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ASSESSMENT OF GROUNDWATER EFFECTIVE VULNERABILITY TO POLLUTION THE CASE OF THE LOBO WATERSHED BUYO, SOUTH WEST OF COTE D'IVOIRE

EVALUATION DE LA VULNERABILITE EFFECTIVE A LA POLLUTION DES EAUX SOUTERRAINES EN MILIEU DE SOCLE : CAS DU BASSIN VERSANT DE LA LOBO BUYO, SUD-OUEST DE LA COTE D'IVOIRE

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ABSTRACT

Rapid and uncontrolled urbanization as well as agricultural activities constitute real threats to groundwater which represents one of the most important natural resources for the supply of drinking water, especially in developing countries. The objective of this study is to assess the risk of pollution of these resources. The method consisted of integrating the intrinsic vulnerability map with that of the pollution indices produced from the pollutants. These pollutants considered as those which threaten the quality of groundwater in the area have been determined using the method of Principal Component Analysis (PCA). The results obtained present an intrinsic vulnerability map dominated by the medium intrinsic vulnerability class. The statistical tests made it possible to identify the land use pattern and the nitrates which were combined to produce the pollution index map. The result of the combination of these two maps shows that the study area remains dominated by the average effective vulnerability class. However, the effective high vulnerability class which shows the areas most threatened by pollution is more observed in the South with a few low occurrences in the North.

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Keywords: Groundwater; anthropic activities; intrinsic vulnerability; effective vulnerability; pollution indices

RESUME

L'urbanisation rapide et incontrôlée ainsi que les activités agricoles constituent des réelles menaces pour les eaux souterraines qui représentent l'une des ressources naturelles les plus importantes pour l'approvisionnement en eau potable surtout dans les pays en voie de développement. L'objectif de cette étude est d'évaluer le risque de pollution de ces ressources. La méthode a consisté intégrer la carte de vulnérabilité intrinsèque avec celle des indices de pollution élaborée à partir des polluants. Ces polluants considérés comme ceux qui menacent la qualité des eaux souterraines dans la zone ont déterminés à partir de la méthode d'Analyse en Composante Principale (ACP). Les résultats obtenus présentent une carte de vulnérabilité intrinsèque dominée par la classe de vulnérabilité intrinsèque moyenne. Les tests statistiques ont permis d'identifier le mode d'occupation des sols et les nitrates qui ont été combinés pour la réalisation de la carte des indices de pollution. Le résultat de la combinaison de ces deux cartes montre que la zone d'étude reste dominée par la classe de vulnérabilité effective moyenne. Cependant, la classe de forte vulnérabilité effective qui montre les zones les plus menacées par la pollution est plus observée dans le Sud avec quelques faibles présences dans le Nord.

Mots clés : Eau souterraine ; activités anthropiques ; vulnérabilité intrinsèque ; vulnérabilité effective ; indice de pollution

INTRODUCTION

Nowdays, groundwater resources play an important role in satisfaction of water supply demands due to climate change and the scarcity or inadequacy of surface water sources. However, pollution of these groundwaters has become a major problem because it remains susceptible to contamination from land-surface activities and other anthropogenic impacts (Thirumalaivasan et al., 2003). There are several types of pollutants that seem to predominate in groundwater, such as heavy metals, nutrients, pesticides and other organic chemicals and fertilizers. Several studies on the quality of groundwater resources have highlighted the surface origin of most of these pollutants and sometimes the type of water (Gelinas et al., 1996; Eblin et al., 2014). These pollutants are leached through the unsaturated zone to the saturated zone resulting in the contamination of these zones and their exposure to very high health risks. (Kouadio, 2019). Controlling this pollution requires estimating vulnerability to pollution, which is considered an intrinsic property of groundwater. Aquifer vulnerability assessments are carried out in areas where water resources are subject to constraints due to anthropogenic activities (Haouchine et al., 2015). Therefore, risk studies can provide valuable information for parties working to prevent environmental degradation (Mendoza and Barmen, 2006). In addition, such studies are useful for assessing the economic impacts of waste disposal in highly vulnerable areas. In addition, they provide preliminary information and decision criteria in areas such as monitoring land use patterns, delineation of monitoring networks and water resource management in the context of regional planning (Collin, 1990). Thus, vulnerability to pollution is presented as one of the best ways to control pollution (Kamenan et al., 2020).

