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Natural vulnerability of water resources in the Formoso River basin, Northern Brazil

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The natural vulnerability characterization provides fundamental support for identification of areas more susceptible from the hydrology point of view, assuring the maintenance of water resource features. In this context, this study aimed to characterize the natural vulnerability of water resources based on long-term streamflows, base flow and aquifers' susceptibility to contamination, for Formoso River basin, located in southwestern Tocantins. For that, subdivision by level 5 Ottobasins and discharge and precipitation data sets, both available from the "Brazilian National Water Agency", and the geological map developed by "Tocantins State Bureau of Planning" (SEPLAN) were used. The final natural vulnerability of water resources presented degrees varying from low to very high. Areas with lower vulnerability were observed in the basin headwaters, mainly due to the greatest both long-term (SY_{qlt}) and 90% of the exceedance ($SY_{90\%}$) specific discharges. "High" vulnerability were identified in most of the middle basin course while "Very High" vulnerability in the lower basin course given by lower SY_{qlt} and $SY_{90\%}$ and by the occurrence of the alluvial aquifers which present high natural susceptibility to contamination.

Key words: Natural resources, hydrology, watershed management.

INTRODUCTION

One of the greatest contemporary environmental concerns is the preservation of water resources given the numerous human activities potentially harmful to this feature, since the demand for them has increased exponentially in the last decade. Among several aspects related to water resources, there is the concern to ensure the maintenance of its availability and quality.

Agricultural and livestock are the human economic activities that spatially have greater demand for landing, Changing significantly the landscape. Normally, these activities are based on the alteration of the natural ecosystems, and they have redefined the land use in large scales throughout the last three Centuries (Ramankutty and Foley, 1999). According to Bartholomé and Belward (2005) almost 16% of the planet's surface is occupied by tillage. However, these activities have been important sources of water pollution mainly if they are developed based on inadequate soil conservation practices (Zhang et al., 2009; Orzepowski et al., 2014), affecting the water quality by soil erosion that carries

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sediments, nutrients, pathogens, pesticides, heavy metals and others (USEPA, 2005). Thus, the groundwater contamination studies have been recognized as essential for mitigation strategies adoption for adequate land use, reducing the impacts on water resources.

The world population reached up 7.2 billion in 2014, with an expansion estimated around 9.6 billion for 2050 (United Nations, 2014). Irrigated agricultural lands cover approximately 15% of cultivated areas, being fundamental for food production aiming to supply this accelerated growth population, as this system has greater productivity (Simonovic, 2002). Worldly, according to Doll and Siebert (2002), irrigated fields are responsible for 90% of all water consumption and more than 40% of food production as well. This way, it is essential to create tools that allow the estimation both surface and groundwater availability as it is associated to the geomorphology of the basins, which is characterized by the climate, geology, soils and topography attributes. In this context, the identification of basins (and sub-basins) with reduced water availability permits to find places in which are priority for encouragement of great management practices adoption, aiming to increase groundwater recharge rate as well as identification of the most strategic sections for dams building for water storage.

Based on these features, the agricultural and livestock planning, especially the integration between water resources management and appropriate land uses, requires detailed studies about natural vulnerability, searching not only for maintenance of water quality and quantity but also for optimization its use. General way, the natural vulnerability can be defined as a set of soil, climate, hydrology and geology attributes of a given hydrograph basin, which control its capacity for self-restoration (Gomes et al., 2002). In the approach of natural vulnerability of water resources, it is considered the environmental fragility of these attributes, however, without taking into account the anthropic activities (Carvalho et al., 2008; Ribeiro et al., 2011).

Vulnerability can be represented in cartography form, which enables better preparation of proposals for sustainable watershed development by management agencies. This type of study is fundamental for decision maker and directs the choices of areas for the conducting of potentially degrading activities (Szlafsztein and Sterr, 2007; Rahman, 2008; Ribeiro et al., 2011). The determination of the vulnerability indicators provides assistance for the prevention and recognition of the more sensitive areas from a hydrological point of view, ensuring the maintenance of the qualitative and quantitative aspects.

