Groundwater Vulnerability Mapping in Two Watersheds Affected by Yacyreta Dam in Paraguay

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Abstract

Musálem, K., McDonald, M., Jiménez, F., & Laino, R. (November-December, 2015). Groundwater Vulnerability Mapping in Two Watersheds Affected by Yacyreta Dam in Paraguay. *Water Technology and Sciences* (in Spanish), *6*(6), 49-61.

Groundwater vulnerability mapping was conducted for two intensive agriculture and urban watersheds draining to the Yacyreta Dam in Paraguay. Two widely used overlaying methods (GOD and DRASTIC) were applied and compared to determine groundwater vulnerability to contamination. Possible effects of climate change on vulnerability values were also assessed using climate change scenarios provided by third authors. Finally, the possible effects of water table variations derived from Yacyreta Dam operations was projected on groundwater vulnerability. Determination of groundwater vulnerability using DRASTIC shows a 56% of the area of the watersheds to be classified as "medium high" (DRASTIC index *140 – 159)* and a 22% as either "high", "very high" or "maximum" (DRASTIC index values 160 – > 200). GOD on the other hand showed a 96% of the area of the watersheds with a "moderate vulnerability" to contaminants (values 0.3-0.5) and a 4% of "high vulnerability" (values 0.51 – 0.6). Vulnerability classes remained the same regardless of any climate change scenarios reviewed, for a 100 year span. Operation by the dam, specifically a five meter elevation of the water table scenario, suggests an increase in vulnerability in lower parts of the watersheds. Finally we compare GOD and DRASTIC models and their suitability regarding the available data for the region and scenario building.

Keywords: DRASTIC model, GOD model, Guarani Aquifer System, climate change.

Resumen

Musálem, K., McDonald, M., Jiménez, F., & Laino, R. (noviembre-diciembre, 2015). Mapeo de la vulnerabilidad del agua subterránea en dos cuencas afectadas por la represa Yacyreta en Paraguay. Tecnología y Ciencias del Agua*, 6(6), 49-61.*

*Se condujo un mapeo de vulnerabilidad del agua subterránea en dos cuencas hidrográficas de agricultura intensiva y áreas urbanas que drenan al embalse Yacyreta en Paraguay. Se aplicaron y compararon dos métodos de sobreposición ampliamente utilizados (*GOD *y* DRASTIC*) para determinar la vulnerabilidad del agua subterránea a la contaminación. También se evaluaron los posibles efectos del cambio climático en los valores de vulnerabilidad utilizando escenarios de cambio climático de terceros autores. Por último, se proyectaron los posibles efectos en la vulnerabilidad derivados de las variaciones en el nivel freático, producto de las operaciones de la represa Yacyreta. La determinación de la vulnerabilidad del agua subterránea utilizando* DRASTIC *mostró un 56% del área de las cuencas clasificadas como de "media alta" vulnerabilidad (índice DRASTIC 140 – 159) y un 22%, ya sea como "alta", "muy alta" o "máxima" (índice DRASTIC 160 – > 200).* GOD*, por otro lado, mostró un 96% del área de las cuencas como de "vulnerabilidad moderada" a la contaminación (valores 0.3-0.5) y un 4% como "alta vulnerabilidad" (valores 0.51-0.6). Las clases de vulnerabilidad se mantuvieron iguales sin importar los escenarios de cambio climático revisados, para un periodo de cien años. Las operaciones de la represa, en específico un escenario de elevación del nivel freático de cinco metros, sugiere un aumento en la vulnerabilidad a la contaminación en las partes bajas de las cuencas. Por último, se compararon los modelos* GOD *y* DRASTIC*, y su adaptabilidad a los datos disponibles para la región y la construcción de escenarios.*

Palabras clave*: modelo* DRASTIC*, modelo* GOD*, Sistema Acuífero Guaraní, cambio climático.*

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Introduction

Groundwater constitutes the largest reservoir of freshwater in the World, accounting for over 97% of all freshwater available on Earth, excluding glaciers and ice caps. The remaining 3% is composed mainly of surface water (lakes, rivers, wetlands) and soil moisture (Quevauviller, 2008). Despite their relevance, contamination of groundwater systems is an increasingly critical problem, once an aquifer is contaminated it is practically unfeasible to clean and the possibilities of remediation involve high economic costs (Wang, 2006).