Several approaches have been developed for assessing the vulnerability of aquifers. These are the DRASTIC (Aller et al 1987), GOD (Foster 1987), AVI (Van Stempvoort et al., 1993) and SINTACS (Civita., 1994) methods. These methods have mainly been applied to the protection of groundwater in porous aquifers. They are able to distinguish the degrees of vulnerability at regional scales where different lithologies exist (Vias et al., 2005). Regarding the DRASTIC method, it has already been applied in several regions by different researchers (Baalousha, 2006; Jamrah et al., 2007). For a better adaptation of this method to environmental conditions, we have integrated different parameters such as the land cover index, lineaments, the thickness of aquifers and the impact of contaminants (Mendoza and Barmen, 2006; Wang et al., 2007). The

integration of contaminants in the study of vulnerability to pollution has been shown by the work of Srinivasamoorthy et al. (2009) who, from statistical studies, identified the pollutants that are the most threatening to justify the presence of the observed threatened areas. However, taking these pollutants into account as factors in determining areas of effective vulnerability remains ignored. The aim of this study is to assess the vulnerability effective to pollution of aquifers from parameters likely to influence the transit of groundwater.

PRESENTATION OF THE STUDY AREA

The study was carried out on the catchment area of the Lobo river (Figure 1), one of the sub-basins of the Sassandra river, located between latitudes 6 ° 18'N and 6 ° 37'N and longitudes 6 ° 85'W and 7 ° 02'W. It took into account the town of Buyo and two villages Gbili and Logbozoa and camps. The Buyo sub-prefecture is located in the west of the Ivory Coast between latitudes 6 ° 10'N and 7 ° N and longitudes 7 ° 30'W and 6 ° 50'W. It is located to the north of the Soubré department, and is bounded by the sub-prefectures of Guiglo, Taï and Duekoué to the west, Issia to the north, Grand-Zattry to the east and Méadji to the south.

These localities were chosen taking into account the activities that take place there, the population density and the available drinking water supply points. The town of Buyo is located on a site with a relief of plateaus whose slopes are gentle, but with the presence of many lowlands and rivers

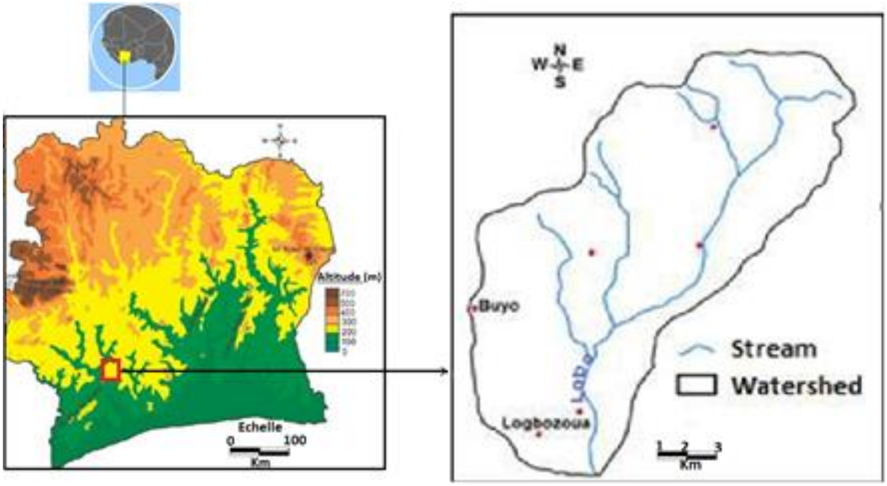

Figure 1: Study area representing the watershed of Lobo

MATERIAL

The material used consists of field material such as the piezometric probe, the multi-parameter probe for the *in-situ* determination of physical parameters, flasks for taking samples of groundwater for chemical analyzes in the laboratory. In addition to field material, we have hydroclimatic data for the assessment of recharge, data from wells and boreholes as well as cartographic data and images Landsat ETM+. This material also consists of software such as ArcGIS for processing images and cartography and Statistica for statistical processing.

