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Using GIS to estimate the susceptibility index in the Gravataí River Basin

Uso do SIG para estimativa do índice de susceptibilidade na Bacia do Rio Gravataí

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Abstract

Using underground water sources has become an important alternative for supplying urban and rural populations. Therefore, this study aims to estimate the susceptibility to contamination of the aquifer at the scale of the Gravataí River Basin, metropolitan region of Porto Alegre. To this end, a database of hydrological and hydrogeological information was created for the area, and as an aid to a geographic information system, the susceptibility index method was used. The results indicated that the area has susceptibility classes ranging from very low (05.61%) to very high (00.08% of the area), with a predominance of a moderate to low class (37.02%). In the areas most susceptible to contamination, there is a higher demand for agricultural activities, especially rice cultivation, which significantly influences contamination due to irrigation flooding. Areas susceptible to contamination were also found near urban areas, highlighting the need for an efficient sewage system. Thus, it can be concluded that the method proved to be effective and can be applied in the environmental planning of the area, serving as support for environmental studies and planning within the Gravataí River basin.

Keywords:
Groundwater, Contamination, Geoprocessing.

Resumo

A utilização dos mananciais subterrâneas tem se tornado uma importante alternativa para o abastecimento da população urbana e rural. Assim, esse estudo tem objetivo estimar a susceptibilidade à contaminação do aquífero na escala da Bacia Hidrográfica do Rio Gravataí, região metropolitana de Porto Alegre. Para isso, foi criado um banco de informações hidrológicas e hidrogeológicas da área, e com auxílio de um sistema de informação geográfica, utilizou-se o método do índice de susceptibilidade. Os resultados indicaram que área apresentou todas as classes de susceptibilidade, variando entre muito baixa (05,61 %) a muito elevada (00,08 % da área), com predomínio das classes moderada a baixa (37,02%), moderada a alta (28,04%) e baixa (22,72%),

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sendo que as demais classes (Muito elevada com 0,08 %; elevada 6,53% e muito baixa 5,61%) representaram 12,62 % da área. Nas áreas mais susceptíveis à contaminação são as que ocorrem maior demanda de atividades agrícolas, principalmente o cultivo de arroz, que é um ponto com grande influência para contaminação, por conta dos alagamentos das irrigações. Obteve-se também a ocorrência de áreas susceptíveis próximas a área urbana, que faz com que se leve em consideração a necessidade de uma rede de esgoto eficiente. Assim, conclui-se que o método se mostrou eficiente, sendo possível sua aplicação no planejamento ambiental da área, servindo como suporte em estudos ambientais e de planejamento dentro da área da bacia hidrográfica do Rio Gravataí.
Palavras-chave:
Águas subterrâneas, Contaminação, Geoprocessamento.

I. INTRODUCTION

The use of geospatial tools is becoming increasingly common in the scientific community due to their ease and practicality, from data acquisition—which is becoming more accessible—to presenting the obtained results. In the case of groundwater, this use is particularly notable for estimating the susceptibility and vulnerability of the environment to human activities.

Among the most varied methods, three can be mentioned, namely GOD (G - Groundwater hydraulic confinement, O - Overlaying Strata and D - Depth to groundwater table) developed by Foster et al. (2002; 2006), DRASTIC (Depth to water table - D, Recharge - R, Aquifer media - A, Soil media - S, Topography - T, Impact of vadose zone - I and hydraulic Conductivity - C), described by Aller et al. 1987). Finally, the SI (Susceptibility Index) method, developed by Ribeiro (2005), simplified the original DRASTIC (ALLER et al., 1987), removing the S and I variables and inserting the LU (Land Use) variable. This change facilitated its application as the changed variables were difficult to obtain, requiring field collections.

The relevance of the aforementioned methods in territorial organization is gaining increasing recognition in the scientific community (ROCHA; CRUZ 2018; FANNAKH; FARSANG, 2022; LIMA et al., 2022; KOESUMA et al., 2022; EMBERGA et al., 2022; MAHDID et al., 2022; SRESTO et al., 2022; Both are very useful for avoiding the occupation of potentially contaminated areas, and maintaining the sustainability of aquifer and reservoir recharges (NASCIMENTO et. al., 2019). Thus, geospatial tools are useful for urban planning, particularly in large population centers, as they aid in decision-making and environmental preservation. In this context, this study aims to estimate the susceptibility to contamination of the aquifer at the scale of the Gravataí River Basin. This area is near Greater Porto Alegre - RS and has a high population density.

