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Contamination Risk Evaluation of Groundwater in the Canton of Portoviejo-Ecuador, using Susceptibility Index and two Intrinsic Vulnerability Models

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Abstract: The present study aims to investigate the applicability of DRASTIC, GOD and SI models in evaluating the groundwater vulnerability and risk of contamination in the Canton of Portoviejo, Ecuador. The groundwater vulnerability to contamination has been evaluated using DRASTIC and GOD models. Both models were able to classify the study area into different sectors of variable vulnerability. The coincidence of the two models is high, especially in the sectors with high vulnerability. Evaluation of the groundwater risk of contamination has been carried out by combining the contaminant load index with the elaborated groundwater vulnerability classes using DRASTIC and GOD methodologies. The resultant maps of both models reveal that in the areas with high vulnerability the land usages tend to introduce high contaminant load and therefore, the groundwater beneath these areas is subject to higher risk of contamination. The risk maps elaborated using DRASTIC and GOD models have more coincidence than vulnerability maps elaborated using the same models. This is partially because of the contaminant load index which is identical in the both cases. The groundwater risk of contamination has been also evaluated using Susceptibility Index (SI) model. The resultant SI risk map was compared with the risk maps elaborated using DRASTIC and GOD. The results indicate a comparable products; however, they have more similarity with DRASTIC outputs. The maps of groundwater risk of contamination in the canton using different models show a comparable results, especially when accepting one risk category shift as acceptable error. The coincidence in this case is 98, 94 and 88% between DRASTIC and GOD, DRASTIC and SI, GOD and SI respectively. The results of the study recommend SI and GOD models to study the risk of groundwater contamination especially in data limitation conditions.

Keywords: Manabi Province, DRASTIC Model, GOD Model, Portoviejo River, Groundwater Protection, Groundwater Contamination, Vulnerability

Introduction

In spite of thousands of articles dealt with the term vulnerability, there is no agreement on the exact definition (Albuquerque *et al*., 2013; Stigter *et al*., 2006). The classic definition of aquifer vulnerability according to Vrba and Zoporozec (1994) is “an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts”. While Albinet and Margat (1970) state that groundwater vulnerability is “the possibility of percolation and diffusion of contaminants from the ground surface into natural water-table reservoirs under natural conditions”. Additionally, Olmar and Rezac (1974) define the term vulnerability as “the danger of endangerment, determined by natural conditions and independent of present source of pollution”.

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Vrba and Zaporozec (1994) distinguished between the intrinsic and the specific vulnerability. The intrinsic (natural) vulnerability was purely defined as a function of hydrogeological factors and the specific vulnerability that is related to specific pollutants. On world wide scale, the majority of vulnerability studies deal with the intrinsic vulnerability and take into account only the natural parameters (Sasal *et al*., 2011; Voudouris *et al*., 2010; Jaunat *et al*., 2016; Gougazeh and Sharadqah, 2009; Sharadqah, 2001; 2011; 2015a).

As vulnerability concept, the term of groundwater risk of contamination is still ambiguous for many researchers. In some studies the intrinsic vulnerability dealt and referred to by risk term and vice versa (Albuquerque *et al*., 2013; Al-Rawabdeh *et al*., 2014; Gaieb and Hamza, 2013).

Risk linguistically means the chance or situation involving such a possibility (Oxford English Dictionary). Depending on this definition, the risk of groundwater contamination may be understood as the chance or probability of such contamination to occur. The probability of contamination is governed by vulnerability and the presence of contaminant. Therefore, evaluating the groundwater vulnerability to contamination is prerequisite for evaluation the risk of contamination of groundwater. This is totally coincided with the definition of Foster and Hirata (1988), in which they define the groundwater pollution risk as "the interaction between the natural vulnerability of an aquifer and the pollution loading that is or will be applied on the surface environment as a result of human activity". Sharadqah (2004) adopted the same definition and suggested an index for contaminant load depending on land use. This index has been used in several studies and it demonstrates clarity, easiness to handle and applicability (Sharadqah, 2010; 2015b).

Protection of groundwater quality is an action and a responsibility that can be practiced efficiently through knowledge of the degree of groundwater susceptibility. Vulnerability maps are a visualization for groundwater susceptibility. Without a good evaluation of groundwater vulnerability to contamination, protection measures may be insufficient and therefore these waters may be contaminated, or these measures may be exaggerated that might lead to an improper land use.

