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Maps of vulnerability to pollution: a useful tool for sustainable groundwater in Douala, Cameroon

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This study is a help approach to protect and prevent pollution of the unconfined aquifer of Douala sedimentary basin. It was conducted in order to identify areas at high risk of contamination and protect them in the long-term. Maps were validated based on field measurements. The assessment was conducted using DRASTIC and GOD methods. Statistical analysis of the maps of vulnerability reveals the concentration of three classes. These methods show on the one hand that the study area has a high risk of contamination and in the other hand that DRASTIC best reflects the reality of the groundwater pollution.
Finally maps of vulnerability permit to stakeholders to adopt two decisions: protect this unconfined aquifer needed by 57 % of the population for water supply by deleting pit latrines inside a radius of 50 m from a well and; use water of boreholes for human consumption.

Introduction

Pollution is a permanent risk of limitation of groundwater resources. Increasing urbanization and economic development contribute to the quantitative and qualitative degradation of groundwater. Thus, the cartography of environmental vulnerability of groundwater to pollution was considered as an effective tool to limit and control the risks of deterioration of water resources. From the data obtained on wells and soil properties, one applied DRASTIC and GOD methods to determine the spatial vulnerability to pollution of the shallow aquifer of the Besseke watershed (industrial zone of Bonabéri) situated in the sedimentary basin of Douala (Cameroon).

The general objective of this study whose was to characterize the aquifer system in order to mitigate its pollution and improve its quality over the long term was the basis of the common reflection of the Douala 4th city council for deleting pit latrines inside a radius of 50 m from a well and implement boreholes in low vulnerability zones to pollution for water consumption.

Methods and data

Presentation of DRASTIC and GOD methods

The DRASTIC method was developed by the Environmental Protection Agency (EPA) in United State of America in 1985 (Aller and *al.,* 1987) to estimate the potential for groundwater pollution (Schnebelen and *al.,* 2002). It assesses the vertical vulnerability based on seven criteria: **D**epth to groundwater; **R**echarge; **A**quifer media; **S**oil media; **T**opography; **I**mpact of the vadose zone and **C**onductivity. Each parameter has a fixed weight [D(5) R(4), A(3), S(2), T(1), I(5) and C(3)] and notes ranging from 1 and 10 depending on the type of aquifer, geology and topography of the study area. The pollution index varies between 23 (for very low vulnerability zones) and 226 (for very high vulnerability zones) and is calculated using equation below (1).

$$DPI = r_D N_D + r_R N_R + r_A N_A + r_S N_S + r_T N_T + r_I N_I + r_C N_C \quad (1)$$

Where: r is the weight (1 to 5) and N (1 to 10), the corresponding note to each parameter and DPI, the DRASTIC Potential Index.

The GOD method is a system that was developed in 1987 by Foster. It shows the vulnerability of the aquifer due to vertical percolation of contaminants through the unsaturated zone and does not cover the lateral migration of contaminants in the saturated zone. This method is based on identifying three criteria: **G**roundwater occurrence; **O**verall aquifer class and **D**epth to groundwater table. Its pollution index that assesses the aquifer vulnerability to pollution is obtained by multiplying these three parameters. The cartography of environmental vulnerability to pollution of aquifers by this method is done by using equation below (2) (Murat and *al.*, 2003).

$$GI = G \times O \times D (2)$$

Where G is the type of aquifer, O, the lithology of the unsaturated zone, D, the piezometric head of the aquifer and GI, the GOD index.

This index has a minimum value of "0" and "1" is the maximum value. In general, these indexes are divided into five classes ranging from "very low" to "extreme" vulnerability. The notes for each parameter also vary between 0 and 1.

The DRASTIC and GOD models were applied using a Geographic Information System (GIS) in which a relational database was created. This procedure allowed to obtain rasters for each parameter of vulnerability.