A hydrograph basin is defined as a group of lands drained by a main river and its tributaries. The Formoso River is a major tributary of the right arm of the Araguaia River (Javaés River), in the southwest of the Bananal Island, Tocantins state, northern Brazil. It belongs to the Tocantins-Araguaia hydrographic region according to the hydrographic division of the Brazilian National Water Agency (ANA). The Formoso River basin has a drainage area of 21,328.57 km^2, which corresponds to approximately 7.7% of the total area of the State of Tocantins and 5.6% of the Araguaia River basin, according to the State of Tocantins Basin Plan.

In Brazil, the states of Minas Gerais and Espírito Santo, both in Southeastern region, have worked with Ecological-Economic Zoning (EEZ), which have as primary purpose to guide the sustainable economic development of these states, allowing the characterization of regions more vulnerable from both socio-economic and ecological point of views (www.zee.mg.gov.br; www.ti.lemaf.ufla.br/zeees.html). The vulnerability of water resources has been fundamental in these zoning studies, as they have allowed the characterization of regions in terms of their natural water supplies and, in same time, areas with greater potential for irrigation, become the use of water resources more suitable for agricultural purposes (Mello et al., 2008). In this context, this study aims to determine the natural vulnerability of water resources taking the surface and subsurface runoff, and aquifer susceptibility to contamination as a reference, for the Tocantins portion of the Formoso River basin. To determine the regions that are more susceptible to contamination, the objective is to provide directional technical support for the integrated management of water resources in this important basin for the state of Tocantins, which already has its own Watershed Committee and which has been suffering the increasing effects of water shortages during drier periods of the year.

MATERIALS AND METHODS

Characterization of the studied site and database

The studied area comprises the Formoso River basin, which is located in the southwest region of the State of Tocantins, Northern Brazil, between 10°28’S and 13°16’S latitude and 48°50’W and 49°57’W longitude. The Formoso River basin is formed by 8 major sub-basins: Escuro, Pau Seco, Taboca, Xavante, Dueré, Lago Verde, Urubu e Áreas Marginais ao rio Formoso (SEMADES, 2007).

The Formoso River basin covers parts of the territory of 21 municipalities, respectively, 18 in the state of Tocantins and 3 in the state of Goias, however, the involvement of the latter are limited to less than 3% of the basin’s area (Figure 1). Livestock and agricultural are the most important land uses, covering 39% of its territory. It is worth mentioning the presence of the “Formoso River Irrigation Project” in the mid-western region of the basin, which has a useful area of 18,000 ha in which rice is grown in the rainy season (October to April), and soybean, corn, beans and watermelon in the dry season (May to September) (http://seagro.to.gov.br). The remaining natural vegetation mainly consist of Brazilian Savanna (34.7%), Savanna Forest (4.7%), Gallery and Riparian Forest (7.4%), Semidecidual Seasonal Alluvial Forest (4.9%) and Savanna Parkland (4.5%) (SEPLAN, 2012).

On the Araguaia plain, Plintosols and Gleysols are predominating, both with drainage impediment and with frequency

