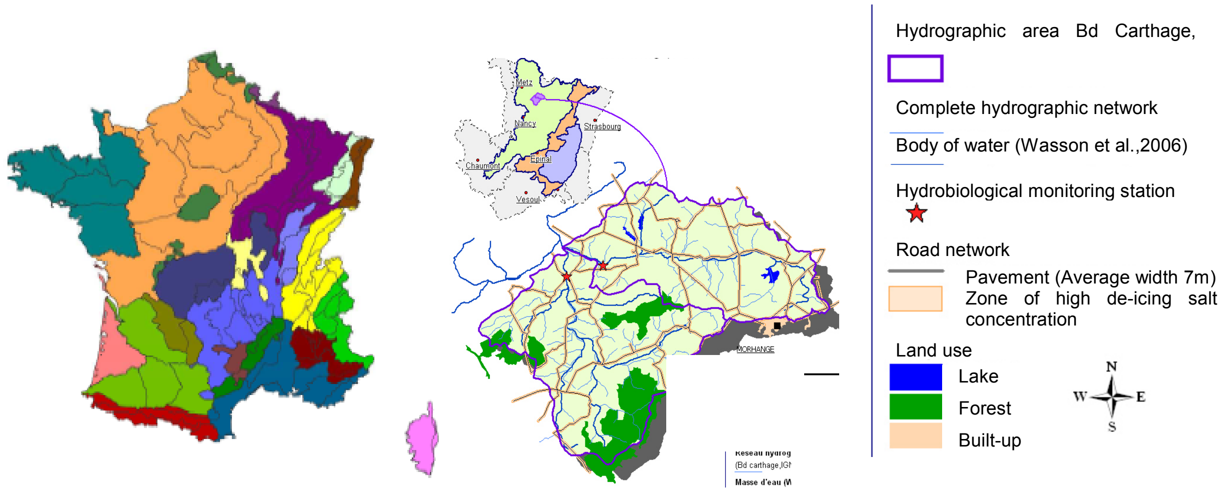

Figure 4 – Geographical scales for applying the model (left: the Hydroecoregions [14], right: a hydrographic area

3.3. Choice of variables and identifying the variables for the model

Based on the work of several French research teams mentioned above, the methodology has been adapted to the problem of diffuse pollution generated by de-icing salts. A literature search was conducted [17] in order to identify appropriate variables for the model with reference to three areas of concern:
- Knowledge of the factors that determine the flows of de-icing salts resulting from the diversity of road networks;
- The transfer and accumulation modes for de-icing salts in natural environments
- The response of natural environments to de-icing salt contamination (i.e. biological and chemical indicators)

Selection criteria were defined for each of these components of the model (i.e. a Pressure component, a State component and an Impact component) in order to retain only the most useful variables.
These selection criteria included:
- the representivity of the variables in relation to the model component in question (Pressure; Sensitivity State or Impact);
- the availability of the variable in the form of geographical databases with uniform coverage of the entire country;
- facility of data access;
- a guarantee that data acquisition will continue in the long term.
*
The three sets of geographical variables were then integrated within a Geographic Information System. A specific type of processing was applied in each localized database, which required the software to perform a great deal of data handling and computation.
Without describing the full procedure used to create each database, the main stages of processing were as follows:

- Surface data (land use, rock permeability, pedology, etc.) were processed in order to arrive at a percentage of the hydrographic area covered by the different types or classes of information. The dominant type was selected for the statistical analysis.
- Linear data (the distance between the station and the road, the hydrographic section), were processed using a dedicated tool, as was the creation of geographical buffer zone and the geographical joining of the maps.
- Station data (such as the altitude of the monitoring stations were simply attached to their respective hydrographic area.

3.4. The selection of data analysis methods

A large number of possible statistical methods were available, and the first of these to be tested (see Section 5.) involved applying a linear regression model to the data. Simple statistical tests were then performed to test the significance of the choice of impact indicator and the explanatory power of each variable in relation to the variability of the observed impacts.

4. THE PRESSURE-STATE-IMPACT MODEL AND ITS INDICATORS

4.1. The pressure indicator

A particular chemical composition (which varies according to the source of the de-icing salts) and a specific intensity (the amount of de-icing salts spread and the influence factors that result from the characteristics of the local road network) corresponds to each type of pressure.
Its spatial distribution depends on the dominant de-icing salt mobilization processes outside the pavement and certain characteristics of the pavement (size, surfacing, exposure, altitude, longitudinal profile, cross-section, etc.) [18][19].