Thus, the study of groundwater vulnerability to pollution can be considered as the first stage in the process of groundwater quality protection, or the scientific participation in the process of protection which is the responsibility of the authority and stakeholders as established by the Ecuadorian Water Law approved by the National Assembly on June 24, 2014.

The deterioration of the quality of groundwater and surface water in the Canton of Portoviejo is a well known problem (Macias and Dيaz, 2010; Garcia *et al*., 2010). The pollution sources are numerous and represent various sectors in which the most prominent are domestic, agricultural and industrial sectors. The wide range of contaminants originated from those sectors turned the quality of Portoviejo river from usable to harmful (Macias and Dيaz, 2010). The nitrogen load to the river from wastewater source only is estimated at 1360 000 kg/year (Macias and Dيaz, 2010). Groundwater is not fully isolated from the surface water and the river itself being contaminated may represent a major threat to the quality of groundwater. Furthermore, contaminants that are already available can reach groundwater washed by water infiltrated through the soil and vadose zone. However, the concentration of nitrate in the waters of the river has not exceeded the limit of 50 mg L^{-1} (Reina and Zambrano, 2012; Garcia *et al*., 2010).

Nitrate is a contamination indicator of groundwater due to its highly solubility, where it practically moves with the water that drags it (Nolan *et al*., 2002; Stumm and Morgan, 1996). This contaminant could move from the groundwater into the river when the groundwater level reaches the river. Groundwater can be recharged by the river water and in this case, contaminants such as nitrate can reach underground water. The waters of the Portoviejo River can contaminate groundwater with nitrate, but if there is no other source of contamination, the concentrations will not exceed the allowed limit since the NO_3 concentration in the river waters is less than 50 ppm (Reina and Zambrano, 2012). Actually, this is not the case, since there are many uses in the Canton area that could contaminate the groundwater with nitrate, particularly the agricultural sector which uses large amounts of nitrogen and organic fertilizers (Garcia *et al*., 2010).

Therefore, assessing and mapping groundwater vulnerability to contamination help the stakeholders and decision makers to locate where groundwater can be easily contaminated and where not. This in turn helps to decide which activities can be allowed in certain areas in order to maintain or even improve the quality of groundwater in accordance with good land-use practices (Kumar *et al*., 2015; Aller *et al*., 1987).

The three models used in this study are widely applied in extensive studies worldwide. DRASTIC model is one of the most widely used for groundwater vulnerability evaluation. It has been applied in many countries on all continents. For example in USA (Rupert, 2001; Beynen *et al*., 2012), Jordan (Gougazeh and Sharadqah, 2009), Portugal (Stigter *et al*., 2006; Lobo-Ferreira and Oliveira, 2003), Cyprus

(Voudouris *et al*., 2010), Ecuador (Sharadqah, 2015a), Argentina (Sasal *et al*., 2011), Sweden (Rosen, 1994), South Africa (Lynch *et al*., 1997), Japan (Babiker *et al*., 2005), among many others. The Susceptibility Index (SI) method (Ribeiro, 2000), is an adaptation of the DRASTIC methodology. It was applied in several countries such as Algeria (Abdelmajid and Omar, 2009), Portugal ((Ribeiro *et al*., 2003; Lobo-Ferreira and Oliveira, 2003; Stigter *et al*., 2006), Tuniz (Gaieb and Hamza, 2013), India (Brindha and Elango, 2015). GOD model has the least requirement of data among the three modes. Since its development it was applied to numerous case studies in Canada (Golder and Monahan, 2005), China (Xu *et al*., 2013), Brazil (Barboza *et al*., 2007; Vogel, 2008; Tavares *et al*., 2009)), Iran (Ghazavi and Ebrahimi, 2015), Nicaragua (Mendoza and Barmen, 2006).

The present study aims to investigate the applicability of DRASTIC, GOD and SI models in evaluating the groundwater vulnerability and risk of contamination in the study area.

Study Area

Portoviejo Canton forms the capital of the Manabí Province which is located in the Pacific coastal region of Ecuador (Fig. 1). The most important feature in the Canton is Portoviejo River, which influences the demographic distribution and the land uses. In the flat areas that surrounding the river the majority of the Canton population reside and the horticulture is the dominant land use (Fig. 2a and 2b). The canton climate belongs to the pacific costal regimen and the long term annual precipitation ranges from more than 1000 mm/y to less than 300 mm/y (INAMHI, 2106). Hydrogeologically, the quaternary deposits close to river course, such as Onszole and San Mateo Formations could form an aquifers. The majority of other formations are dominantly clay, shale or lutites; however, they become locally or in some horizons more sandy. Therefore, the possibility of storing some water cannot be rule out.