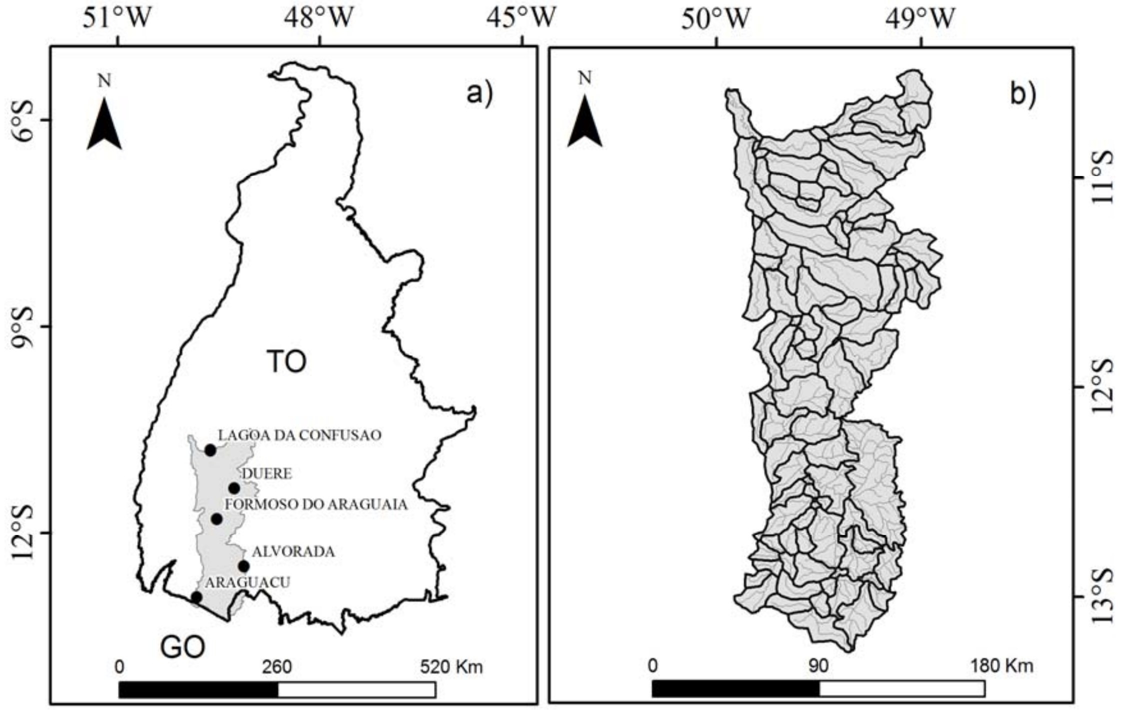

Figure 1. Location of the Formoso River basin in the states of Goiás (GO) and Tocantins (TO) (a) and level 5 Ottobasins of national hydrographic division and hydrography (b).

of floods in rainy season (IBAMA, 1994).

Metasediment/Metavolcanic, crystalline and cenozoic formations are the predominant geomorphological domains in the basin. Metasediment/Metavolcanic and crystalline domains are related to the so-called fissure aquifer, and presents limited hydrogeological favorability. The cenozoic formations, in turn, have a porous aquifer, characterized by having a primary porosity and better hydrogeological favorability (CPRM, 2014). Figure 1a shows the location of the Formoso River basin with emphasis on the municipal centers inserted in the basin.

Aiming to develop the zoning of the natural vulnerability of water resources in the Formoso River basin, subdivision by level 5 Ottobasins was considered, available from Brazilian National Water Agency (ANA, 2013). The level 5 Ottobasins of the Formoso river are shown in Figure 1b.

One of the main challenges for the development of hydrological studies for the basin is the low availability of discharge gauging stations. In order to minimize this limitation, we selected stations from other Araguaia River sub-basins, near the Formoso River, with homogeneous climatic and physiographic characteristics (SEPLAN, 2012). Based on these sub-basins, we proceeded to fit the equations for the hydrological regionalization of the hydrological indicators considered in this study. Long-term discharges data sets of the following stations were obtained from the Hidroweb/ANA (ANA, 2013): 25070000, 25090000, 25750000, 26720000, 26750000, 26790000 and 27370000.

Natural vulnerability of water resources

The water resources has been treated within the natural vulnerability concept established by the Ministry of Environment, as advocated in the Ecological-Economic Zoning (EEZ) developed for the states of Minas Gerais and Espírito Santo (Carvalho et al., 2008). This concept relies on the natural capability of the environment to recover itself when affected by anthropic activities. This means that the concept of vulnerability established concerns biotic (native flora and fauna) and abiotic characteristics (soil, climate and hydrology), that is, human activities are not considered. Thus, regarding to water resources the variables that can express its natural vulnerability are water availability and the possibility of geological aquifers contamination, just like applied by Mello et al. (2008) in the EEZ of Minas Gerais state.