With this knowledge base, the geolocalized data available from road managers was summarized. Once they had been processed and allocated to the road network the applied quantities of de-icing salts were then displayed. The figure below shows the pressure indicator, expressed in tonnes of de-icing salts per unit surface area of the hydrographic area for a test zone (the Vosges Département).

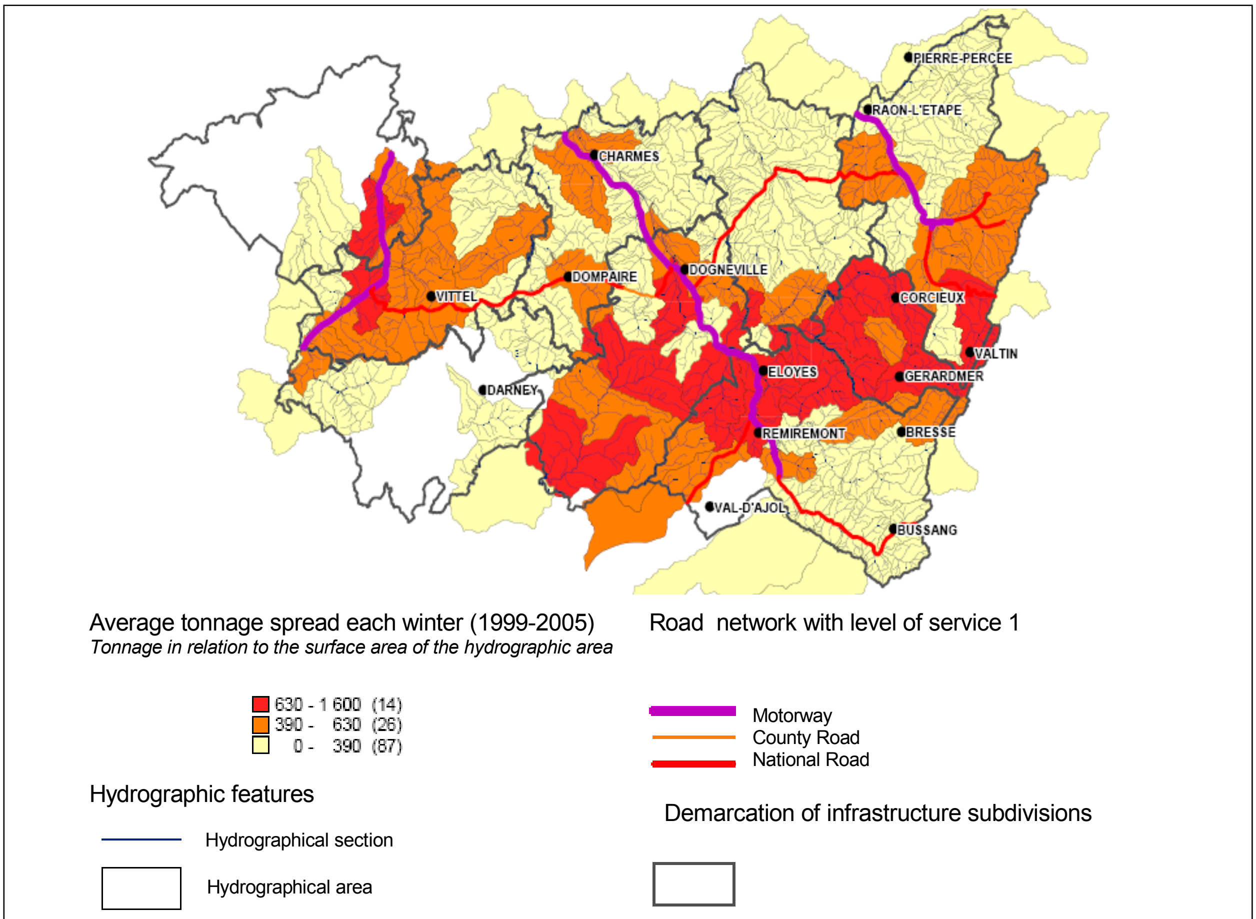

Figure 5 – Display showing the pressure indicator. Average quantities spread each winter

4.2. The impact indicator

A type of alteration (chemical or biological) is associated with each type of impact. The alteration affects either the structure and/or in the operation of the aquatic environment.

As road de-icing salts alter the chemical structure of the various bodies of water [18] [20] [21][22] [23] and [24], it seems plausible that they will disturb the structure and operation of hydrosystems. However, the loads (threshold values) and the critical times required for such problems to develop are largely unknown (we have been unable to find any publications on this topic).
In the light of this, we decided to use the chloride ion content of the water as an indicator. As this needs to be comparable between a variety of natural environments the chloride ion concentration was expressed as the divergence from a reference value (in order to remove the natural variations in the concentration of the element) as shown in Figure 6. A network of monitoring stations (upstream of any disturbances) and a network of impacted stations (downstream of the road network) was also obtained from those supplying data for the test zone.