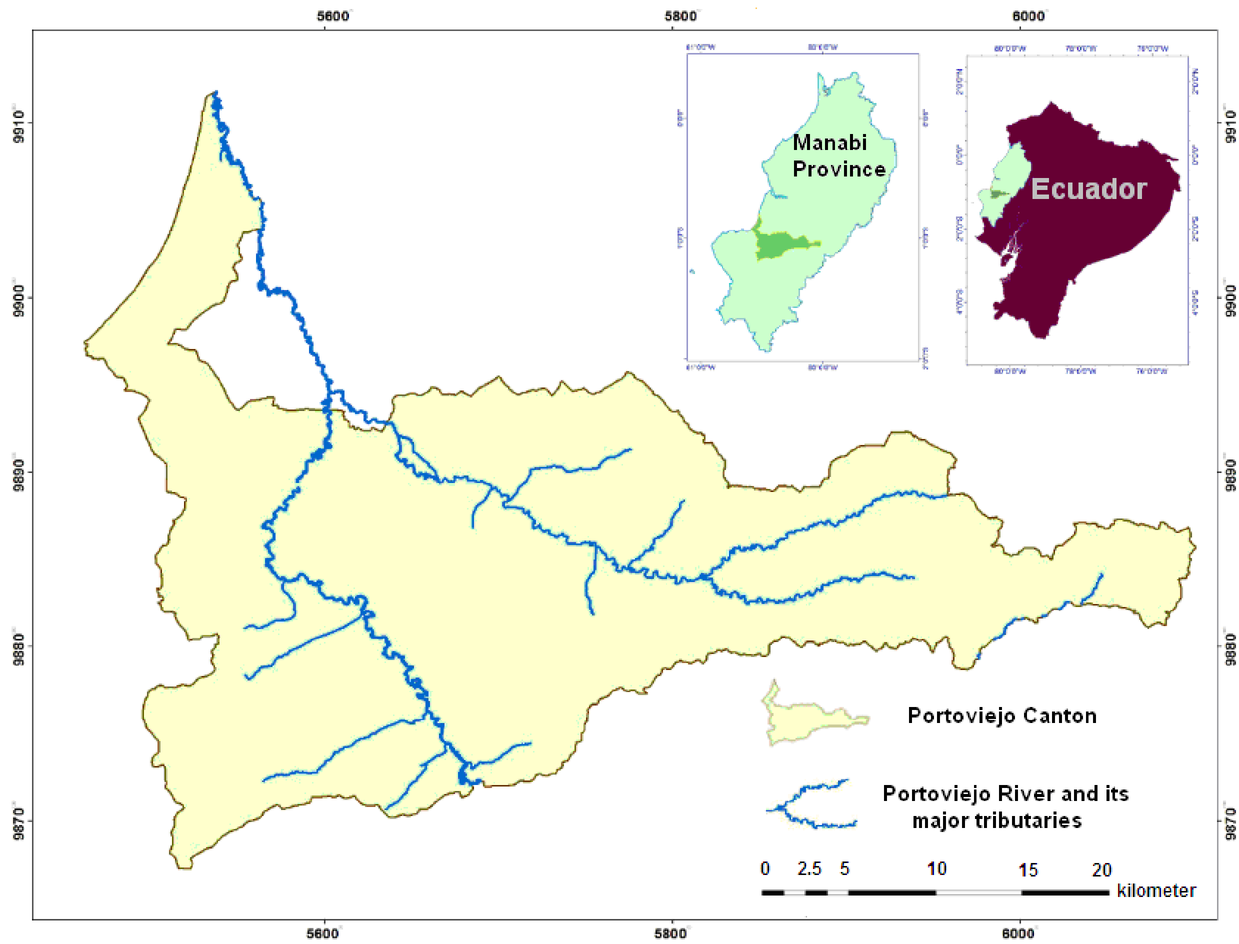

Fig. 1. Study area map

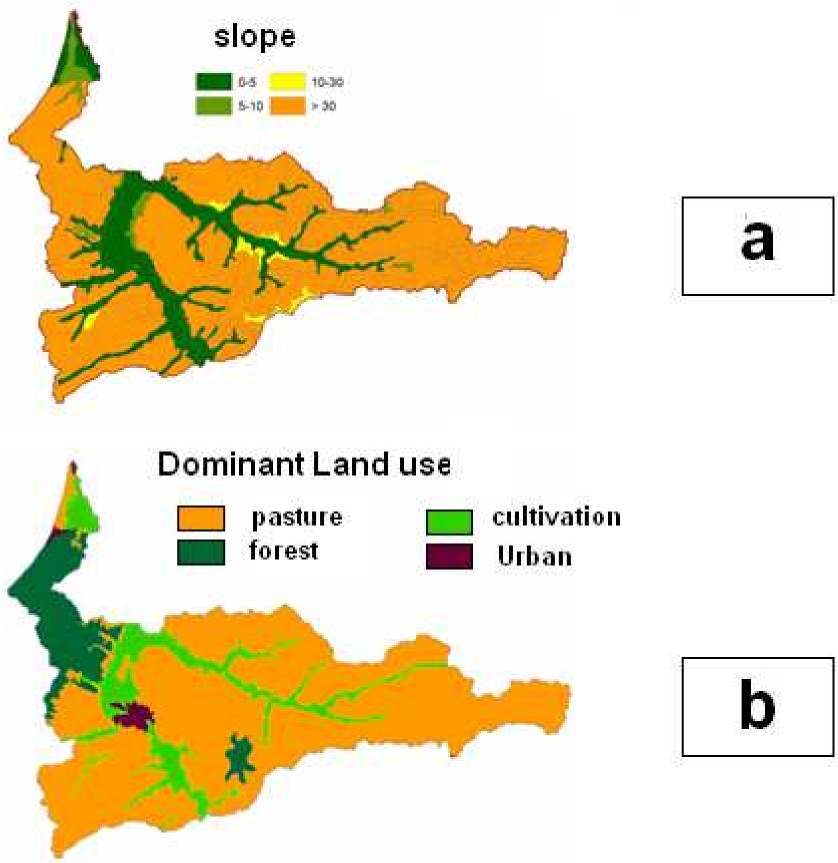

Fig. 2. (a) Topographical slope of study area (%) (b) Dominant land use in study area

Methodology

Groundwater Vulnerability to Contamination Study

To assess groundwater vulnerability to contamination which is sometimes a prerequisite to evaluate the risk of groundwater contamination, two intrinsic methodologies have been adopted. These are DRASTIC methodology (Aller *et al*., 1987) and GOD Methodology (Foster, 1987). The three models used in the actual study are belong to Overlay and Index Methods (OIM). This type of methods is based on combining maps of various physiographic attributes by assigning a score to each attribute (NRC, 1993). Qualitative or sometimes quantitative indices are derived, that bring together the key factors that govern the contaminant transport from the land surface to groundwater (e.g., depth to groundwater, net recharge, geology) (Connell and van den Daele, 2003). Thus OIM-based ground water vulnerability mapping models essentially integrate ratings and attributes of those important factors (Hamerlinck and Ameson, 1998). In the simplest methodologies, maps of attributes are overlaid and areas with a combination of certain characteristics (e.g., shallow groundwater table with high net recharge) are evaluated as having higher vulnerability.

