A Spatiotemporal Model For Estimating Risks Of Pollution For Underground Fresh Water Management

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EXTENDED ABSTRACT

This article explores the integration of a risk of aquifer pollution modeling within an environmental information system. Coupling modeling/GIS offers a new dimension, richer as far as analysis is concerned but also sensitive to data quality and variables used in models coherence.

Like many south pacific coral islands, underground water is the only fresh water resource of the Loyalty Islands and is a valuable resource. The Loyalty Islands and the French government have launched a multidisciplinary project (entitled SAGE) that aims at providing a decision support system for fresh water resource management based on interoperable geographical information.

To answer the expectations of these islands, and their inhabitants, the SAGE program aims at analyzing, organizing and delivering information relative to the fresh water resource. Several scientific topics are involved to study every aspect of the fresh water resource. Geology, hydrology, geography, remote sensing bring further information on the likely resource evolution. Each of these topics requires its own data often belonging to different companies and administrations. The data distributions as well as their membership in their owner involve a distributed approach. Each company continues to maintain its own information systems. Nevertheless, these data are available for the consultation, the processing being made on an information system dedicated to the program.

The goal of the system is to deliver geospatial data related to fresh water management over the World Wide Web based on the Open Geospatial Consortium (OGC) specifications.

The objective of the OGC project is to define transparent access to heterogeneous geodata and geoprocessing resources in a networked environment. For that, the OGC Project provides a comprehensive suite of open interface specifications that enable developers to write interoperating components that provide these capabilities.

Using these specifications, the Information System offers the possibility to access to distributed data. By making geographic data sharing effective, users requests progressively evolved towards the provision of services adapted to their use rather than simple data access.

From the spatiotemporal modeling aspect, the pollution risks are analytically simulated by a 2D Gaussian approximation centered on the geographic source of the pollutant. The different pollutions, depending of their impact on the public health can then be approximated in order to provide a static risk mapping.

The methodology, which allows considering the spatiotemporal dynamic of those risks, is integrated in the interoperable geographical information system. The dynamic is based upon a hydrologic model capable to compute the underground water trajectories from some geologic features. This model relays on data collected by hydro geological studies and remote sensing products. Speed and circulation direction of underground water is computed using the free software ASM (Aquifer Simulation Model).

The ongoing work is focused on implementation of Geo Web Services dedicated to modeling. Since our system is based on interoperable data servers, “modeling server” is responsible for integrating information from the data servers and then carries out modeling processing. The interest of such an approach is to share, not only data but also software in a distributed manner.

1. INTRODUCTION

Like many Pacific coral islands, the Loyalty Islands archipelago (one of the three Provinces of New Caledonia) is missing fresh land water resources. Fresh groundwater (a water lens in this case) represents the only fresh water resource for these islands. The increase in population, the many development projects and the environmental cares of politics has led the Loyalty Islands Province (Province des Iles Loyauté - figure 1) to start an ambitious program (entitled SAGE) that aims at providing a decision support system for fresh water resource management based on interoperable geographical information.

Figure 1. *Loyalty Islands Province*

The main goal of the program SAGE is

- to understand fresh groundwater circulation mechanisms,
- to model human related pollution risks on the Loyalty Islands, New Caledonia, by merging data issued from different domains (hydrogeology, geography, sociology)
- to integrate this modeling into an Information system.

This project provides decision support as well as environment protection and country planning prearrangement tools to environment and rural development departments of Loyalty Islands Province.

Initial work by the geoscience researcher (geology, hydrogeology, pedology) in the SAGE program produced the following results on which the approach related in this article is based on:

- Underground run-off understanding from hydrogeological parameters known by bibliography;
- Risks map concerning fresh water lens pollution and decision support system for country planning.

These two constituents lay the foundation of a tool for decision support system as far as the environmental management of the Loyalty's fresh water lens is concerned. As regards pollution sources, the modelling discussed in this article is generic enough to incorporate others hazards and to visualize their impact as long as the system database contains the information.

2. INFORMATION SYSTEM

The SAGE system is an information system using an architecture that conforms to the OGC standards. The necessity of offering the information on the internet is due to the configuration of these islands. Their low population as well as their spaced out distribution limit the technical competence in each of those islands. The trained staff is in the main island (Lifou) but must be able to make updates in the field and see the result from any place they are.

Geographic Information Systems (GIS) definitively tends to distributed and interoperable architecture sometimes called "online" GIS (Leprince et al., 2003) or (geo)services network (Badard et al., 2003). They are so-called when non-architecture dependant operations, known as services or geoservices (if they concern geographic information) are the base to build an information system. The interest in such approaches is

- the information distribution and diffusion to different actor communities (managers, technical departments, private and public sectors),
- the greatest access to data between producer and user,
- the increase in data and their diversification as well as costs reduction.