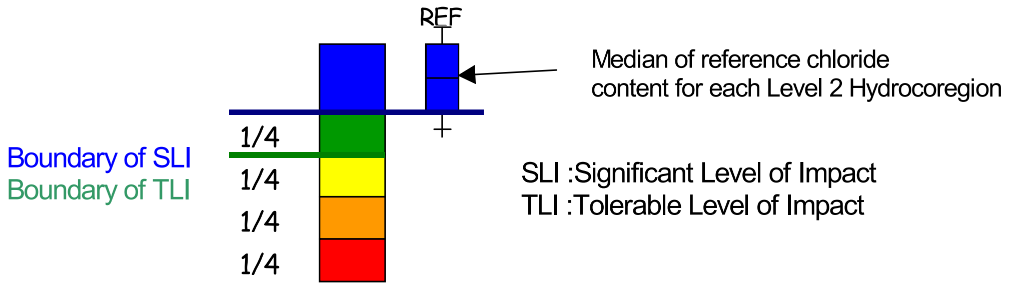

Figure 6 – Impact level: difference of the chloride concentration from a reference value.

The search for relevant reference values led to the compilation and statistical processing of data according to the two geographical scales that were selected for applying the model. This work showed that the Level 2 hydroecoregions scale was sufficient to show the natural reference levels for chloride in the water. The median value of the data was calculated for each impacted station and related to the reference level of each (the median chloride concentration at the Level 2 HER scale). The result is shown in Figure 7 below, which provides a useful diagnosis.

NB : Awaiting the definition of the relevant thresholds (bioecological studies, a functional analysis of benthic communities …), the classes given in Figure 7 were arbitrarily defined on the basis of simple statistical processing.