Regarding to natural availability, this study considered two components, which are easier to obtain for entire the basin. The first is associated with surface water availability and has been associated to the long-term average specific yield indicator (SY_{qlt}), which is widely used in studies on surface water use, especially for flow regularization through dams. The second component aimed to characterize water availability during the dry season, which is markedly severe in the basin, and during which the streamflows are essentially controlled by the groundwater sources whose availability reflects the natural regulatory capacity of the sub-basins. This component was portrayed by two indicators: (a) Specific discharge associated with 90% flow retention ($SY_{90\%}$), which is widespread in water resources management in Brazil and considered the benchmark for the granting of water resources use in the state of Tocantins and also in the context of federal rivers; (b) Regulatory reserve volume of the aquifer (V) (Castany, 1967), which allows inferences about the natural storage capacity. Thus, it is understood that the greater the water availability, the less natural vulnerability of the sub-basin.

To infer about the aquifer susceptibility to contamination, geological and geomorphological units were interpreted as function of their potential for leaching of contaminants, like the type of rock, and existence of faults. For this indicator, it was considered that the higher the susceptibility to contamination, the higher the natural vulnerability of the basin. Figure 2 shows a schematically

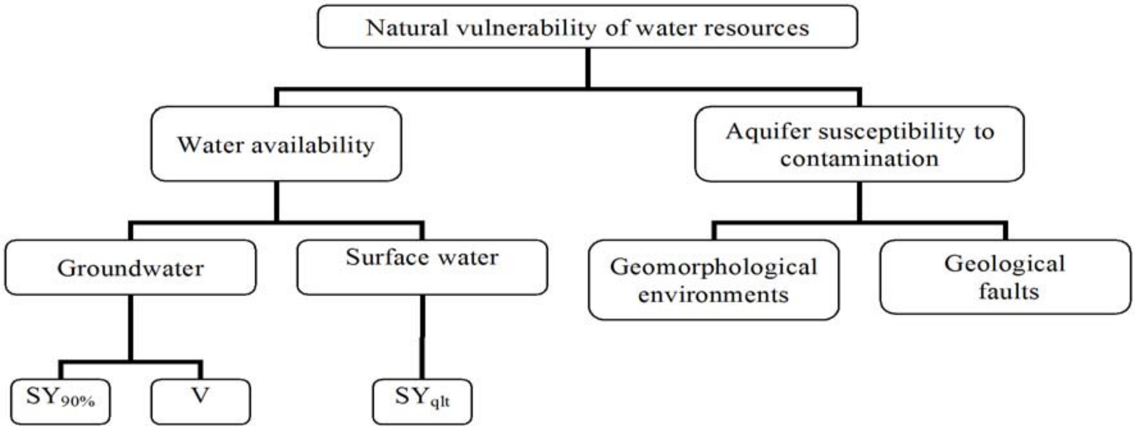

Figure 2. Organogram of the indicators used to assess the natural vulnerability of water resources in the Formoso River basin, Tocantins state, northern Brazil.

organogram, detailing the procedure adopted for characterization of indicators used to express the natural vulnerability of water resources.

Specific yield with 90% retention ($SY_{90\%}$)

The natural water availability can be evaluated by the behavior of the base flow, which is the main component of the streamflow during the dry period. This indicator is linked to the capability of the basin to groundwater recharge (Mello et al., 2008).

The minimum flow associated with percentiles of 90% ($Q_{90\%}$) identifies the amount of flow that is equaled or exceeded in the watercourse 90% of the time, and is obtained from the flow retention curve. Having obtained $Q_{90\%}$, in m³ s^{-1}, the regionalization of these flows, considering as an explanatory variable, the drainage area of the sub-basins, was performed as described below:

$$Q_{90\%_{sub-ba\sin_i}} = a \cdot Ad_{sub-ba\sin_i}{}^{b} \qquad (1)$$

Where *a* and *b* are regression adjustment parameters and *Ad* is the drainage area of the sub-basin in km².

The adjusted regionalization equation was used to calculate $Q_{90\%}$ for each level 5 Ottobasin of the Formoso River (Figure 1b). Subsequently, the specific discharge, in L s^{-1} km^{-2}, was obtained for each sub-basin, according to Equation 2:

$$SY_{90\%_{sub-ba\sin_i}} = \frac{Q_{90\%_{sub-ba\sin_i}}}{Ad_{sub-ba\sin_i}} \cdot 1000 \qquad (2)$$

After obtaining the regionalization equations, hydrological zoning was conducted using ArcGIS 9.1® software. For each indicator, the value intervals for the interpretation of vulnerability as “Very High”, “High”, “Medium” and “Low”, were defined based on irregular intervals, maintaining the same number of observations (sub-basins) in each class.