Groundwater is a hidden source which is quantitatively much more significant than surface water, and for which pollution prevention and quality monitoring and restoration are even more difficult than surface waters, mostly due to its inaccessibility (Quevauviller, 2008). Prevention of contamination is critical for effective groundwater management (Babiker, Mohamed, Hiyama, & Kato, 2005), especially considering the uncertainty about future climate scenarios. Projections indicate that climate change will vary by region and locality, bringing a modification on the frequency of extreme climate phenomena, such as floods and droughts (Bergkamp, Orlando, & Burton, 2003). Groundwater is extensively used by humans as drinking water, with some countries depending almost entirely on it, while others only partly, highlighting the relevance of groundwater quality and quantity conservation as an adaptation strategy to climate change (Quevauviller, 2008).

Groundwater vulnerability to contamination maps are becoming more in need because, on the one hand, groundwater represents the main source of drinking water, and on the other high concentrations of human/economic activities, e. g. industrial, agricultural, and household, represent real or potential sources of groundwater contamination (Rahman, 2008). The concept of groundwater vulnerability mapping is useful for environmental planning and decision-making, and different methods have been developed for the determination of aquifer pollution vulnerability (Gogu & Dassargues, 2000). These methods, mostly based on index and overlaying techniques, have been used under distinct geological contexts: DRASTIC, SINTACS, AVI and GOD (Exposito, Esteller, Paredes, Rico, & Franco, 2010), and they have also been addressed in comparative studies (Agüero & Pujol, 2002; Gogu & Dassargues, 2000; Lobo-Ferreira & Oliveira, 2004; Napolitano & Fabbri, 1996). The nature of the index is to assign values to each hydrogeological characteristic, which are later combined to calculate an overall vulnerability value in order to classify regions into different units of potential contamination (Kumar, Bansod, Debnath, Thakur, & Ghanshyam, 2015).

An estimated 80% of the potable water supply in Paraguay in South America is made from underground water. Cabral (2005) estimates that at least 38% of the population of the Country lives on the Guarani Aquifer System and is supplied by its waters and that certain conditions, specifically intensive agriculture and urban wastes are or will be risking water quality of the Guarani Aquifer System, specially due to widespread use of land for intensive soybean production as well as other crops (e. g. maize, sunflower). Global concerns about the association of soybean production and other crops as a major source of groundwater contamination (Clay, 2004) have been taken as subject of interest for this study, specifically for two catchments located in this region. Our study aimed to determine current groundwater vulnerability to contamination of the "shallow aquifers" using DRASTIC and GOD models for the Mboi Cae and Quiteria River watersheds and to assess possible effects of climate change on vulnerability categories as well as water table changes derived from the Yacyreta Dam operations. Our two study watersheds are locally perceived as a single socio-hydrological unit, sharing one watershed committee and common actors involved in its management. This study focuses on the area of both watersheds located within the influence of the Guarani Aquifer System and the Yacyreta Dam. Groundwater mapping was carried out to provide the resulting maps to the watershed committee, but also as

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a comparative exercise of the suitability of the application of the two models, specifically data input, considering available information for this region. Groundwater vulnerability maps are presented here as an intrinsic characteristic of the studied site in the possible threat of contaminants including, but not limited to, soybean intensive production (For a list of contaminants associated with soybean intensive agriculture see: Paraíba *et al.*, 2003).

Materials and Methods

The Guarani Aquifer System is one of the largest groundwater reservoirs of the planet (Oporto & Vassolo, 2003; Fariña *et al*., 2004). It is located in South America between 12° and 35° latitude South and 47° and 65° longitude West. It is estimated that the aquifer contains a reserve of 45 000 cubic km of water covering an area of approximated 1.2 million sq km of which 840 000 sq km belong to Brazil, 225 500 sq km to Argentina, 71 700 sq km to Paraguay and 58 500 sq km to Uruguay (Cabral, 2005). In Paraguay, the Guarani Aquifer System is located in the eastern side of the country, forming a strip that extends from North to South, along the Parana River (Fariña *et al*., 2004), part of La Plata river basin.