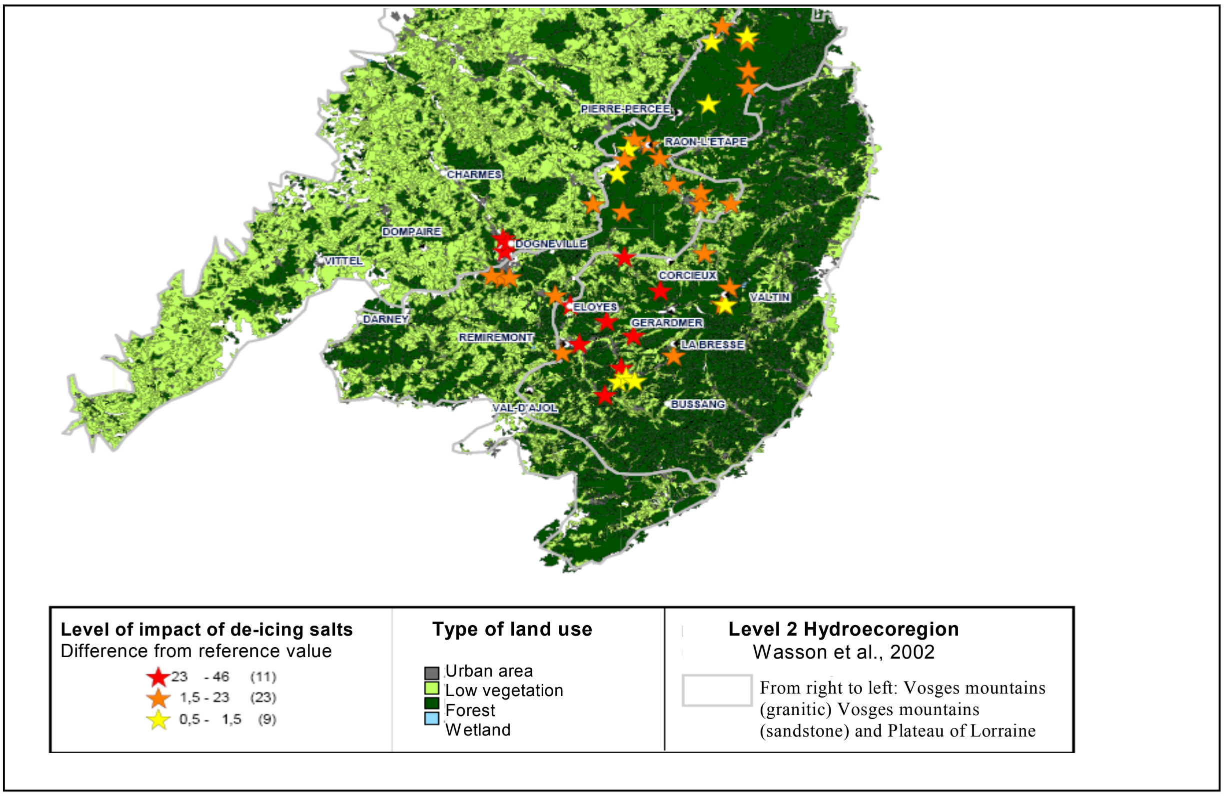

Figure 7 – The impact levels (Difference from the chloride ion reference value)

4.3. The indicator for the state of sensitivity of hydrosystems

A sensitivity as regards structure and functioning is associated with each state of the hydrosystem. The structure is defined as all the abiotic conditions in the environment (environmental factors at the level of the catchment area and the physical and chemical characteristics of the water at station level) and the organisms that live there in interaction with the environment. Its sensitivity may therefore be expressed by a combination of environmental factors that influence the level of concentration of the de-icing salts in the water bodies.

Functioning consists of the dynamics of the functional processes of this structure: self-purification capacity, the degradation of organic matter, primary productivity, etc. In the current state of our knowledge no reliable indicator can be extrapolated to cover the entire range of hydrosystems.

As the choice and expression of the explanatory variables determines the model's explanatory qualities an exhaustive search for influence factors was undertaken in order to test the contribution of each without prejudging their importance (Figure 8)

As the influence factors can interact with each other (rainfall and altitude, for example) several plausible combinations were tested statistically by applying a linear model.

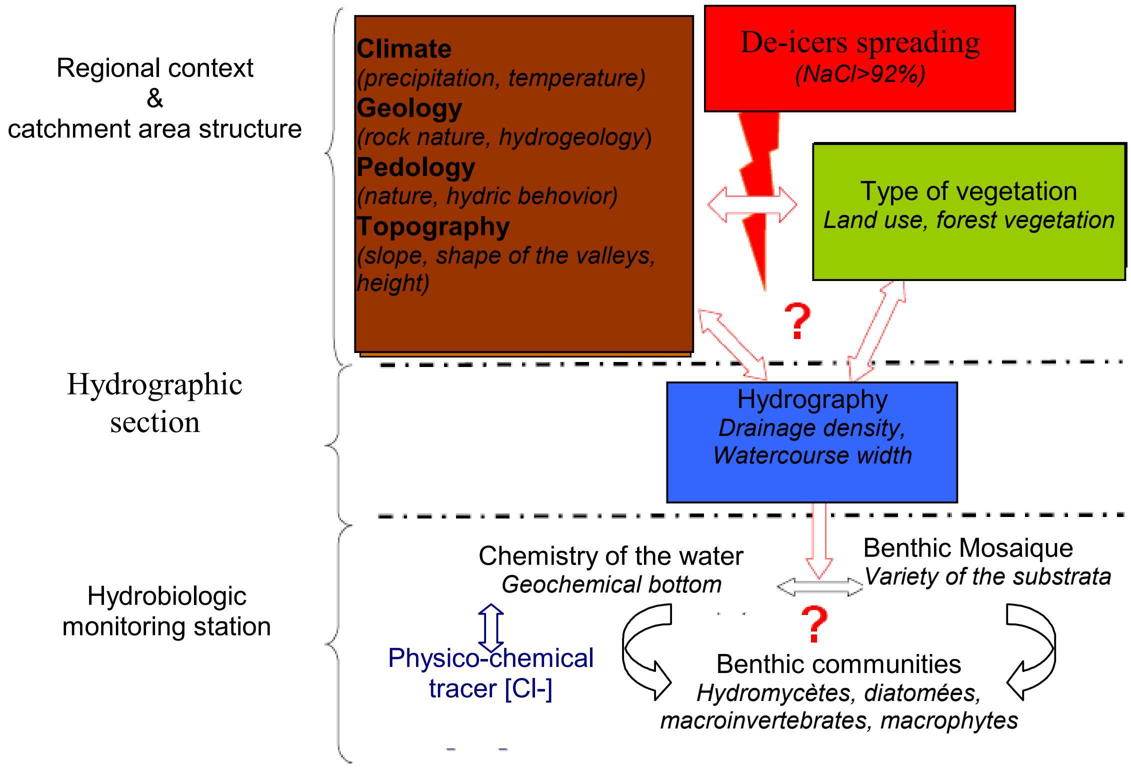

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Figure 8 – The plausible variables for constructing an indicator for the sensitivity of hydrosystems.