In order to propose a standard interface for information sharing and for promoting remote and heterogeneous data mediation, the SAGE system has adopted Open Geospatial Consortium (OGC) standards. There are already many different pieces of open-source software that implement OpenGIS server standards: Mapserver implements WMS, GeoServer implements WMS and [WFS-T], PostGIS implements [SFSQL], [DeeGree] implements WMS and WFS, and so on. The

SAGE system is the application which will bring data sources to the desktop, and integrate them with local data sources for standard business processes — data viewing, data editing, and data printing.

3. FRESH GROUNDWATER CIRCULATION MODELLING

This section describes hydrological modelling leading to groundwater path calculation. SAGE system makes the most of these paths by using a "map" divided up into meshes; each mesh owns "movement speed" and "movement direction" attributes. These attributes allow, to completion, a dynamic movement and potential pollutant concentration calculation.

The necessary inputs for the modelling are built from a GIS, the "movement attributes" is retrieved from an hydrological-dedicated soft. Using these inputs the information system can compute dynamic pollution risks. Groundwater paths slowly evolve in time and the hydrological model input data are considered as reliable.

The hydrological principle on which the two modelling presented here rely is first explained before the data description and proposed methodology for path calculation.

3.1 Data

Data was collected via geological studies in the field and moreover by satellite and remote sensing products. So exokarsts (visible fracture in karstic soils) and fractures of which locations were detected by RADARSAT and SPOT 4 image processing are taken into account to estimate the soil geological properties using porosity and permeability calculation.

It should be noted the data sets are stored inside databases potentially and remotely plugged into the GIS. An update or a refining of these ones effortlessly allow to also update the modelling.

3.2 Fresh groundwater path computation

To represent spatially geological data at this stage we must have introduced the notion of mesh, unit spatial element in which geological properties (permeability, porosity, etc) are homogeneous. So each island gets a georeferenced grid in function of spatial data granularity and technical capabilities of the hydro geological model used.

Speed and circulation direction computation inside each mesh is entrusted with an hydrological model (we have decided on an free software: "Aquifer Simulation Model" (ASM) (Kinzelbach, 2003)). Actually we does not aim to develop another hydrological model but to feed our system with the results of ASM.

As a result modeling provides for each mesh a underground water propagation speed and direction. These two parameters allow computing the movements of water dropped in any place on Maré or Lifou island. These paths can then be evaluated and plotted directly on a map (Figure 2).

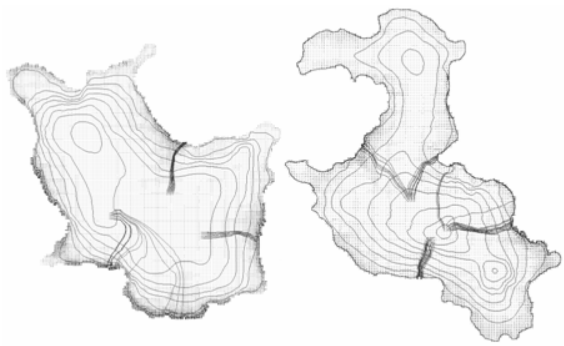

Figure 2. *Underground water paths shown by shading related to elevation contours for Lifou (right) and Mare (left) islands*

4. MODELLING POLLUTION RISKS

The main benefit of integrating a fresh water circulation model to an Information System consists in the quantification of the spatiotemporal pollution risks. In the Loyalty Island's specific case, the environmental hazard is defined as the frequency and the intensity with which any source of pollution may reach the ground water. We will specifically pay attention to pollution coming from human activities such as wastewater, agriculture or uncontrolled dump site. Risk appears when resource vulnerability meets with environmental hazards. The main risks known in the Loyalty Islands are the drilling pollution risk (water pumping pollution), and/or environmental pollution (essentially lagoon pollution).

4.1. Pollution quantification and diffusion model

Quantifying pollution is not a simple task because the pollution sources vary and there are numerous kinds of pollutants. In order to measure pollution across a wide area, such as an island, it is necessary to list the pollutants released from each source. This can be problematic when wastes are made up of complex constituents. Illegal garbage dump analysis provides a useful approach to record waste volumes and compositions. In these conditions, we can consider that there are as many particular cases as garbage dumps. Also, pollutants are often express with very different units. The reasoning adopted for our study consisted in finding a pollution indicator in connection with the water intended for human consumption quality. According to this assumption, we had to find for each pollutant, listed or not, a tool that let us knows its danger level when it is ingesting through consumption water.

At this stage, in order to simplify pollutants emission temporal management, we will use the followings assumptions.

Assumption A. Pollutant quantity is constant and continuous emitted.