The different phases to elaborate vulnerability maps through GIS are described as follows:

- Data collection and creation of database in MapInfo 8.5 from digitizing the topographic map;
- Create a database in Excel for descriptive data to develop analytical and thematic maps. Such data must be in raster to facilitate their manipulation in a GIS. This data base requires use of several software like ArcGIS 9.3, MapInfo 8.5 and Surfer 8.0;
- Score calculation and allocation of weighted notes;
- Converting shapefiles into GRID: With the extension "Spatial Analyst" in ArcGIS 9.3, shapefiles of each parameters are converted into GRID of 1 meter x 1 meter. The interpolation method to "raster" chosen is the "ordinary kriging" with a semi-variogram model named "spherical type". Each "raster" file is then reclassified by assigning to each class the corresponding notes;
- Calculating the vulnerability index, classification and development of the vulnerability map: with the tool "raster calculator" of "spatial analyst" extension in ArcGIS 9.3, the formula for calculating DRASTIC and GOD index is applied by combining "reclassified under GRID raster formats". Based on ratings assigned to each parameter, the maximum and minimum index is recalculated in Excel. According to the classification made by the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) in 1995, the calculation of proportions of vulnerability class is evaluated as in the equation below (3).

$$index(\%) = 100 \times [D_i - \min] / \max - \min (3)$$

Where Di is the vulnerability index calculated by recombination of GRID files, Min and max, the minimum and maximum of the index recalculated in Excel.

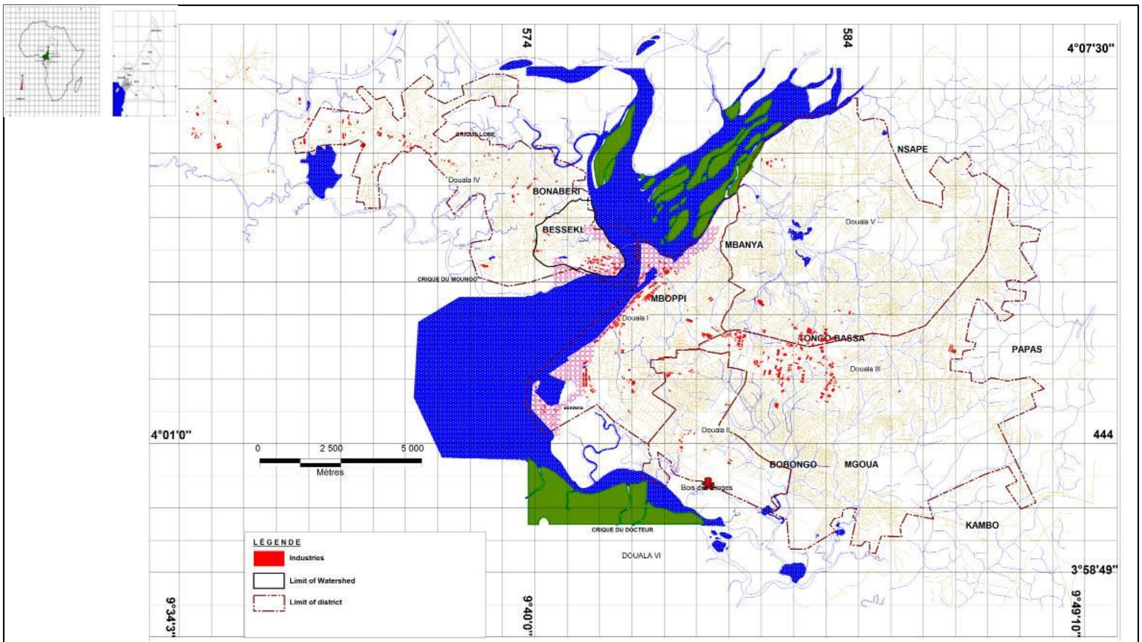

Figure 1. Geographical location of the watershed of Besseke in Douala (Cameroon)

Data collection

- The depth of water table (D) was measured in 115 wells selected and spatially distributed in the study area in 2010, by means of a sound and electric probe. The unit of water table is in meter.
- According to Feumba and *al.* (2011), the main factor of supplying aquifer in the study area is rainfalls. Rainfalls data collected from the Regional Directorate of Meteorology of Douala on 37 years were used for the calculation of the net recharge (R). The estimated annual recharge was done using equations of Williams and Kissel in Jha and Sebastian (2005) below (3, 4 and 5).