Within the aquifer system, we selected two watersheds which are of local interest for the Yacyreta Binational Entity and the local watershed committee and where the largest urban populations in the Itapua Department are being affected by the Yacyreta Dam project in Paraguay and intensive agricultural activities account for at least 80% of the total area of the watersheds. The watersheds of the Mboi Cae and Quiteria Rivers (286 sq km and 352 sq km respectively) are located in the Itapua Department of Paraguay, both draining to the Parana River, which partially constitutes the political boundary between Paraguay and Argentina (Figure 1). We used two models for groundwater vulnerability mapping: DRASTIC, originally published by Aller, Bennett, Lehr, Petty, and Hacket, (1987) and GOD published by Foster, Hirata, Gomez, D'elia, and Paris (2002). These

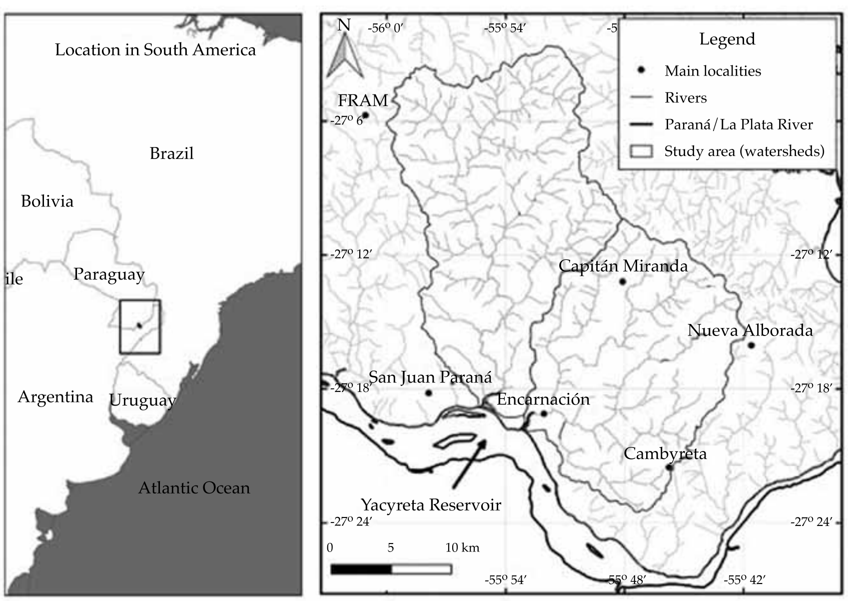

Figure 1. Location of the study area, Mboi Cae and Quiteria watersheds in Itapua Department, Paraguay. Yacyreta binational reservoir partially shown (Argentina and Paraguay). Sources: NaturalEarth, Military Geographic Institute of Paraguay and Musálem (2010).

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Table 1. Summary of the sources of information and processes followed to obtain DRASTIC and GOD ratings for the watersheds of the Mboi Cae and Quiteria Rivers in Paraguay.

Parameters	Source	Summary of process followed	Units
Depth to Water	Profiles of 41 wells reported by SENASA (local water sanitation agency) showing static and dynamic levels of the water table within the watersheds	Static levels were interpolated using IDW for the area of the watersheds	Depth in meters
Net Recharge	Geology maps (Military Geographic Institute Paraguay, 1986) and hydrogeology studies that estimated net recharge for Basalts, and Sandstone in the Guarani Aquifer. Santa Cruz and Silva (2002) in Laino (2005), Külls (2003), Schmidt (2009)	Net recharge was estimated by geology in function of precipitation. For sandstone areas, an estimated value from literature review was used directly	Millimetres per year
Aquifer Media	Geology Maps (Military Geographic Institute Paraguay, 1986)	The rock which serves as aquifer, pores or fractures related to the vulnerability to pollution	Lithology
Soil Media	Soil Maps (Military Geographic Institute Paraguay, 1986). Local soil taxonomy and textures (Global Consultores, 2008)	Soil taxonomy subgroups were linked to texture and translated into vulnerability ratings	Texture
Topography	Contour lines of Paraguay (Military Geographic Institute Paraguay, 1986)	Contour lines were processed into a Digital Elevation Model. Using GIS slope was calculated and translated to vulnerability ratings	Slope (%)
Impact of Vadose Zone Media or Overlying strata	Profiles of wells provided by SENASA + Geology maps of Paraguay	Direct reading of profiles from SENASA and confirmation with geology maps	Lithology
Hydraulic Conductivity	Direct data from works reporting local values (Godoy, 1991; De Salvo, 1991; in Fariña 2009)	Direct values reported from authors translated into vulnerability ratings	Meters/day
Groundwater Confinement	Data reported by Schmidt (2009)	Characteristics translated into vulnerability ratings (GOD only)	Confinement

models being trialed in several subsequent works: in India (Kumar, Thirumalaivasan, & Radhakrishnan, 2014; Rahman, 2008; Shahid 2000), Paraguay (Laino, Jiménez, Velazquez, Paez, & Casanoves, 2006, Larroza, Fariña, Baez, & Cabral, 2005), Japan (Babiker *et al*., 2005), El Salvador (Vignola, 2005), Nicaragua (Obando, 2005), Mexico (Ceballos & Avila, 2004; Exposito *et al*., 2010), Portugal (Lobo-Ferreira & Oliveira, 2004), USA (Chowdhury, Iqbal, & Szabo, 2003), Costa Rica (Agüero & Pujol, 2002), and Italy (Napolitano & Fabbri, 1996). Input data and sources for the models is presented in Table 1. Data of the hydrogeological conditions was obtained for each parameter using different sources and methods and explained in Table 2.