METHODS

Intrinsic vulnerability

Intrinsic vulnerability combines several criteria that characterize the aquifer. These are seven criteria which are the depth of the water table, recharge, aquifer, soil type, topography, unsaturated zone and hydraulic conductivity. The production of the highly intrinsic factor map was made using the DRASTIC method. The depth of the water table represents the static levels which have been recorded in the field from the piezometric probe. The values obtained vary from 3.6 m to 20.9 m. The recharge corresponding to the infiltrated water layer remains uniform over the entire extent of the study area and equal to 200 mm. The type of aquifer is more based on its nature. Thus, it could vary greatly depending on the nature of the underlying rocks that are in our study area. They are schists and granitoids. For the purposes of this study, the soil type is represented by topsoil with constant thickness. The slopes were generated from the STRM images. In the Buyo region, they remain low, varying from 0 to 5%. The unsaturated zone represents the layer that is part of the surface to the edge of the water table. Its determination required the combination of two conditions which are the nature of this zone which is identical to the type of aquifer and its thickness. To determine the recharge, we are based on the piezometric method which allows this value to be determined from the variation in the water level. This method deduces the recharge from the responses of the water table to the requests.

It applies only to free water table and requires a good knowledge of the characteristics of the aquifer and of the piezometric variations of the aquifer over time. However, the traditionals wells used in the context of this study and whose depths generally do not exceed 20 m only capture free water tables. Also, the presence of preferential flow paths within the unsaturated zone does not in any way limit its application (Healy and Cook, 2002). Its use is based on a certain number of constraints (Healy and Cook, 2002): no perturbation by pumping, no significant delay effect during transit through the unsaturated zone in free water table. Based on these constraints, we considered that the water table therefore went from a level n_1 to a level n_2 after a time t observed during the same rainy season.

$$C = (n_1 - n_2)/t \quad (1)$$

With n_1: the value of the static level of the first campaign; n_2 = the value of the static level of the second campaign and t: the time which represents the three months.

Pollution indices factor

The pollution indices factor highlights the criteria that explain the pollution in the area. The statistical test of principal component analysis was adopted to identify possible pollutants that could strongly influence the quality of groundwater resources in the area. These statistical tests have already been used by Faye et al. (2020) and Amadou et al. (2014). for the determination of the mineralization in order to understand the mechanisms at the origin of groundwater pollution. The combination of land use and pollutants such as nitrate has already been adopted by Brink et al. (2008) to assess the threats to the quality of groundwater resources

The determination of land use is made from Landsat ETM+ satellite images from december 2015. Several processing methods will be applied to the image that has been pre- processed. With regard to the type of pollutant, the identification of the different parameters is carried out from the statistical test which identifies the parameter that influences the phenomenon of groundwater pollution in the area. The method adopted is Principal Component Analysis (PCA).

Elaboration of the effective pollution vulnerability map

The map of effective pollution risk areas was made from geographic information systems (GIS) and multicriteria analysis (MCA) by the combination of the various factors that are intrinsic vulnerability and pollution indices. The weighting coefficients were determined from the following formulas (Doumouya et al., 2012)

$$V_{pi} = \sqrt[n]{\prod_{i=1}^{n} N_i} \tag{2}$$

$$W_i = \frac{V_{pi}}{\sum_{i=1}^{n} V_{pi}} \tag{3}$$

with Vpi = Eigenvector of each factor; Ni = Value of each factor or criterion and Wi the weighting coefficient of each factor