DRASTIC Vulnerability

DRASTIC Vulnerability maps of the study area have been elaborated depending on the hydrogeological framework parameters and based on seven mapped parameters (Table 1). Each parameter has been separately evaluated and then superimposed all to get the DRASTIC index (Equation 1). This index is then reclassified using GIS software to different vulnerability classes producing DRASTIC map of groundwater vulnerability to contamination:

$$DI = 5Dr + 4Rr + 3Ar + 2Sr + T + 5Ir + 3Cr \quad (1)$$

Where:

DI	=	DRASTIC Index
5, 4,…3	=	Parameters weights
r	=	Rating
D,R,A,S,T,I,C	=	DRASTIC model parameters

DRASTIC parameters, weights and ratings are defined in Table 1.

Table 1. Drastic model weights and ratings (modified after Aller *et al*., 1987)

DRASTIC parameters	Parameter symbol	Weight	Range	Rating
Depth to Water (m)	D	5	30.3 to 0>	1 to 10
Net Recharge (mm)	R	4	0 to >254	1 to 9
Aquifer media	A	3	Massive Shale to Limestone karst	1 to 10
Soil media	S	2	No shrinking clay to absent	1 to 10
Topography (%)	T	1	18 to 0>	1 to 10
Impact of vadose zone	I	5	Confining layer to limestone karst	1 to 10
hydraulic Conductivity (m/day)	C	3	0.4 to >82	1 to 10

Table 2. GOD model Ratings (modified after Foster, 1987)

Parameter	Range	Rating
G	No aquifer to unconfined aquifer	0 to 1
O	Clay to karstified limestone	0.4 to 1
D	100 to 0 (m)	0.4 to 1