Aquifer regulatory reserve at the beginning of the recession period (V)

This indicator allows inferring on the volume available for aquifer discharge at the start of the recession period. In this sense, the greater the stored volume, the greater it’s natural regulatory capacity and therefore the lower its natural vulnerability. Its quantification for each fluviometric station was carried out according to the method of Barnes (Castany, 1967), as presented in Equations 3, 4, 5 and 6. Subsequently, the V regionalization was calculated using the drainage area as the explanatory variable. Then, this equation was applied to calculate V values for the level 5 Ottobasins of the Formoso River. Furthermore, it presents the procedure for obtaining V in hm³:

$$Q_t = Q_0 \cdot e^{-\alpha \cdot t} \qquad (3)$$

$$\ln(Q_t) = \ln(Q_0) - \alpha \cdot t \cdot \ln(e) \qquad (4)$$

$$\alpha = \frac{\ln(Q_0 / Q_t)}{t} \qquad (5)$$

$$V = \frac{Q_0 \cdot 0.0864}{\alpha} \qquad (6)$$

in which Q_t is the streamflow rate at time *t* in m³ s^{-1}; Q_0 is the streamflow rate at the start of the recession, m³ s^{-1}; *α* is the coefficient of discharge of the aquifer, day^{-1} and *t* are equivalent to the number of days elapsed between Q_0 and Q_t.

Long-term average specific yield discharge (SY_{qlt})

The long-term average discharge (Q_{lt}) is the average flow observed at a particular gauging station. Having obtained the Q_{lt}, in m³ s^{-1}, the regionalization of the streamflow was also conducted considering the drainage area as an explanatory variable as described below:

$$Q_{LT_{sub-ba\sin_i}} = a \cdot Ad_{sub-ba\sin_i}{}^{b} \qquad (7)$$

in which *a* and *b* are the regression adjustment parameters and *Ad* is the drainage area of the sub-basin in km².

The regionalization equation was applied to calculate Q_{lt} for each level 5 Ottobasin of the Formoso River. Subsequently, it was

Table 1. Geomorphological environments, corresponding scope and degree of vulnerability considered in the Formoso River basin.

Geomorphological domain	Hydrogeological domain	Hydrogeological subdomain	Occurrence (%)	Vulnerability to contamination
Unconsolidated sedimentary deposits	Cenozoic formation	Alluvium	7.4	Very High
Unconsolidated sedimentary deposits	Cenozoic formation	Araguaia	11.3	High
Unconsolidated sedimentary deposits	Metasediments/ metavolcanic	Metasediments/ metavolcanic	0.4	Average
Basements on complex styles	Crystalline	Crystalline	7.2	Low
Basements on complex styles	Cenozoic formation	Alluviums	0.0	Very High
Basements on complex styles	Metasediments/ metavolcanic	Metasediments/ metavolcanic	0.2	Average
Bands of folds and metasedimentary cover	Crystalline	Crystalline	25.7	Low
Bands of folds and metasedimentary cover	Cenozoic formation	Alluviums	5.7	Very High
Bands of folds and metasedimentary cover	Cenozoic formation	Araguaia	0.3	High
Bands of folds and metasedimentary cover	Metasediments/ metavolcanic	Metasediments/ metavolcanic	41.9	Average

converted into specific yield discharge, in L s^{-1} km^{-2}, according to Equation 8:

$$SY_{qlt_{sub-basin_i}} = \frac{Q_{LT_{sub-basin_i}}}{Ad_{sub-basin_i}} \cdot 1000 \qquad (8)$$

Aquifer contamination susceptibility (ACS)

The potential for aquifer contamination corresponds to susceptibility of groundwater contamination by toxic substances that may reach the aquifer mainly by the leaching process (Mello et al., 2008). The geological map of the basin was used to qualitatively characterize the ACS indicator, following the methodology proposed by Mello et al. (2008) for the EEZ of Minas Gerais state. Sites with geological faults had their vulnerability increased one step up, since they represent points that facilitate the leaching process and subsequent contamination (Mello et al., 2008). Table 1 presents the existing geomorphological environments and hydrogeological domains in the Formoso River basin, their subdomain and the interpreted vulnerability to the contamination.