On this basis, correlation matrices were developed for each factor to determine at the level of each cell the value of the intrinsic vulnerability factor (Vp) of the aquifer to pollution and of the pollution index factor (Ip) (Table 1). The combination of these two factors made it possible to determine the effective vulnerability to pollution (Vep):

$$V_{ep} = W_c V_p + W_r I_p \tag{4}$$

With Wc and Wr respectively the weighting coefficient of the intrinsic vulnerability factors and pollution indices

Table 1: Table of the weighting coefficients of the different factors

Criteria	Eigenvector (V)	Weighting Coefficient (W)
Intrinsic Vulnerability (Vp)	1,73	0,65
Pollution Indices (Ip)	1,24	0,35

From the values of these coefficients, Eq.(4) becomes:

$$V_{ep} = 0.65 V_p + 0.35 I_p \tag{5}$$

RESULTS AND DISCUSSION

Intrinsic vulnerability to pollution

The intrinsic pollution vulnerability map (Fig. 2) was developed using the DRASTIC method. The results have allowed to distinguish 3 vulnerability classes ranging from low vulnerability classes to the so-called strong class and which respectively cover 15%, 65% and 25%. Analysis of these results shows that the middle class, which remains the largest class, is found throughout the study area with the exception of a few pockets in the central area. This class is generally located in areas where the geological formations are schists. The high risk class remains limited to 2 small pockets in the South and is found in sectors where the water tables are at very low depths associated with layers of saprolites representing the unsaturated zone of generally granitic with often low thicknesses.

Pollution indices

Physico-chemical parameters influencing water quality

The pollution indices were developed from the criterion of land use and the pollutant most influencing the quality of groundwater in the area (Fig. 3). The different methods have produced important results. First, the statistical treatments made it possible, from the analysis of factorial designs, to identify nitrate as the parameter that most influences pollution.

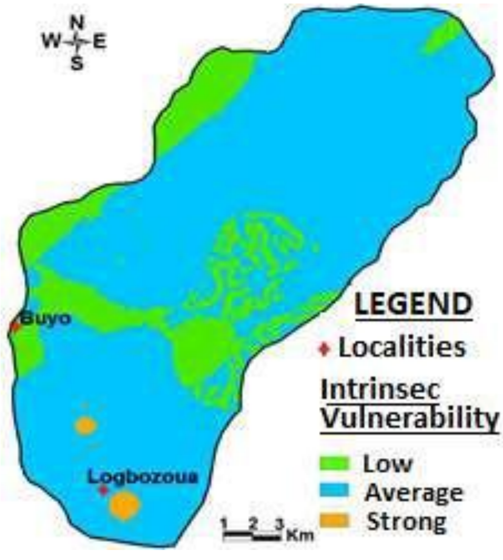

Figure 2: Map of Intrinsic Vulnerability

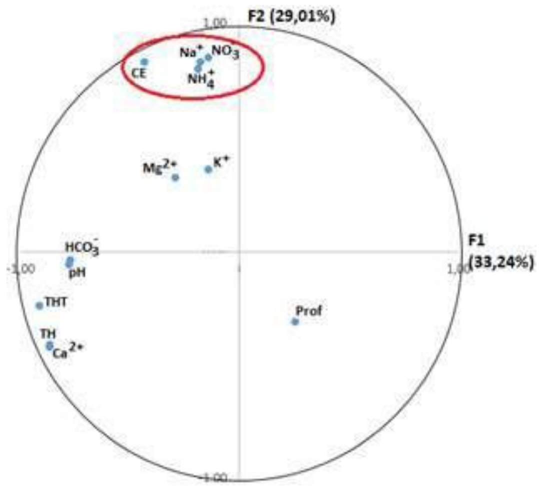

Figure 3: Principal component analysis of physico-chemical parameters

Principal component analysis shows a group formed by nitrate, ammonium and sodium at the positive end of axis 2 while the depth is located in the sensed direction of the same axis. The results of these statistical tests indicate that nitrates are positively correlated with ammonium, sodium and conductivity and negatively correlated with depth and could therefore influence the pollution of groundwater resources. They were therefore integrated to develop the pollution indices layer.