Table 3. SI model: Weights, ranges and rating

SI parameters	Parameter symbol	Weight	Range	Rating
Depth to Water (m)	D	0.186	30 to 0>	01 to 100
net Recharge (mm)	R	0.212	0 to > 254	0 to 100
Aquifer media	A	0.259	Massive Shale to Limestone karst	0 to 100
Topography (%)	T	0.121	18 to 0>	0 to 100
Land use	LU	0.222	Water bodies to Industrial waste discharges, landfills	0 to 100

GOD Vulnerability

GOD model is one of the easiest methods to evaluate the vulnerability of groundwater to contamination. It includes only three parameters. Those are Groundwater occurrence (G), Overall aquifer class (O) and Depth to groundwater (D) (Foster, 1987). GOD vulnerability index is obtained by applying the multiplicative formula of GOD model (equation 2). This index is then reclassified to different GOD vulnerability classes:

$$GOD\,index = Gr * Or * Dr \tag{2}$$

Where:

r = The parameter rating that can be shown in Table 2

G, O, D = The *GOD* model Parameters

Groundwater Contamination Risk Mapping

To evaluate the groundwater risk of contamination in the study area, three models have been applied: DRASTIC model combined with the contaminant load, GOD model combined with contaminant load and SI model. The contaminant load map derived from the land use map (Fig 2b). Each use assigned a unique contaminant load. The forest area assigned low contaminant load, the pastures and arable assigned moderate contaminant load and the cultivated area which subjected to natural and chemical fertilizers assigned high contaminant load. The Risk categories then obtained as the matrix solution (Fig. 3).

The Susceptibility Index "SI" model is a modification of DRASTIC method (Ribeiro, 2000). SI method applies four of DRASTIC seven parameter with their corresponding nomenclatures and add a fifth parameter which is Land Use (LU). Each of the five parameters has a weight and assigned a rating value ranges between 0 and 100 (Table 3). The overall SI risk index is calculated as shown in the Equation 3 and then reclassified for different risk classes (Table 4):

$$\begin{aligned} SI &= 0.186\,Dr + 0.212Rr \\ &+0.259Ar + 0.121Tr + 0.222LUr \end{aligned} \tag{3}$$

Where:

SI = Susceptibility Index

0.186, 0.212.., 0.222 = Parameters weights

r = Rating

D,R,A,T,LU = SI Parameters

Mapping the vulnerability and risk of groundwater contamination required data processing, classification, evaluation. All the data management processing for all factors considers by the three models have been concluded in an integrated GIS environment. Initiating from the row source data (Table 5), an exhaustive data manipulation and data management processes have been done to come out with parameters ratings layers.

Table 4. Criteria for the Risk evaluation using SI method

Risk Category	Very Low	Low	Moderate	High	Very High
SI Index	<40	40-50	50-70	70-80	> 80

Modified after (Ribeiro, 2000)

Table 5. Data used to generate the parameters ratings, their format, source and extension

Information Layer	Format	Source	Extension	Generated parameter DRASTIC	GOD	SI
wells	Excel sheet	SENAGA, Portoviejo *	Portoviejo Canton	D	D	D
Recharge	paper map	CRM **	Manabí Province	R	-	R
Hydrogeology	Digital map	MAGAP (2005a)	National	A,C,I	G, O	A
Geological	Digital map	MAGAP (2005b)	National	A,C,I	G,O	A
Taxonomy	Digital map	MAGAP (2002a)	Manabí Province	S	-	-
DEM	Digital	Provincial Council of Manabí	Manabí Province	T	-	T
Land use map	Digital map	MAGAP (2002c)	Manabí Province	Contaminant load	Contaminant load	LU
Map of soil texture	Digital map	MAGAP (2002b)	Manabí Province	S	-	-
Weather data	Text and spread sheets	INAMHI (2014)	Manabí Province	R	-	R

SENAGA: National Secretary for Water. (Not Published data)
CRM (Manabí Rehabilitation Center): Predecessor Entity to SENAGA. (Not Published data)