Natural vulnerability of water resources in the Formoso River basin

As the vulnerability was treated qualitatively, values were allocated for the final weighting of the vulnerability of the indicators for each vulnerability level as follows: "Low" = 1; "Medium" = 2; "High" = 3 and "Very High" = 4. Based on the EEZ of Minas Gerais (Mello et al., 2008), the composition of the final vulnerability weighted by the indicators described above, was carried out considering the following weights: SY_{qlt} =30% ; $SY_{90\%}$ = 22.5%; V = 22.5% and ACS = 25%. Thus, the final vulnerability (FV) was obtained according to Equation 9:

$$VF = \sum_{i=1}^{4} Vi \cdot Pi \qquad (9)$$

in which Vi is the value of the vulnerability of indicator i and Pi is the weight associated with the indicator i. The final vulnerability classification was considered as: "Low": 1 ≤ FV <1.75; "Medium": 1.75 ≤ FV <2.5; "High": 2.5 ≤ FV <3.25 and "Very High": ≥ 3.25. Qualitatively, in terms of the final results of the vulnerability, Mello et al. (2008) observed that different weights produced similar results, that is, for a given sub-basin, the FV will change if other weights are considered but its vulnerability classification remains the same. This occurs because the geographic reference is the same, equivalently describing the physical behavior of the indicators in qualitative terms.

RESULTS AND DISCUSSION

Surface water availability

The vulnerability associated with the long-term average specific yield discharge (SY_{qlt}) is of great importance due to the widespread use of this flow in studies on flow regulation and quantification of the watershed hydraulic energy potential. The regionalization equation obtained for Q_{LT} is presented in the following sequence:

$$Q_{LT\,sub-basin_i} = 0.0184 \cdot Ad_{sub-basin_i}^{\;0.9651} \quad r^2 = 0.99 \qquad (10)$$

The SY_{qlt} value classes in establishing the vulnerability were: "Very High": SY_{qlt} ≤ 14.16; "High": 14.17 ≤ SY_{qlt} ≤ 14.83; "Medium": 14.84 ≤ SY_{qlt} ≤ 15.31; "Low": SY_{qlt} ≥ 15.32.

Figure 3a shows the SY_{qlt} map for level 5 Ottobasins of the Formoso River. To interpret this figure, it is considered that the larger the SY_{qlt} value, the lower the vulnerability, namely, the higher the water availability.

It can be observed that small headwater basins showed less vulnerability. This can be attributed to the higher specific yield inherent in headwater regions, where the total precipitation is higher and there is preservation of