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II. MATERIALS AND METHODS

CHARACTERIZATION OF THE STUDY AREA

The Gravataí River Basin (Figure 1) is part of the Guaíba Hydrographic Region (U). The Basin has an area of 2,015 square kilometers and a population of 1,379,259 inhabitants, of which 1,349,232 live in urban areas and 30,027 in rural areas (SEMA, 2020). The basin comprises two different regions: the upper part, where agricultural activities predominate; and the lower part, which contains urban-industrial areas and wetlands due to its convenient access to water (FEPAM, 2020).

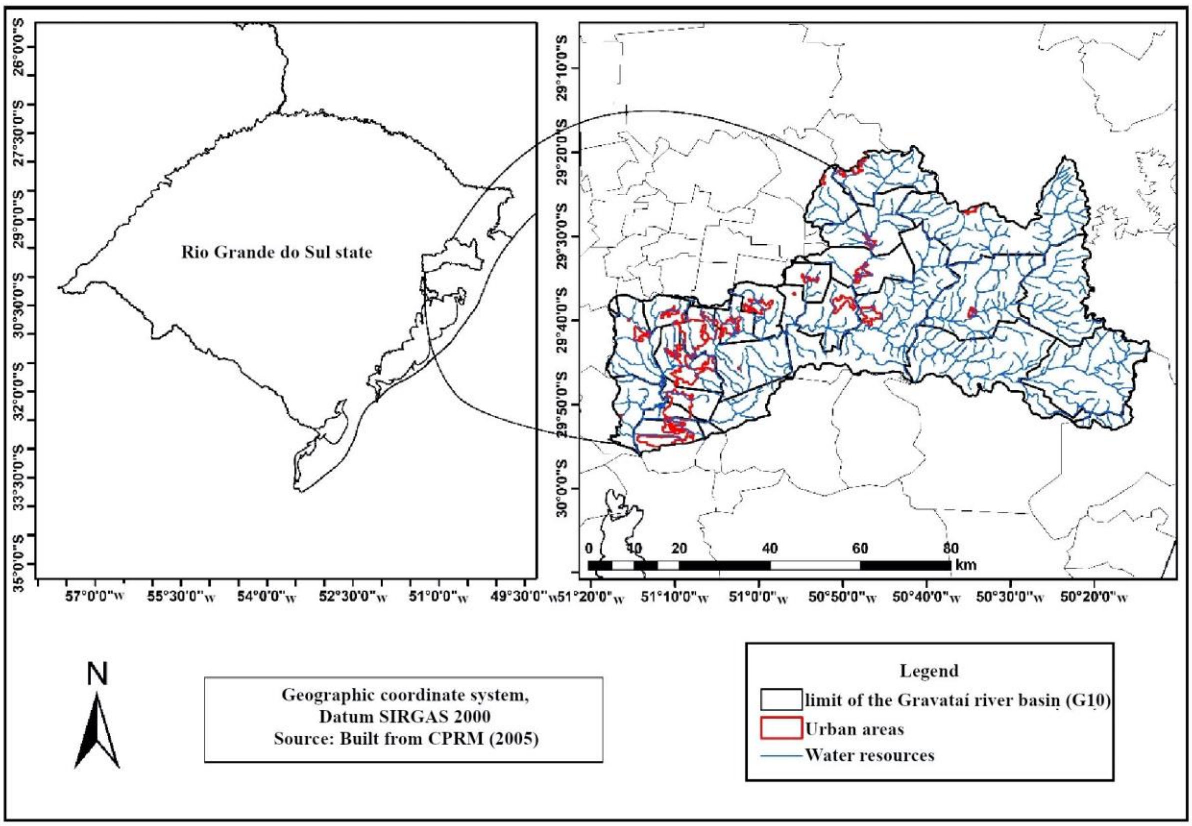

Figure 1 - Location of the Gravataí River Hydrographic Basin - G10. Source: Built from FEPAM (2005).

GEOLOGICAL AND HYDROGEOLOGICAL CHARACTERIZATION

According to Guasselli (2018), the geological formation of the Gravataí Basin reveals that the connecting channel lacks defined edges. The formations imply that swampy areas correspond to swampy deposits formed by accumulated sand, silt and plastic clay (RUBBO, 2004).

Companhia Riograndense de Saneamento (CORSAN), the company responsible for public water supply, sources water from the Gravataí river basin to serve the urban population. Residents of the basin have access

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to this water through surface streams and wells located in the municipality of *Santo Antônio da Patrulha* (RUBBO, 2004). Rubbo et. al. (2002) state that the Gravataí river basin has numerous lithologies (Figure 2).

According to Hausman (1995), underground water reservoirs are a distinctive feature of the basin's landmass. The Gravataí River runs between the geographic formations in the state, thereby being part of numerous established hydrogeological provinces. Thus, Figure 3 illustrates the hydrogeological features within the Basin area.