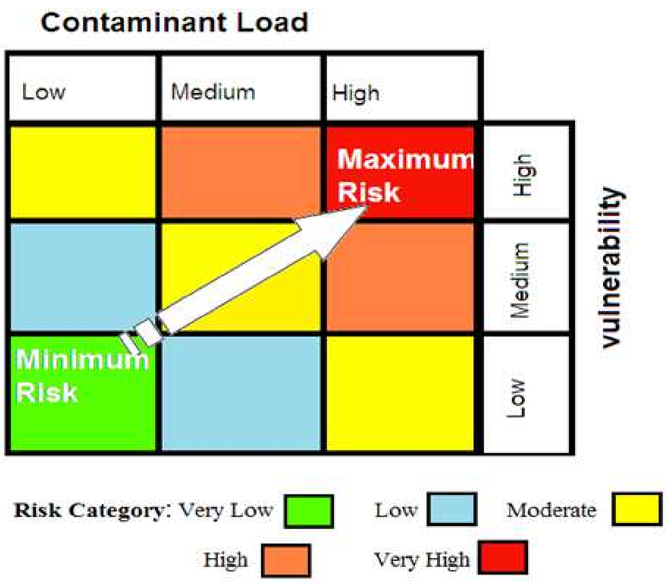

Fig. 3. Risk matrix obtained by combining vulnerability class with contaminant load (modified after Sharadqah, 2004)

Results and Discussion

The results show that DRASTIC and GOD models are able to classify the groundwater's vulnerability of the study area to distinct levels (Fig. 4).

The two models agree that the flat area around the Portoviejo River is more vulnerable than the tilted areas away from the river. In this flat area, the groundwater is very shallow and the aquifer is of the quaternary deposits. This shows that the combination of the D, A and T parameters of the DRASTIC model have the greatest contribution in the distribution of the DRASTIC vulnerability classes. Likewise, the D and O parameters of the GOD model have the greatest contribution in the distribution of the GOD vulnerability classes. The results of vulnerability distribution as percentage of study area using GOD and DRASTIC models are shown in Fig. 5. However; the two model don't totally coincide in the spatial distribution of each vulnerability class. Consequently, These result might be misleading if the spatial relationships ignored. Because it might find a similar areal percentage of certain vulnerability class derive from two different model, but the spatial distribution of these areas could be different. Table 6 lists the spatial coincidence of the groundwater vulnerability classes derived by the two models. The results show that the spatial coincidence between DRASTIC and GOD vulnerability classes is 43%. But the majority of differences between the two models is within one degree of difference. So, if one class shift is accepted as acceptable error, the coincidence between the two models reach 76% which is similar or even more than what reported in some studies (Abdelmajid and Omar, 2009; Gogu *et al*., 2003). As in many studies, GOD model ascribe more areas a high vulnerability (Gogu *et al*., 2003; Díaz *et al*., 2009).

The results of the risk study show closer results obtained from the three models (Fig. 6). That's essentially due to unified contaminant load distribution in the three models. So the variability in the groundwater risk to contamination will depend only on the vulnerability. As vulnerability influence is only 50% on risk classes in case of DRASTIC and GOD and 78% in case of SI method, consequently the outputs of models for risk study will have less variation than vulnerability.

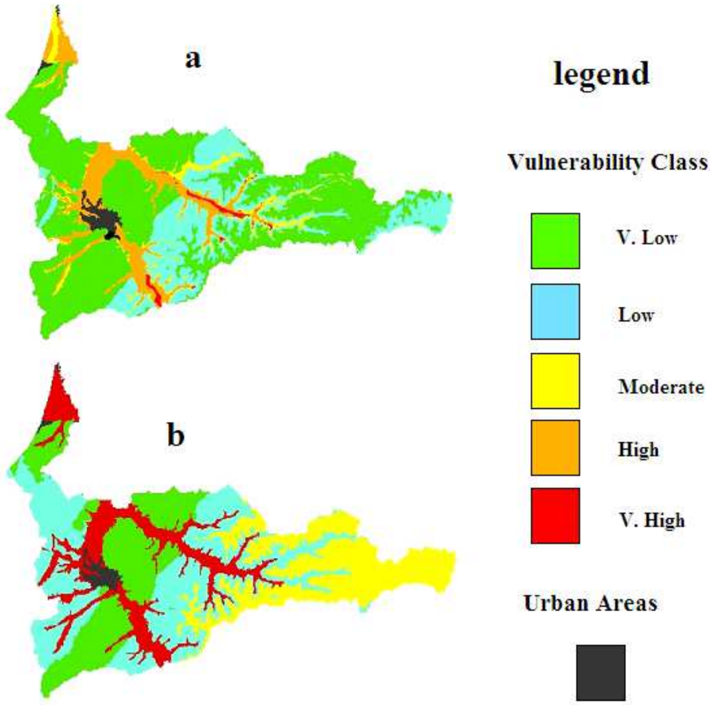

Fig. 4. Groundwater vulnerability to contamination in the study area: (a) using DRASTIC Model (b) Using GOD Model