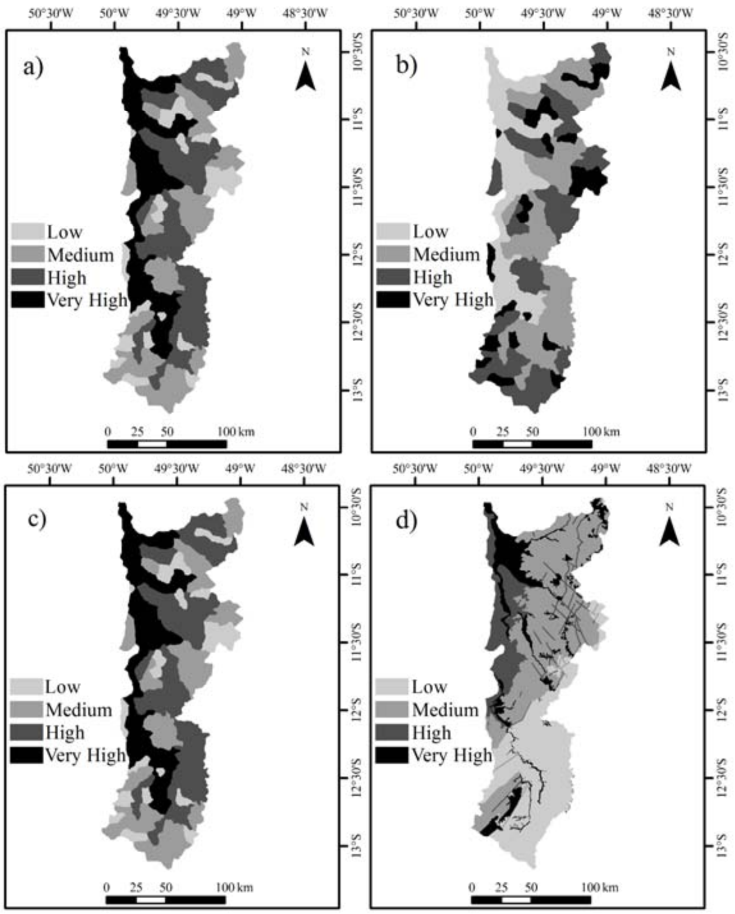

Figure 3. Natural vulnerability associated with the components: long-term average specific yield discharge (a), aquifer regulatory reserve volume (b), specific yield with 90% retention (c) and aquifer natural susceptibility to contamination (d).

native vegetation, favoring the recharge process, and runoff on slopes (Alvarenga et al., 2012; Menezes et al., 2009; Mello and Curi, 2012). Also in this context, for the middle and lower course of the Formoso River basin, have higher drainage area and the vulnerability ranged from "High" to "Very High". In these areas, the soils are deeper and flat, favoring evapotranspiration and possibly stretches where the watercourses become influent. In these regions, the construction of dams would be a plausible option, since they would allow the storage of water in the rainy season and its use to become the watercourses perennial during the severe drought period that occurs in the region.

Groundwater vulnerability

The identification of vulnerability associated with the volume of the aquifer regulatory reserve at the beginning of the recession is of great importance in the context of the Formoso River basin, in which the lower order watercourses have an intermittent flow regime. The regionalization equation of this variable shows a good adjustment, as shown in the following sequence:

$$V_{sub-basin_i} = 834765 \cdot Ad_{sub-basin_i}^{0.5491} \quad r^2 = 0.98 \qquad (11)$$

To assess the vulnerability associated with V, it was taken into account that sub-basins that have lower regulatory reserves, are more vulnerable. To classify the vulnerability of this component the following classes have been applied: "Very High": V ≤ 15.02 hm³; "High": 15.02 hm³ < V ≤ 24.85 hm³; "Medium": 24.85 hm³ < V ≤ 51.55 hm³; "Low": V > 51.55 hm³.

In Figure 3b, it is presented the vulnerability map associated to V. As can be seen, the headwater regions were more vulnerable than the middle and lower watercourse of the Formoso River basin. In this context, it is clear that this indicator is able to capture the vulnerability

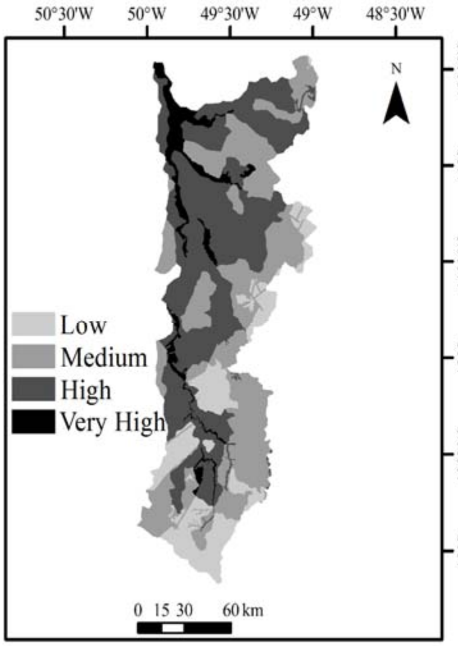

Figure 4. Final natural vulnerability of water resources to Formoso River basin, TO.

of the aquifer discharges, where intermittent watercourses occur in the headwater regions. This is essential to weigh the vulnerability associated with the groundwater availability, jointly with the $SY_{90\%}$ indicator.