Among these parameters, the conductivity values in this zone remain largely lower than the WHO standards; this parameter will therefore not be taken into account. Only the three pollutants of nitrate, sodium and ammonium were combined to produce the pollutant layer.

Pollution indices map

The combination of the layer of pollutant and the land use map produced the pollution index map (Fig. 4). The analysis of this map shows the existence of 3 classes which are the low, medium and high classes covering respectively 25%, 60% and 15% of the study area. However, they are still dominated by the middle class, which occupies the entire study area, particularly the northern part of the zone. These zones are located in localities where nitrate levels remain low with a land use pattern consisting of fallow land and therefore less polluting. As regards the high vulnerability class, it is found more in the South where one generally finds bare soil, synonymous for the most part with human presence and therefore an increase in the frequency of human activities, as well as high nitrate levels indicating the existence of a source of pollution from surface sources.

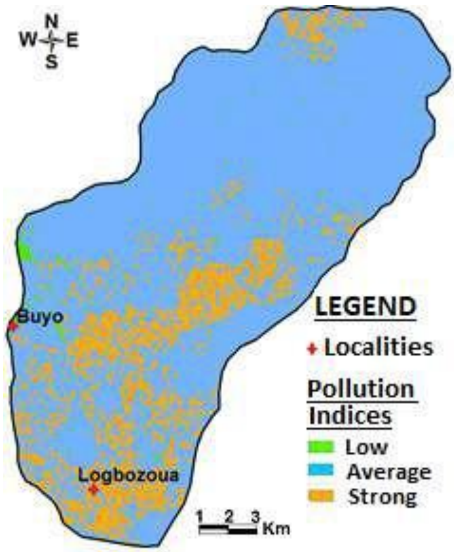

Figure 4: Map of Pollution Indices

Effective vulnerability to pollution

The effective pollution vulnerability map highlights the risk areas (Fig. 5). It is the result of a cross between the intrinsic vulnerability and pollution indices. The analysis reveals the existence of three classes: weak (20%), medium (65%) and strong (15%).

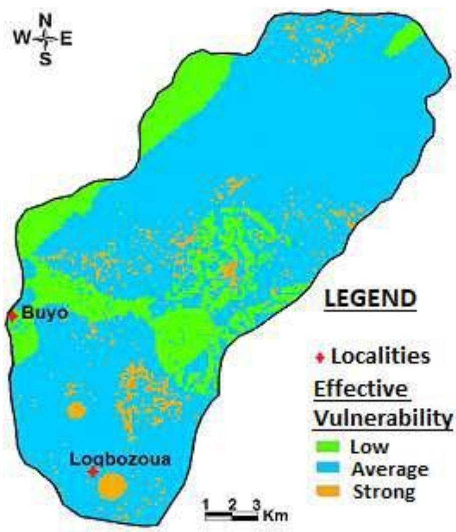

Figure 5: Map of Effective Vulnerability

The area remains dominated by the average class which globally covers the entire northern area with a weak presence in the southern part. As for the strong class of effective vulnerability to pollution, it is present in the southern part but in greater proportion with a very low presence in the northern end. This class is most often observed in transformed areas such as bare or inhabited soils, accompanied by strong anthropogenic activities such as agricultural and especially domestic operations, poor management of domestic wastewater due to almost non-existent or absent, especially in certain localities where there are uncontrolled discharges.

This map shows once again the impact of human activities on the quality of water resources in general and particularly groundwater resources.