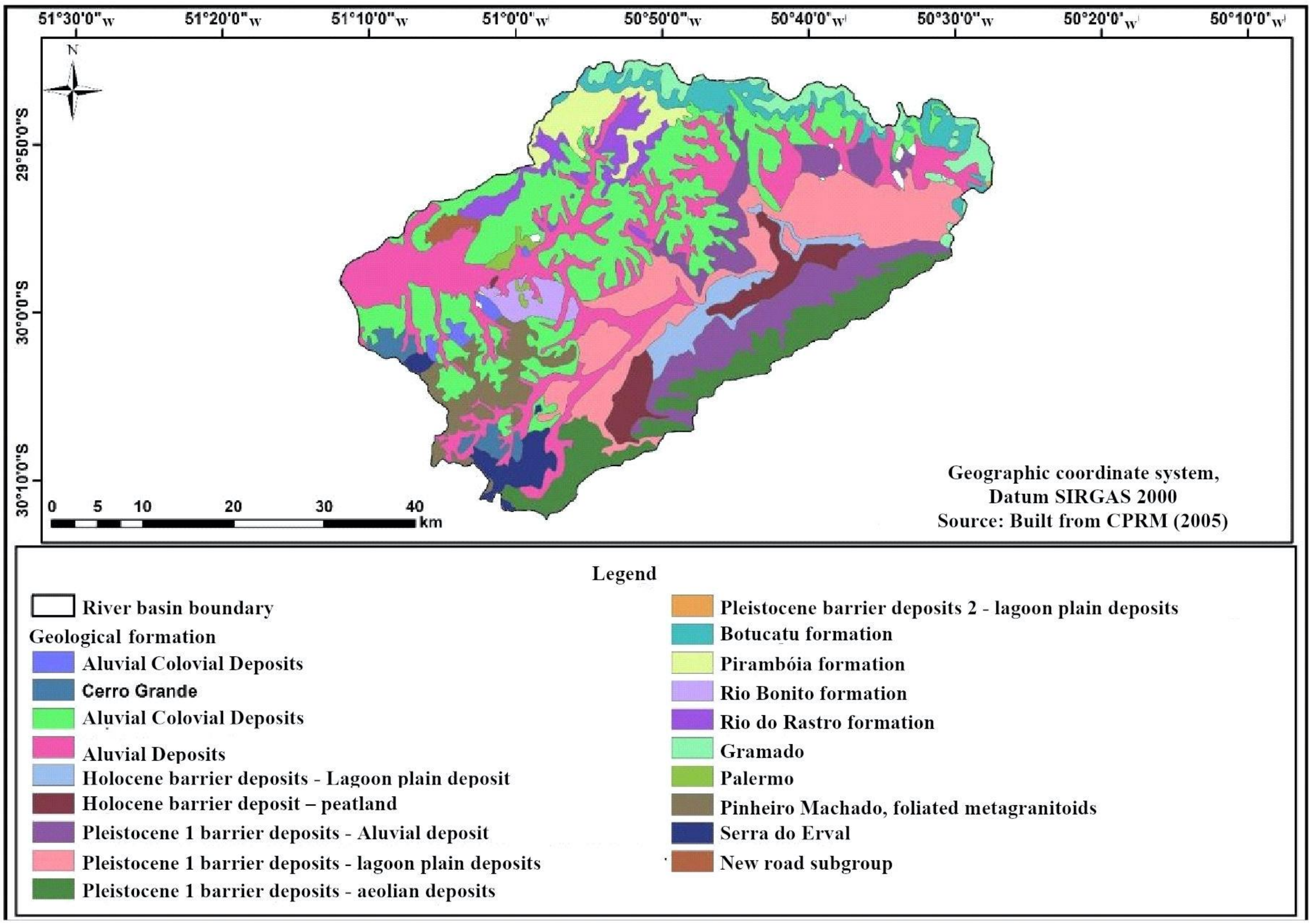

Figure 2 - Geological formations present in the Gravataí River Hydrographic Basin - G10. Source: Built from CPRM (2006).