$PI = [(P - 15.05)^2 / P + 22.57]$ (3) for dry sandy loam clay soils and sandy loam;

$PI = [(P - 19.53)^2 / P + 29.29]$ (4) for loam and clay loam soils;

$PI = [(P - 22.67)^2 / P + 34.00]$ (5) for wet clay soils and silty soils;

Where PI is the index of percolation and P the total annual of rainfall.

The different terms (proportion in % evaporation and runoff) of water balance was estimated by the Thornthwaite (1948) method. These proportions have allowed the calculation of the net recharge using water balance equation below (6).

$I = P - (E + R)$ (6)

Where I is the infiltration, P total rainfall, E and R actual evapotranspiration and runoff respectively.

The aquifer media (A) was determined by directs observation of soil samples in saturated zones of representative wells of the study area. The grain size curve of these samples was used to determine the texture of the saturated zone.

- The soil map (S) realized permits to identify soil types of the study area. The triangular diagram textures of Food Agriculture Organization were used to determine different type of soil.
- The topographic map at scale of 1/5 000 (sheet 10 of Douala, drawn in 1963-1964 by the National Geographic Institute in Paris) was obtained at the National Institute of Cartography of Yaoundé in Cameroon. This map allowed the calculation of different slopes (T) as a percentage of the study area.
- Curves of the grain size analysis of the unsaturated zone (I and O for DRASTIC and GOD method respectively) were used to determine the textural composition. In addition, direct observations of lithological logs of wells permitted to determine the net texture of the unsaturated or vadose zone.
- The hydraulic conductivity (C) is approximated according to Hazen formula [$k=100*(D_{10})^2$ where **k** is the hydraulic conductivity in m/s and D_{10} in meter, the effective diameter of solid particles at 10% in the grain size curve]. Based on abacus of Banton and Bangoy (1997) and assuming a hydraulic gradient (i) of 1, effective porosity (n_{eff}) was determined. Using these values, one calculates the effective rate of fluid particles (V_{eff} in m/s) of the saturated zone according to the formula of Darcy law: [$V_{eff}=k*i/n_{eff}$]
- For GOD method, only the parameter G has been assessed differently. This study is focused on the unconfined aquifers and according to GOD method, the scores of this parameter vary between 0.7 and 1. Four classes (0.7, 0.8, 0.9 and 1) for this type of aquifer were defined on the basis of the thickness of the unsaturated zone because if unsaturated zone is thicker, pollutant takes time to reach the aquifer. The note "1" is given to the less thicker and "0.7" to the more thicker;

The superposition of seven/three rasters provides respectively the map of DRASTIC and GOD index that takes place on the basis of a linear combination of the different values for each polygon in the attribute table of the mesh and applying MAPAQ (1995) classification, different classes of vulnerability are defined and maps of vulnerability are obtained.

Control and validation of vulnerability maps

After obtaining a map of vulnerability, the reliability of the results can be estimated by sensitivity analysis or validation with field measurements. For this study, validation was tested by field measurements. Indeed, several authors such as Mohamed (2001); Jourda and *al.* (2006); Hamza and *al.* (2007) and Kouame (2007) checked the validity of vulnerability assessment methods to pollution based on chemical data of groundwater. The validity of the assessment of vulnerability to pollution by these methods for this study was tested by the number of coliforms (FC) and faecal streptococci (FS) in 22 water samples in 4.36 km². This activity was carried out by a comparison between the distribution of FC and FS in the Besseke aquifer and the distribution of vulnerability classes.