DISCUSSION

The combination of GIS and MCA has produced important results. These results are enriched by the use of statistical tests to highlight the impact of the characteristics of the study area on the choice of factors to be included in the development of different factors. However, the correlation between nitrate, ammonium and sodium shows the surface origin of pollutants. According to Singh et al. (2005), the grouping formed by these parameters could be taken as proof of their mutual correlation. The negative correlation of nitrate and ammonium to depth parameters shows that these parameters are higher in shallow wells. This is consistent with observations made by Hudak (1999) in central Texas, USA and Liu et al (2005) in Alabama, USA who observed high conductivities and nitrate concentrations in shallow wells as in our study in addition, the works have ammonium concentrations above the WHO standard (0.5 mg / L). It could be due to improper handling buckets by the people. They are sometimes placed on the ground as noted by Gelinas et al. (1996). However, the wells of Buyo City present higher grades than those of other water points. This is undoubtedly to be put in line with the high population density observed in this district, the lack of sanitation and the lack of appropriate sanitation devices to protect groundwater. In terms of individual sanitation, the equipment corresponds in the great majority of cases to very poorly maintained latrines and sumps close to the water table (Chippaux et al., 2002). Thus, pollution of domestic origin is to be blamed around these water points. In general, the content of nitrogenous elements in the watershed is low. However, concentrations in some wells exceed WHO standards for drinking water. This is particularly the case of the wells in the city and more precisely of those of Buyo city. Indeed, this district is the most densely populated part of the basin, followed by the two villages Gbili and Logbozoa. Thus, the levels of nitrogenous elements, signs of contamination of anthropogenic origin (domestic pollution) of groundwater, are higher in areas with high population density

The assessment of effective vulnerability to pollution is one of the best approaches to determining the risk of groundwater pollution in the region. It is presented as a very important method for the prevention of pollution (Mangoua et al., 2018). It made it possible to map the areas which are effectively threatened by pollution based on factors presenting an intrinsic vulnerability and a pollution indices. Analysis of the results shows that the site remains dominated by the average effective vulnerability class. The classes of strong effective vulnerability to pollution which constitute the most threatened are found in areas where the intrinsic vulnerability to pollution remains very high, as has been indicated from several studies on the vulnerability to groundwater pollution (Dibi et al., 2015). These are mainly areas where the depths of the water tables are shallow accompanied by layers of saprolites of a granitic nature with often medium to low thicknesses. This could be explained by the fact that upon weathering, granites give layers generally poor in clay and therefore more permeable (Lachassaagne et al, 2015). Also, there is a link between the intrinsic vulnerability and the pollution indices which result in the superposition between the different classes as indicated by the different validation results of the pollution vulnerability maps. Note that the hydrogeological parameters which constitute the intrinsic parameters of the aquifer strongly influence the presence of nitrates (Shih-Kai et al., 2013). The classes of high effective sensitivity to pollution observed in areas impacted by pollution indices are found where inhabited areas coexist and areas with intense anthropogenic activities, especially at the edge of watercourses. The type of pollution in these localities is most often of superficial origin, as is the case with nitrates.

This observation could be justified by the presence of high levels of nitrates in groundwater testifying to surface pollution linked to significant human activities. The integration of the land use map into the assessment of vulnerability to groundwater pollution has already been done through several studies (Worralla and Kolpin, 2004). The impact of land cover on the increase in nitrate levels has been further shown in the work of Zhang and Hiscock (2011). This work indicated that depending on the different activities carried out on the surface, the nitrate contents vary. The combined use of the DRASTIC method associated with land use and quality parameters such as nitrate, in the case of our study, to assess the potential risk of groundwater pollution has already been adopted by Lima et al. (2011).

CONCLUSIONS

At the end of this study which objective is to assess the risk of effective pollution of groundwater in the Lobo watershed, important results have been obtained. It first allowed, from statistical tests, to determine the parameters that most influence the pollution of these resources, namely nitrate, ammonium and sodium. These parameters are used to create pollutant layer. However, nitrate remains the most important pollutant. The combination of the map of pollutant layer and that of the land use pattern in the GIS made it possible to map the pollution indices. The location on the land-use map of the high nitrate content reflects its surface origin. The intrinsic vulnerability map produced remains dominated by the medium vulnerability class. The results from the combination of the pollution index map and the intrinsic vulnerability map led to the identification of risk areas. These are the zones where the low efficiency of pollution remains high. These classes are found in localities where the water tables are shallow with saprolites of low thickness and generally of granitic nature. In addition to this, there is the presence of bare soil, which is a symbol of human presence. In these areas, high nitrate levels often reach 70 mg/L.

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