The second vulnerability attribute associated with the groundwater component was the specific yield discharge with 90% retention ($SY_{90\%}$). The $Q_{90\%}$ calculation for the Ottobasins was performed according to Equation 12:

$$Q_{90\% \, sub-ba\sin_{i}} = 0.0059 \cdot Ad_{sub-ba\sin_{i}}^{0.633} \quad r^2 = 0.81 \qquad (12)$$

For this indicator, the lower the flow value, the greater the vulnerability. In this sense, the vulnerability associated with $SY_{90\%}$ the following value classes were considered: “Very High”: $SY_{90\%} \leq 0.38$; “High”: $0.39 \leq SY_{90\%} \leq 0.61$; “Medium” : $0.62 \leq SY_{90\%} \leq 0.85\%$; “Low”: $SY_{90\%} \geq 0.86\%$. As can be seen in Figure 3c, the lower watercourse of the Araguaia River showed greater vulnerability. In other words, headwater basins, despite higher recharge (as detected by the $SY_{90\%}$ indicator), have less regulation ability, that is, they drain faster due to the topographical conditions, storing water for less time, which makes them more vulnerable from this point of view.

Aquifer susceptibility to contamination

The degree of vulnerability due to the aquifer contamination susceptibility was established through the interpretation of the source material, as portrayed in Table 1. The higher the aquifer contamination susceptibility, the higher its vulnerability will be, especially in locations with geological faults, because these are points that facilitate the leaching process and subsequent contamination.

Figure 3d presents the map of aquifer contamination susceptibility. Higher hydrogeological vulnerability can be seen in the alluvium subdomain, which extends along the main river basin channels, since this litological unit is more susceptible to contamination. The lower vulnerability inherent in the crystalline subdomain, can be observed in the southeastern part of the basin, while the “Medium” vulnerability inherent in the metasedimentary subdomain, prevails in almost the entire middle watercourse.

Final vulnerability

The final vulnerability of water resources, which is the product of the weighting of the four components previously treated, showed a classification from “Low” to “Very High” vulnerability degree, as shown in Figure 4.

Some regions with “Low” vulnerability were found in the headwater region of the south of the Formoso River basin. This result is primarily related to the combination of “Low” vulnerabilities for the SY_{qlt} and $SY_{90\%}$ indicators and the presence of the crystalline hydrogeological subdomain, which presents “Low” vulnerability to aquifer contamination. “High” vulnerability prevailed in most of the middle watercourse region of the Formoso River, indicating that special cares are needed for the sustainable development of these sites. The “Very High” vulnerability class occurred mainly in the lower watercourse of the Formoso River. Although this region had presented “Low” vulnerability for the indicator associated with the aquifer regulatory reserve volume, it resulted in “Very High” vulnerability for the SY_{qlt} and $SY_{90\%}$ indicators and “High” for aquifer contamination susceptibility, as it inserted within of alluvium hydrogeological subdomain, as described by Chae et al. (2004) and Chae et al. (2009). In this context, the alluvium subdomain region, especially in the lower watercourse of the Formoso River, can be considered as a priority for water resource conservation in the Formoso River basin. However, this study allows the detection of other points of great importance. The reduced aquifer regulatory reserve volume in the Formoso River headwaters region indicates these areas as priority for the application of basin management techniques. Engineering techniques to stimulate the terracing, construction of infiltration basins, direct planting and adopting techniques that favor water infiltration into the soil can be implemented by water resource managers, aiming to increase the water yield and especially to perennial the headwater watercourses.

Conclusion

1. It was possible to indicate the areas with “Very High” final vulnerability degree as priority for the planning and management of water resources and land use in the Formoso River basin.
2. The interpretation of vulnerability associated with the aquifer regulatory reserve volume allowed the identification that the headwater regions are priorities for the development of watershed management techniques, seeking to become the watercourses perennial.
3. It was evident that in the middle and lower watercourse, where the specific surface and groundwater discharges are reduced, the construction of dams aimed at water storage is essential to promote water use during severe period of drought, which occurs in the Formoso River basin.

Conflict of Interest

The authors have not declared any conflict of interest.

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