Results and discussion

Results

DRASTIC method best reflects the reality of the groundwater pollution. The map obtained has defined five classes of vulnerability (figure 2). DPI varies between 115 and 164. According to this figure, the feature that emerges from the study area is the lack of correlation between the topographic profile and vulnerability where in principle, limits of watershed which normally represented by high elevation should be less vulnerable than the central parts of the basin occupied by plains. However, according to Nguendo and *al.* (2008), the most vulnerable areas are located along rivers and in areas where sanitation systems are very poor.

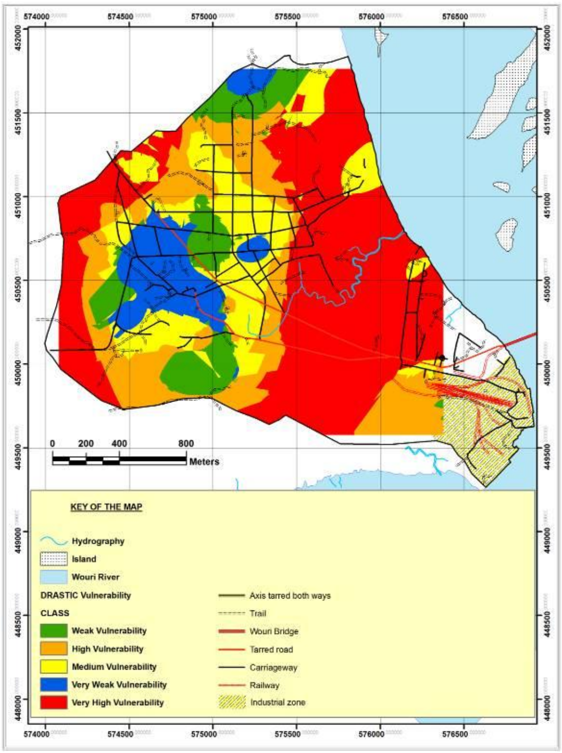

Figure 2. Map of vulnerability to pollution by the DRASTIC method

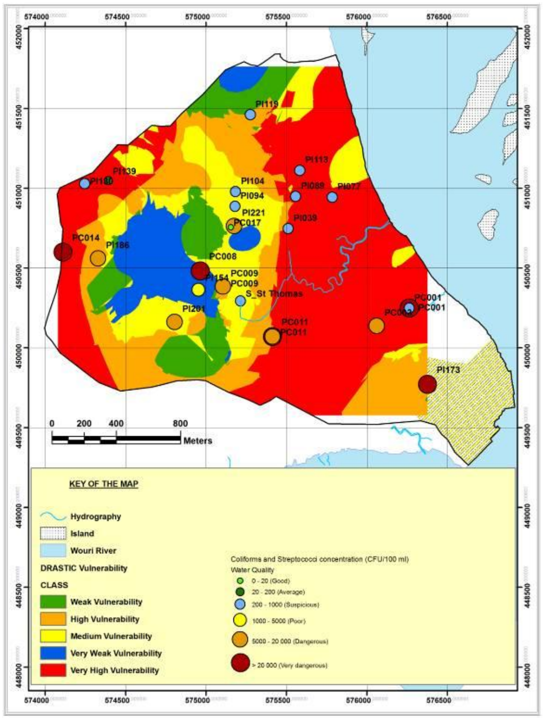

Figure 3. Map of vulnerability and risk zone according to spatial distribution of coliforms and faecal streptococci

Discussion of the data obtained on the vulnerability maps

In North Pas-de-Calais (France), DPI> 125 (BRGM/RP, 2005). It is 102 for the aquifer of Sra Maashrichtien Ouertane in Tunisia (Bahri and *al.,* 2007), and for groundwater of Jerash in Jordan, DPI> 160 (Hammouri and EL-Naqa, 2008). It is between 75 and 193 for Meskiana aquifer (East Algeria, Gouaidia and *al.,* 2011). In the Besseke watershed, DPI>135 for zone with high vulnerability.