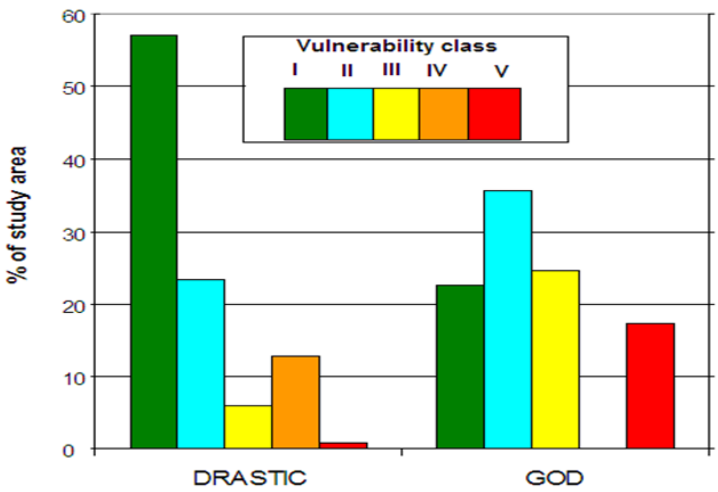

Fig. 5. Percent share of the vulnerability classes in the area of Portoviejo Canton using DRASTIC and GOD models

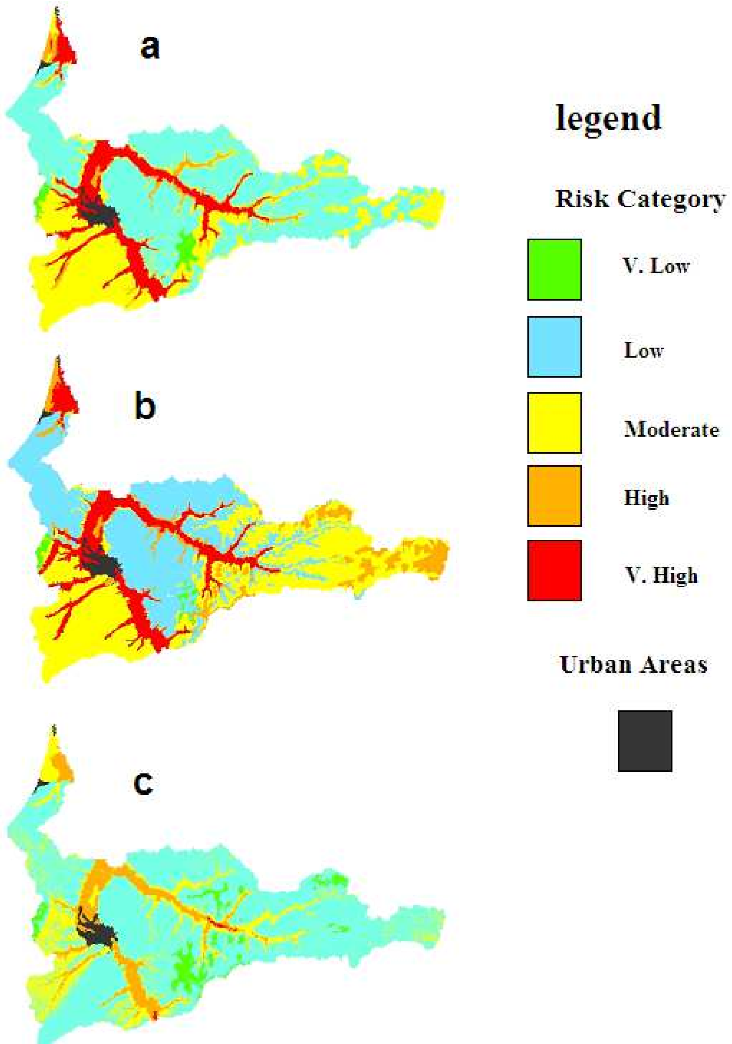

Fig. 6. The Risk of Groundwater contamination in the study area (a) Using DRASTIC Model (b) Using GOD Model (c) Using SI Model

Table 6. Spatial distribution comparison between DRASTIC and GOD vulnerability classes

		DRASTIC				
		I	II	III	IV	V
GOD	I	**22.669**				
	II	*14.146*	**19.32**	2.164		
	III	20.54	*3.69*	**0.554**		
	IV					
	V		0.468	3.313	12.8	**0.82**

Bold: Total coincidence, Italic: One class of difference, Underlined: More than one class of difference