Assumption B. Pollution spatial distribution is Gaussian centred on the pollution centre of mass.

Assumption C. Pollution associated with an environmental hazard is p % contained in the associated area. So it leaks from this area 1-p % of this pollution.

Under these assumptions, we consider that within the i^{th} considered area (S_i) associated with the i^{th} pollution source (a garbage dump for example) maximum volume pollution is at this area centre of mass called $P_i=(x_i, y_i)$ and that pollution diffusion around point P_i is done within the plane (X, Y) according to two dimensions Gaussian with variance covariance matrix like in equation 1.

$$\Sigma_i = \begin{bmatrix} \sigma_X^2 & \sigma_{XY}^2 \\ \sigma_{YX}^2 & \sigma_Y^2 \end{bmatrix} \text{ (equation 1)}$$

This matrix allowed, in particular, determining the suitable ellipsoidal form for the considered area.

Pollution diffusion into the ground (Z axis) is considered homogeneous. Pedological and geological parameters have not been taken into account for modelling and it has been assumed that:

Assumption D. Pollutant flow time between the surface of the ground and the fresh water ground is insignificant wherever you are on the island.

The formula used to model the pollution related to anthropic effects is represented below (equation 2).

$$z = Ce^{-\frac{a}{2}(P\text{-}P_i)'\Sigma_i^{-1}(P\text{-}P_i)} \text{ (equation 2)}$$

Where z = source pollution global risk for each point $P=(x,y)$ in the plane; C = a coefficient proportional to pollutant danger; a = coefficient such as *(1-p)* % pollution is confine to S_i area; $P_i=(x_i, y_i)$ is the i source surface centre.

By extension, point *(x, y)* pollution global risk (Z_{total}) correspond to each pollution source caused risks sum

$$z_{total} = \sum_{i=1}^{n} z_i \text{ (equation 3)}$$

Cartographic representations are established from a 100m on side mesh. Thus, risk maximum resolution is about one hectare. Mesh size is chosen in order to chart the studied phenomenon. It is assumed that within each mesh, pollution quantity is plane (*X, Y*) homogeneous.

If we consider a unique pollution source, the pollution emitted disperses as follow in plane (*X, Y*):

4.2. Pollution spatial and temporal transfer

Knowing preferential fresh ground water displacement model also allow predicting the pollutants preferred directions once they are in contact with the confined fresh groundwater. From this perspective, maps presented previously build up a transitional step for the pollution risks model's phase. Once these maps established, they were combined with the water circulation model.

As it is not possible to chart modelling dynamic aspect on a unique map, we made a pollution displacement's inventory of fixtures for different times t (t0, t1, t2, …, tn).

The fresh ground water circulation model, shows the way pollutants infiltrate in the underground water and to determinate which area may be subjected to those pollutants (downstream from pollutants dumping). Speeds and concentrations mesh by mesh are also obtained with a circulation's simulation of all the identified pollutants.

Used dynamically, it is possible to observe pollutions spread and to quantify sources' risks as far as the lagoon. The next two cartographies particularly render an account of the quantitative aspect of the pollution dumping.

Thus, the Province of Loyalty Island Environment Department have a system that allow evaluating the most worrying elements related to populations' health and environment (lagoon pollution).

Others prospecting scenarios can also be evaluated with the same principle, like moving garbage dump to a less dangerous area for sanity risks. Finally, if an important pollution rate is detected on a determined area (drilling water, lagoon resurgence…) this tool also include possibility to go back up to the most likely source by displaying the estimated way the pollutant took.

5. CONCLUSION AND PERSPECTIVES

The Information System now offers a wide possibility range to cross information. By making geographic data sharing effective, users requests progressively evolved towards the provision of services adapted to their use rather than simple data access. Geographic information, up to now reserved to specialized services, finds thus its real users.

Coupling modelling/GIS offers a new dimension, richer as far as analysis is concerned but also sensitive to data quality and variables used in models coherence.

A first research axis, further to works presented in this article, concerns space management within modelling. The proposed approach is based on a mesh but it can be interesting to consider spatial entities (paths, structure linked with habitat, hydrographic network, etc.). It should then be relevant to evaluate paths in relation with those entities eventually considered as sensible while currently all meshes are of the same nature. A paths hierarchical system could then be proposed, according to their estimated danger, which should help the user in his decision.

Finally, geoservices approach general implementation should consist on dedicate modelling, all the more so as there are many modelling algorithms, on a specific server (that could be called *Web Model Server*) queried by the application program when a request needs the modelling procedure services. Modelling server is responsible for integrating information from the data servers and then carries out modeling processing.. This solution's main difficulty lies in the communication protocol between application program and modelling server, and in input/output specifications that should seriously be studied.

The interest of such an approach is to share, not only data but also software in a distributed manner.

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