DRASTIC Calculation

The acronym DRASTIC corresponds to the initials of seven base maps as follows: D: Depth to water / R: Net Recharge / A: aquifer media / S: Soil media / T: Topography / I: Impact of the vadose zone/ C: Hydraulic Conductivity. Each of the parameters is mapped and classified either into ranges or into significant media types

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Table 2. Data used and considerations for the application of the groundwater vulnerability models DRASTIC and GOD. Values were reclassified to vulnerability classes respectively, using DRASTIC (Aller *et al.*, 1987) and GOD (Foster *et al.*, 1987) indexes for final computation. For more details about the data calculations see Musálem (2010).

Parameter	Data processing: considerations and limitations	Data ranges
Depth to water	Water table depths were obtained from wells provided by local water sanitation agency. Data was extrapolated to the whole area of the watersheds using Inverse Distance Weighting from ArcGIS. A Raster with Depth to water of the watersheds was reclassified into vulnerability values according to each author. Wells were distributed irregularly in the watershed with more data concentrated in lower parts of the watershed. However wells outside the watersheds were used to perform interpolation. Values were directly translated into DRASTIC and GOD ratings, according to index by Aller *et al*. (1987)	Depth of water varied from superficial waters (0 m in sources) to 75 m
Recharge	Considerations by Santa Cruz and Silva (2002) in Laino (2005) from the Pilot program Concordia – Salto were taken into account. This study was presented in a research made by the Guarani Aquifer System Project regarding stratigraphy and hydrogeology and estimated a 3% net recharge of annual precipitation in Uruguay. Considering that the study area has a similar hydrogeological area (Alto Parana formation and the Guarani Aquifer System) the same value of 3% of precipitation was used for areas with basaltic geology within the watersheds. For areas with sandstone from the Misiones Formation and for sediments, studies by de Guarani Aquifer System Project reported by Külls (2003) established a recharge of 136 to 150 mm/year and by Schmidt (2009) a net recharge for the Alto Parana Formation of 77 mm/year The distribution of geological formations, sandstones, basalts and sands was obtained from geology maps available at the Military Geographic Institute in Paraguay (1986). Most of the watersheds are located in basaltic geology areas, with alluvial deposits close to the mouth of the rivers	Recharge ranges from 50 to 178 mm/year depending on geology information and registered annual rainfall obtained from data of the Paraguayan national meteorology service. Total precipitation varies from 1 878 to 1 988 mm per year for both watersheds
Aquifer media	Information about geology was taken from geological maps of Paraguay (1986) and translated directly to a "typical rating" according to DRASTIC methodology by Aller *et al*. (1987). Aquifer media refers to the consolidated or unconsolidated rock serving as an aquifer	Three categories were found in the watersheds: (1) bedded sandstone or limestone; (2) sand and (3) basalts
Soil Media	Distribution of soil taxonomy was obtained from digitalized soil maps of Paraguay (Military Geographic Institute). Secondly, each soil subgroup was related to its texture according to three different studies carried out in the area: A report consisting of soil studies based on field observation, morphology and physical and chemical analysis of soil horizons done by Global Consultores (2008) in the watersheds for Yacyreta Binational Entity; a Masters thesis research conducted by Laino (2005) where DRASTIC model was used; an d an unedited geological study by Gonzalez (2005) (in Laino 2005) in the area; also the Soil Taxonomy Keys by USDA Soil Survey Staff (2006) were consulted. Subgroups texture was translated to DRASTIC ratings using Aller *et al*. (1987)	Soils found in the watersheds were Lithic Udorthent (basaltic) (most dominant), Rhodic Paleudult and Typic Kandiudox which by literature were determined to have clay and fine clay textures Typic Paleaquult and Typic Albaquult areas had loam, fine loams and sandy loam textures
Topography	Contour lines were available at 10 meters for this area and transformed into a TIN (triangulated irregular network) and finally into a raster with a (10 x 10 m) 100 sq m pixel size. Slope was calculated using Arc GIS and translated to DRASTIC by raster reclassification with DRASTIC index	Slope in percent ranged from 0%, mostly in lower parts of the watersheds, to 40% in the upper areas

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Table 2 (continuation). Data used and considerations for the application of the groundwater vulnerability models DRASTIC and GOD. Values were reclassified to vulnerability classes respectively, using DRASTIC (Aller *et al.*, 1987) and GOD (Foster *et al.*, 1987) indexes for final computation. For more details about the data calculations see Musálem (2009).