Table 7. Classification the study area to different risk categories using DRASTIC, GOD and SI model

	Risk Category (% of total Study area)				
Model	I	II	III	IV	V
DRASTIC	1.85	51.33	30.60	4.46	11.76
GOD	1.00	36.31	39.89	9.14	13.66
SI	3.70	68.22	18.87	9.03	0.18

Table 8. Spatial distribution comparison between DRASTIC, GOD and SI model risk categories. Values expressed as percentage of total study area

			DRASTIC					SI				
			I	II	III	IV	V	I	II	III	IV	V
GOD	Risk Category	I	**1**	-	-	-	-	**0.88**	*0.12*	-	-	-
		II	*0.64*	**33.92**	*1.5*	-	0.25	*0.64*	**32.89**	*2.76*	0.02	-
		III	0.21	*17.39*	**21.67**	0.62	-	0.71	*31.28*	**7.9**	-	-
		IV	-	0.02	*7.02*	**1.97**	*0.13*	1.47	3.93	*3.67*	**0.07**	-
		V	-	-	0.41	*1.87*	**11.38**	-	-	4.54	*8.94*	**0.18**
SI	Risk Category	I	**1.53**	*0.7*	1.47	-	-					
		II	*0.13*	**48.97**	*19.03*	0.06	0.03					
		III	0.19	*1.66*	**10.09**	*4.02*	2.91					
		IV	-	-	*0.01*	**0.38**	*8.64*					
		V	-	-	-	-	**0.18**					

Bold: Total coincidence, Italic: One class of difference, Underlined: More than one class of difference

The results of DRASTIC risk show that 11.76, 4.46, 30.6, 51.33 and 1.85% of the study area belong to very high risk, high risk, moderate risk, low risk and very low risk respectively. Similarly, the results of GOD risk show that 13.66, 9.14, 39.89, 36.31 and 1% of the study area belong to very high risk, high risk, moderate risk, low risk and very low risk respectively. The results of SI model risk show that 0.18, 9.03, 18.87, 68.22 and 3.7% of the study area belong to very high risk, high risk, moderate risk, low risk and very low risk respectively (Table 7).

Table 8 shows the aerial and spatial distribution for risk categories derived from the 3 models. The spatial coincidence between DRASTIC and GOD vulnerability classes is 70%. The spatial coincidence between DRASTIC and SI vulnerability classes is 61% and the spatial coincidence between GOD and SI vulnerability classes is 42%. If we consider one vulnerability class as acceptable error the spatial coincidence rise to 99, 95 and 89% between DRASTIC and GOD, DRASTIC and SI, GOD and SI respectively. The results demonstrate that DRASTIC is more close to both models which seem very reasonable. That's because it shares same contaminant load classification with GOD model and shares 4 parameters out of seven with SI model. The least coincidence is between GOD and SI. They shares just the D parameter, furthermore, it has different weight in each model.

Where, the contaminant load govern 50% of the risk value output in GOD and DRASTIC models.

Worldwide, DRASTIC model is more common than GOD and SI. The actual study shows a comparable result especially for evaluation the risk of groundwater contamination. That may indicate the ability of using GOD or SI as an alternatives to DRASTIC model. Furthermore, DRASTIC requires more data than the other two models, so in the conditions of data limitation, using GOD or SI models could represents a good advantage.

Conclusion

- The results shows that both, DRASTIC and GOD models were able to classify the study area to several zones of distinct vulnerability
- The spatial coincidence in the same vulnerability class using DRASTIC and GOD model is 43%, but the coincidence become more than 76% if one vulnerability class shift is considered as acceptable error
- DRASTIC and GOD models agree that the areas close to Portoviejo River have higher vulnerability than areas more far from river course
- The results of groundwater risk of contamination maps show that DRASTIC, GOD and SI agree that the areas surrounding the River Portoviejo is of highest risk, although their findings may vary considerably in the areas with less groundwater contamination risk
- GOD risk results are the closest to DRASTIC results, because both use the same contaminated load values
- The results of SI model is more close to DRASTIC model than to GOD, because they share 4 parameters
- Accepting one risk category as acceptable error, the coincidence in the three models results is very high, where it is ranging between 89 to more than 97%
- In the presence of detailed information about the hydrogeological system, DRASTIC is best because it incorporates more parameters. The SI and GOD models may be preferred to study the risk of groundwater contamination especially when detailed information is lacking

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Ethics

The author declares that this is an original research and they have no ethical issues or copyrights conflict.

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