This disparity of index may be related to notes assigned to various parameters (Murat, 2000). Limitations of different classes are not absolute values, but relative values (Jourda and al., 2006). These limits can then vary from one study to another and from one region to another. In all cases, these methods of intrinsic vulnerability can be a good idea to sensitive zone in order to forecast necessary protection for vulnerable area. However, vulnerability to pollution increases with the index. This is explained by the fact that in each study, a parameter may be more important than the other depending on climatic and geological conditions of the study area. In Besseke watershed, parameters which have considerable weight are "Depth", "Impact of the vadose zone", "Topography" and "Soil". In addition, 40% of study area are flooded-zones and, the quantity of rainfall is high (3 600 mm/year). Finally, ¾ of the mapped area has a "high vulnerability".

Validation of maps of vulnerability to pollution and study of the contamination risk of the aquifer

Map of vulnerability for this study has been tested and validated by bacteriological analyses of groundwater. The classification used for FC and FS was done according to Ngnikam and *al.* (2011). By overlaying results of the bacteriological analysis of monitored wells to the map of vulnerability obtained by the DRASTIC method, risk zones of the watershed of Besseke were defined. Figure 3 (see above) shows the distribution of pathogens in Besseke aquifer and risk zones according to spatial distribution of FC and FS in the aquifer. In view of the Figure 3, we note that:

- One well (PC017) has a good water quality and is in the class of "very low" vulnerability. Nevertheless, well PC008 and PI154 located in zone of very low vulnerability have a high number of FC and FS. This is due to the unplanned occupation of land by pit latrines within a radius less than 50 metres from the well. In addition, porosity and hydraulic conductivity of the vadose zone control infiltration of pollutants;
- 70% of wells analyzed have a very poor and suspicious water quality. All these wells are located in the classes from "moderate" (24%) to very high (46%) vulnerability;
- This aquifer has a risk of pollution that extends downstream to upstream with the exception of NNW and centre zones;
- Moderate and high risk of contamination represents 22.62% and 77.38% respectively from pollution by FC and FS;
- Monitored wells located inside the very low vulnerability area and which have a critical bacteriological quality are surrounded by a lot a pit latrine inside a radius less than 50 m.

It is therefore necessary to stakeholders to apply important decisions in order to protect and manage groundwater in the long terms and finally, preserve health of the population.

Conclusion

In this study, the unconfined aquifer of the watershed of Besseke (industrial zone of Bonabéri-Douala, Cameroon), available through wells with a maximum depth of 10 meters was studied. To this end, the combination of the model DRASTIC-GOD/SIG allows showing maps which essentially reflect the reality of the aquifer. By cons, no correlation was observed between the topographic profile and maps of vulnerability.

From the hydrogeological data and maps of vulnerability, three major proposals have emerged: implementation of protection areas around wells, respect of technical standards to drill a wells (for instance, a thickness of two meters of unsaturated sandy or loamy soil under a latrine is able to effectively stop groundwater pollution, and magnitude of the lateral pollution will be limited. Moreover, when the aquifer is shallow, a sand barrier placed around pit latrine can prevent pollution) and proposal of latrines adapted to flooded and non-flooded zones.

At the end of this study, we recommended with help of stakeholders of the Douala 4^{th} City Council through MAFADY project, to develop an urban plan area and respect distance calculated between a sanitation facilities and a well; avoid achieve deep latrines (maximum 2 m of depth) and build waterproof latrines in flooded-area; keep a distance between well and pit latrines as to ensure a circulation time of groundwater for at least 50 days, which represents a distance of 50 m; sensitize households do not reject wastewater inside latrines.

In order to preserve in the long term water resources and health of population, four boreholes in low vulnerability zones are used for water supply by populations.

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Notes/s

MAFADY means "Maîtrise de la Filière Assainissement dans la zone côtière de Douala et les quartiers spontanés de Yaoundé au Cameroun". Research project supported by the SPLASH program.

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