Parameter	Data processing: considerations and limitations	Data ranges
Impact of the vadose zone or overlaying strata	According to Aller *et al*. (1987) the vadose zone is defined as that above the water table which is unsaturated or discontinuously saturated. Reading of 23 well profiles were used to determine characteristics of the material below the typical soil horizon and above the water table	Basalt geology was predominant in the watersheds. Other smaller fractions of sand and sandstones were also found, however no wells were found for this areas, typical values were assigned according to found geology
Hydraulic Conductivity	Fractured basalt has been reported by Fariña (2009) to have a very high hydraulic conductivity, ranging from to even higher levels, supported by work carried out by (Godoy 1991 and De Salvo 1991 in Fariña 2009). The given explanation for such a high level of hydraulic conductivity is the presence of horizontal and vertical fractures and their interconnection in the Alto Parana Geological Formation. Since this was the only available information regarding hydraulic conductivity, a constant raster was created with this value	43 m/d based on Fariña (2009)
Groundwater confinement	Data for groundwater confinement was directly taken from studies made for the Guarani Aquifer System Project and reported by Schmidt (2009). The area of the watersheds is considered to be part of the "basalt aquifer" or Alto Parana Formation which is an unconfined aquifer, which contrasts with sandstone aquifers (typically called Guarani) and Cuaternary Aquifers which are considered confined. Guarani Aquifer System consists of different aquifers interconnected or interrelated between them. The basalt aquifer typically receives direct recharge from precipitation, but also contributes through dripping to the inferior located Guaraní aquifer (Misiones Formation) and the Permian aquifer (Guaraní-Independencia) (Schmidt, 2009)	Unconfined aquifer

which have an impact on pollution potential. Each factor or parameter is assigned a subjective rating between 1 and 10. Weight multipliers are then used for each factor to balance and enhance its importance. The final vulnerability, the DRASTIC index, is computed as the weighted sum overlay of the seven layers, according to Aller *et al*. (1987).

Drastic index categories were also taken from Aller *et al*. (1987) case study for the DRASTIC methodology assigning a color scheme known as "US national color code for DRASTIC index ranges" (Table 3). We used this same categorization to determine changes derived from water table changes (section 3.3) and climate change scenarios (section 3.4). Due to its relevance as a frame of reference seldom utilized it is presented in this paper.

GOD Calculation

GOD is the acronym for the following parameters: groundwater confinement (G) in the aquifer under consideration; overlaying strata (O) or vadose zone in terms of lithological character and degree of consolidation that determine their contaminant attenuation capacity (equivalent to impact of the vadose zone for DRASTIC); and depth to groundwater table (D) or to groundwater strike in confined aquifers (See Table 3 for more details in how data has been obtained and prepared for the models). According to GOD

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Table 3. DRASTIC index classification from Aller *et al*. (1987) and interpretative values according to US national color code.

DRASTIC index rate	Color	R, G, B	Potential vulnerability
Lower 79	Violet	238, 130, 238	Minimum
80-99	Indigo	75, 0, 130	Very Low
100-119	Blue	0, 0, 255	Low
120-139	Dark green	0, 128, 0	Medium Low
140-159	Light green	0, 255, 0	Medium High
160-179	Yellow	255, 255, 0	High
180-199	Orange	255, 127, 0	Very High
Higher 200	Red	255, 0, 0	Maximum

methodology the resulting aquifer vulnerability to pollution index is considered as the product of these three parameters, which is translated into a proposed categorization by Foster *et al*. (2002).

Changes in Groundwater Vulnerability from Dam Operations

An increase in water table due to Yacyreta dam operations has been debated, in face of the final 5 meter rise of the the Yacyreta reservoir to full capacity (years 2008-2009). Information of hydrogeological studies carried out by Lotti-Associatti (1999) and a review made by hydrogeologist Miguel Auge (n/a), regarding the possible effects of water table elevation to the aquifer, show that still little is known on how groundwater will behave after the water level of the dam changes from 78 m to 83 m. On one side of the predictions Lotti assures that due to the "strong basaltic" hydrogeology of the area, only a small "marginal fringe" of approximately 12.5 meters will be affected generating changes in the water table; in the other hand, Auge opposes this prediction by stating that there is not enough hydrogeological data available in the area to determine how change in the water level of the reservoir will affect groundwater, concluding the need for a stronger sampling using boreholes and the use of tridimensional models instead of the two dimensional models used by Lotti. So far no complementary studies or field data has been found in literature regarding changes in water table until this publication.