Thus, the indicator of hydrosystem sensitivity should be seen as the combination of various influence factors. This will provide the basis for a typology of hydrosystem sensitivity.

5. THE RESULTS OF APPLYING THE PRUSSURE-STATE-IMPACT MODEL

Applying the linear model to the entire dataset (created by cross referencing the pressure, the sensitivity of the hydrosystems and the impact levels) provides a number of results.

The selected model explains 63% of the observed variation in impact levels. All the influence factors contribute to the explanation, which confirms the quality of the bibliographic sources. However, fewer variables made a significant contribution (Figure 9). These will be selected in order gradually to build up a sensitivity typology for environments:

-the surface area of the catchment area,
-the type of land use,
-the type of soil,
-the geology
-the drainage density
-the watercourse width
- the hydroecoregion

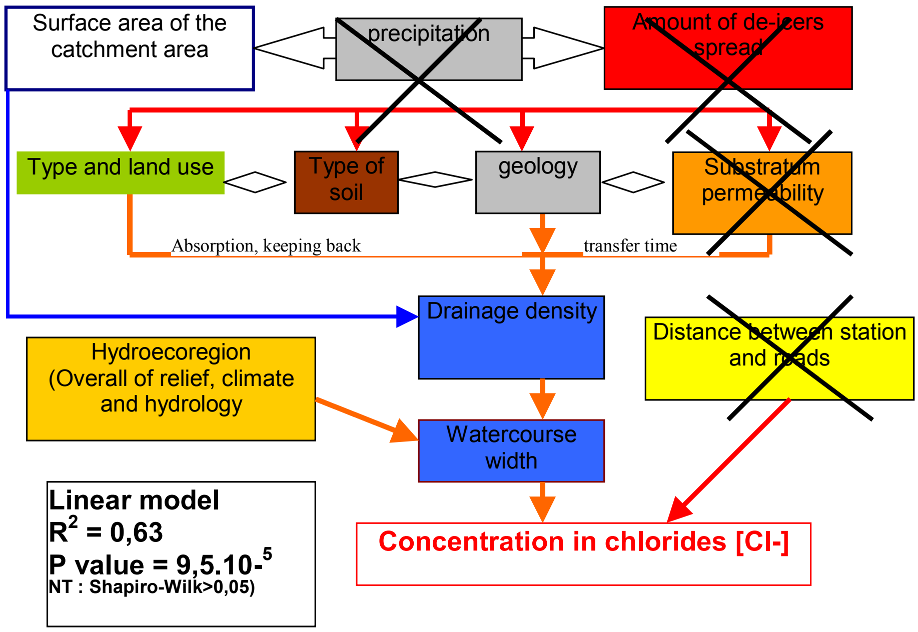

Figure 9 – Result of applying the linear model to the full dataset

As the explanatory power of the pressure from spreading is negligible compared to that of the environmental factors, a number of hypotheses may be advanced which deserve to be checked at a later date:
- inaccurate reporting of the quantities spread due to the division of the areas strictly upstream of the measurement stations may be responsible for on overestimation of the quantities reaching the measurement station.
- in order to have an explanatory function, the pressure may need to be expressed as a flow.

6. CONCLUSION AND OUTLOOK

In this applied research project we have attempted to achieve the highly ambitious goal of identifying, understanding, predicting, spatializing and ranking the impact of de-icing salt pollution on the varied natural environments that are present in France. Despite the enormous scale of the problem, the Pressure-State-Impact model has enabled us to answer a great many fundamental questions such as the geographic scale, the selection and form of the indicators, and the availability and uniformity of the geolocalized data.

The research has enabled us to develop the first version of a spatial analysis tool for the impacts of spreading road de-icing salts by creating a platform for geolocalized data for the various indicators used in the model: data on the pressure caused by salt spreading, the sensitivity of natural environments to de-icing salts and the physical and chemical quality of surface water bodies.

Application of the model to a test zone in North-Eastern France has revealed that the current model has some limits and allowed us to identify some interesting ways in which the explanatory model could be improved. To this end, we envisage fuller collaboration with other French organizations such as the CEMAGREF Laboratory of Quantitative Hydroecology in Lyon and the French Central Public Works Laboratory (LCPC) in the context of a projected doctoral thesis. This thesis should improve our ability to evaluate impacts of this type (water chemistry and bioevaluation) and develop a validated model that can be extrapolated to the entire country and perhaps adapted for other toxic compounds that are deposited on pavements due to the fact that sodium chloride acts as an early tracer of diffuse pollution.

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