A worst case scenario was used to visualize and compare possible changes in aquifer vulnerability to pollution, where the change in the water table is equivalent to the elevation of the dam reservoir (5 m). Although unlikely to actually occur, considering information from Lotti, it serves the purpose of showing the extreme event of affecting the water table (depth to water parameter in DRASTIC and GOD) in the whole area of the watersheds.

Changes in Vulnerability from Climate Change Scenarios

We used climate change scenarios in mean annual precipitation and mean annual temperature caused by global climate change according to three different greenhouse gases emission scenarios considered by Limia (2000) and Gonzalez (2005). Our climate change scenarios considered changes of mean anual precipitation (+16.2% and -11.5%) in a 100 year span. These changes in precipitation were used to change values in net recharge, estimated locally as 3% of precipitation for the basaltic area of the watersheds (Table 4).

Results and Discussion

Vulnerability mapping as a result from application of GOD and DRASTIC models is shown in

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Table 4. Wells used for the determination of "depth to water" (D) through the interpolation of static level to determine aquifer vulnerability in the watersheds of Mboi Cae and Quiteria, Itapua, Paraguay.

Well	Locality	Depth (m)	Date (year)	Flow (m^3/s)	Static level (m)
IT-P0010	Capitán Miranda	116	-	24.00	24.50
IT-P0011	Capitán Miranda	115	-	12.00	0.00
IT-P0012	Capitán Miranda	122	1996	40.00	30.60
IT-P0022	Fram	62	1980	30.00	0.00
IT-P0031	Jesus	139	1984	5.00	65.00
IT-P0034	Trinidad	78	1986	12	35.00
IT-P0041	San Juan del Paraná	184	1992	4.60	3.70
IT-P0042	San Juan del Paraná	100	1996	35.00	3.00
IT-P0047	B° San Juan	137	1993	35.00	10.00
IT-P0048	B° San Juan	146	1995	30	27.00
IT-P0049	Cambyreta	206	1993	30.00	55.00
IT-P0051	Nueva Esperanza	228	1996	20	0.00
IT-P0052	Ita Paso	282	1997	10.00	19.05
IT-P0055	Polidedortivo (Diben)	264	1992	15.30	0.00
IT-P0058	Potrero Santa María (Villa)	99	1995	60.00	15.00
IT-P0067	Campichuelo	217	1997	40.00	21.10
IT-P0068	San José Obrero	80	1998	20.00	10.50
IT-P0078	Puerto Samuhu	117	1998	4.50	23.50
IT-P0079	San Blas Independencia	170	1998	25.00	23.50
IT-P0084	San Miguel Kuruzu	140	1997	30.00	34.50
IT-P0085	Azotea	306	1998	29.00	0.00
IT-P0086	B° Guazu-Arroyo Pora	158	1997	40.00	7.70
IT-P0088	Chaipe	117	1997	70.00	1.00
IT-P0089	Chaipe	129	1997	41.00	4.20
IT-P0090	La Paz	116	1997	40.00	0.00
IT-P0091	La Paz	163	1997	16.00	5.05
IT-P0124	Santo Domingo	152	2000	25.00	14.00
IT-P0125	Pradera Alta	121	2001	38.00	8.00
IT-P0136	Copetrol Santa María	0	1996		0.00
IT-P0141	Paso Guembe	118	2003	3	75.50
IT-P0198	Virgen de Itacua	91	2001	15.00	21.00
IT-P0203	B° San Juan	135	1996	50.00	10.40
IT-P0247	San Antonio Ypecuru	232	2002	10.10	18.50
IT-P0278	Ita Paso	286	2001	8	30.00
IT-P0279	Ita Paso	306	2002	8.00	20.00
IT-P0281	8 de Diciembre (Ita Paso)	200	2003	10.13	15.00
IT-P0336	San Blas Cerro Cora	103	2001	20.00	29.00
IT-P0362	Fram	285	2005	40.00	15.00
IT-P0372	San Luis del Paraná	162	2004	7.97	30.00
IT-P0388	San Nicolás Bº Guarani	222	2003	8.44	14.85
IT-P0389	Ytororo	190	2003	9.70	0.00

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Figure 2 for current conditions and predictions of change in groundwater vulnerability derived from dam operations. Results of GOD model show a 96% of the area of the Watersheds with values of 0.3 – 0.5 (moderate vulnerability to pollution) and 4% (Values 0.51 - 0.6) resulted as high vulnerability. Higher values are present in lower areas of the watersheds, where depth to groundwater is minimal and alluvial sands are present. DRASTIC model shows a 56% of the area of the watersheds to be classified as "medium high" (DRASTIC index 140-159) and a 22% percent as either "high", "very high" or "maximum" (DRASTIC index values 160 – >200).

Worst case scenario regarding water table change increase in 5 meters showed changes in vulnerability categories in DRASTIC. While "low" and "medium low" values lowered from 21.7 to 9.11% of the watersheds, and medium high values lowered from 56 to 50% of the total area of the watersheds, "high", "very high" and "maximum" values increased from 22% to 40% of the watersheds.

Changing the precipitation values, hence changing net recharge estimations, using climate change scenarios for a 100 year span, did not seem to affect the final DRASTIC outcome. Even though values changed in the resulting maps, vulnerability categories remained the same. Climate change scenarios were not analyzed with GOD model, since recharge values cannot be changed directly within the model,

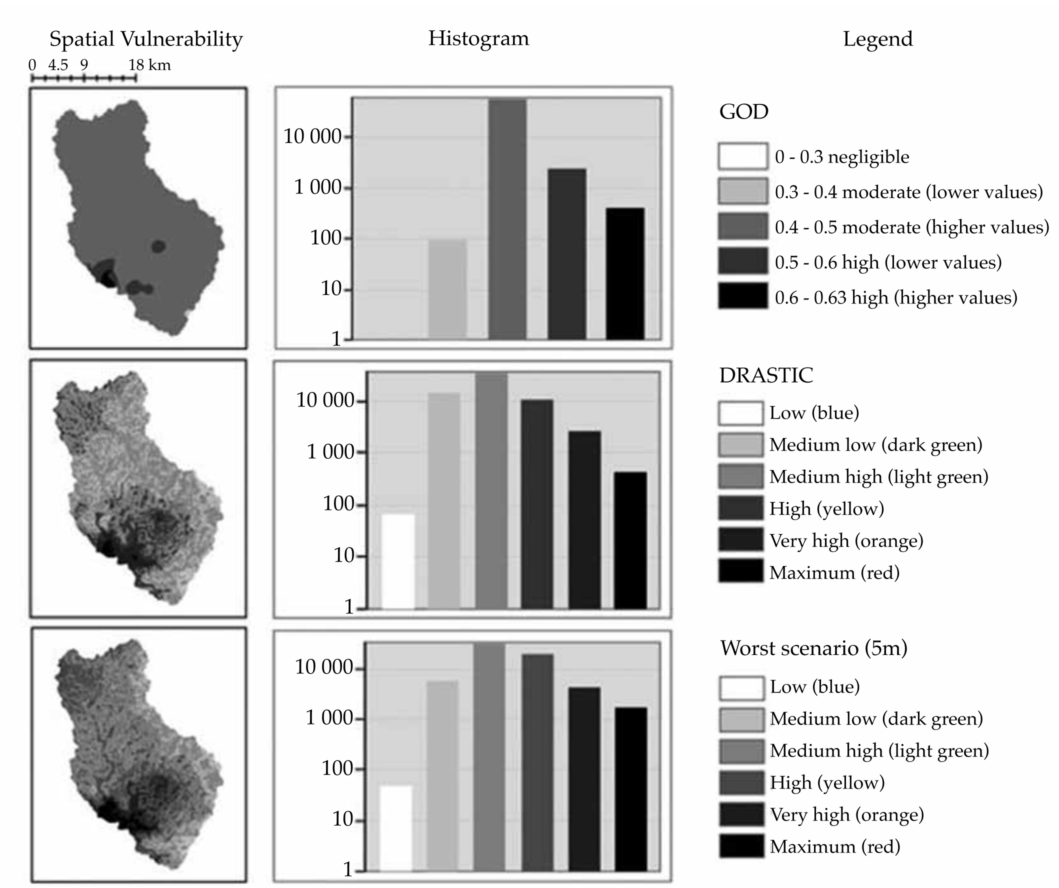

Figure 2. Aquifer vulnerability to pollution according to GOD and DRASTIC models and a worst case scenario for DRASTIC assuming water table increase from dam operations. Watersheds of the Mboi Cae and Quiteria Rivers in Paraguay.

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but instead focuses on geological characteristics of the overlaying strata.

Discussion

DRASTIC outcome maps show a more heterogeneous distribution of vulnerability classes compared to the GOD model. Similar remarks were made by Agüer*o* and Pujol (2002) while discussing their experience in applying the same models in the Central Valley of Costa Rica. Despite the DRASTIC model being used worldwide to determine aquifer intrinsic vulnerability, a constant discussion is the relation of the DRASTIC index with the real pollution found in the aquifer. Leone, Ripa, Uricchio, Deak, & Vargay (2009) after studying the vulnerability and risk evaluation of agricultural nitrogen pollution for Hungary's main aquifer using DRASTIC and GLEAMS models conclude that DRASTIC, as a parameter/qualitative method, performs better in the general correspondence of trends, which means a correspondence between higher nitrate content and higher DRASTIC scores. However, this is not necessarily true for all areas where these and other pollutants have been sought, thus, papers where investigation on areas which were evaluated with these techniques, and when applied to areas which are already contaminated are still in great need to understand the application of these models and their prediction capacities and results.

As a first approach, and not withstanding the need of proper further water quality analysis, we propose the use of these models, which can also provide help determining knowledge gaps of hydrogeological characteristics of the watersheds. It should also be noted that the application of these models, does not seek to evaluate on specific threats, which would require each threat to be studied independently, but instead, intends to determine the intrinsic hydro-geological settings and their vulnerability, which could better lead to determining areas which could be directed towards conservation or special management considerations.

According to Rupert (1999), DRASTIC, despite being used to develop groundwater vulnerability maps in the United States, has met with mixed success, since it is usually not calibrated to measure contaminant concentrations, suggesting necessary improvements to the DRASTIC groundwater vulnerability mapping by calibrating the rating scheme. However, DRASTIC still can be considered a first approach to GVP, specifically when information is limited or when the vulnerability concept does not include only a particular pollutant threat or risk but as described by Lobo-Ferreira and Oliveira (1997) "vulnerability is the one that refers to the intrinsic characteristics of the aquifer, which are relatively static and beyond human control". Despite our study agreeing with this general concept, we consider human activities, such as the effects of large dam operations influencing water table could affect vulnerability to pollution.

Locally, Laino (2005) found distinct values in neighboring Capiibary River watershed. After comparison of classes, 36% showed a "low" vulnerability and 64% a "medium low", "medium high" and "high" categories. The categorization used by Laino was different from the used for the present study, thus comparing both studies was only possible at this level. This situation leads to suggest a standardization of results for easier comparison among studies.

Our experience in application of both models, is in accordance to remarks by Gogu and Dassargues (2000) considering the concept of groundwater vulnerability as a useful tool for environmental planning and decision-making, we also found that simple models provide similar results to the complex ones. To our experience, a simpler model (such as GOD) is more likely to meet data input available currently for Paraguay, however loosing in finesse of the final result. Since DRASTIC and GOD are a first step towards assessing groundwater vulnerability and considering that literature review suggests reconfirming data with specific contaminants and risks, a further validation of the model at the local level is suggested for future research, including analysis of groundwater quality and monitoring.

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Conclusions

Aquifer vulnerability to pollution was found to be intermediate-high similarly using both DRASTIC and GOD models, more detailed results were obtained when using DRASTIC which was also in demand of data which was not readily available for the study area or at the appropriate scale. Higher vulnerability values were found towards the lower parts of the study area with both models showing similar descriptors and values in the respective scales. A "medium to high" vulnerability shows that concerns about pollution of the aquifer in the midterm should be considered to instrument possible programs dedicated to the minimization of contaminants in agriculture, but also, since the highest vulnerability areas are located in the lower parts of the watersheds, where urban areas are settled, our results suggest the need to identify pollution sources in urban areas as a possibly major threat to the shallow aquifer. It was also unexpected that climate change scenarios didn't show changes in vulnerability classes. This highlights the importance of groundwater protection, study and conservation as a mitigation strategy to climate change and justifies the need to better understand management practices and their impact in groundwater.

We propose the use of the National Color Code as a frame of reference for future DRASTIC applications allowing a simpler comparison of results. It should be noted that vulnerability assessment implies uncertainties associated with the calculations and limitations of the data used (National Research Council, 1993; Kumar *et al*., 2015), thus, this uncertainties are acknowledged for this study as well, and recommend further work and more data to progress towards better approximations.

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