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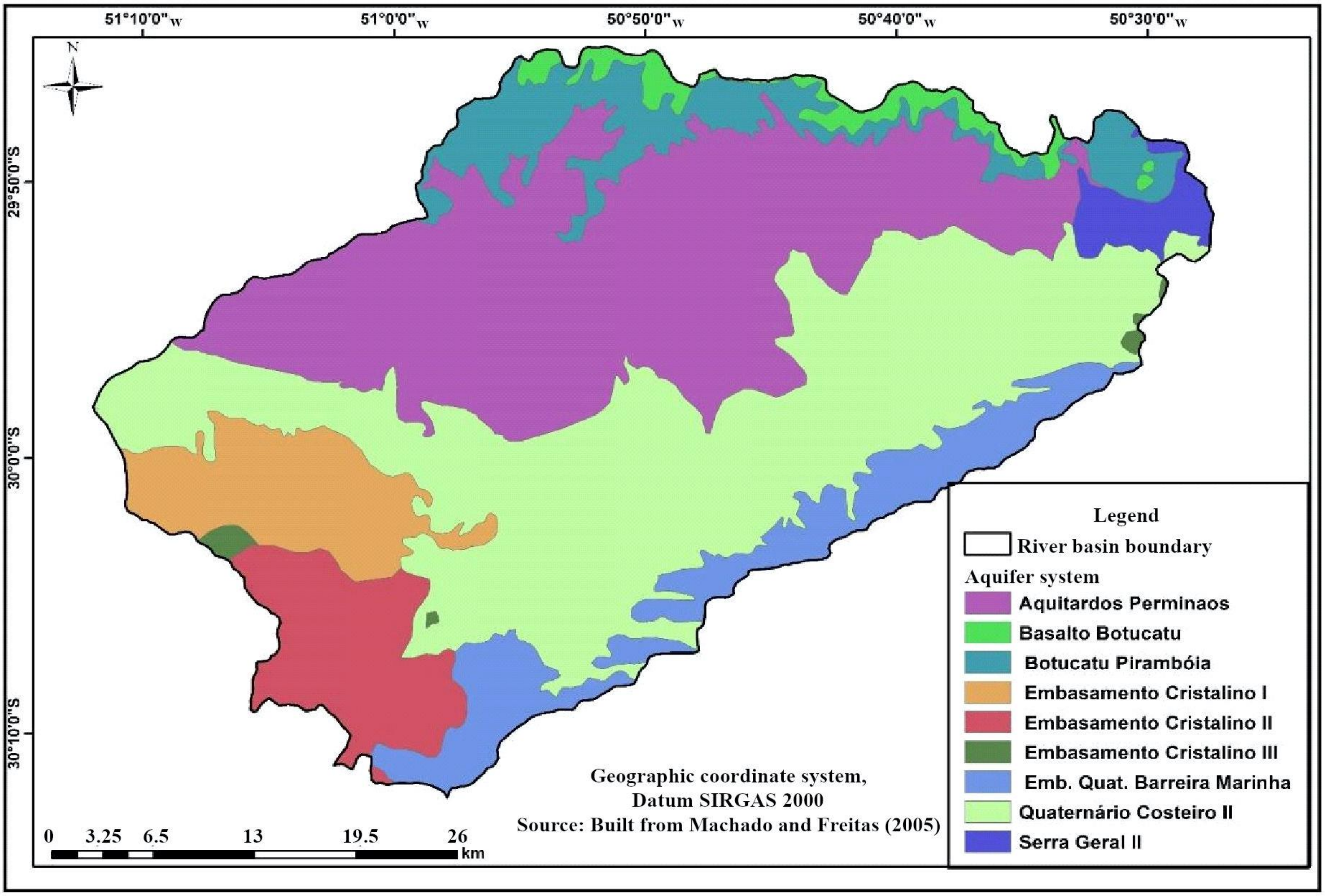

Figure 3 - Hydrogeological formations in the Gravataí River Hydrographic Basin - G10. Source: Built from Machado and Freitas (2005).

ESTIMATION OF THE SUSCEPTIBILITY INDEX TO AQUIFER CONTAMINATION

The database used consists of satellite images, vector data, and spreadsheets. Within this database, geoprocessing tools were applied using a geographic information system. Following the approach proposed by Veríssimo (2010), in map algebra, the scores of variables D, R, A, and T were extrapolated tenfold from the original values proposed by Ribeiro (2005). This adjustment was made to facilitate a better comparison with the LU variable. This application has been effectively used in previous studies carried out by Favaretto et al. (2020), Lunardi et al. (2021), and Borba et al. (2020; 2022).

To collect hydrogeological data (both the distance from the water table - D and the aquifer material - A), information was collected from a total of 1,425 wells on the Groundwater Information System (SIAGAS) website, available at: http://siagasweb.cprm.gov.br/layout/pesquisa_complexa.php for the study area, which have variable collection dates.

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From these, information from 490 tubular wells was used to present the necessary data (Lithology, static level and construction profile). Parameter D (depth of the water table) was scored according to the depth in meters, as shown in Table 1. This parameter was interpolated using the Inverse Distance Weighting (IDW) method with a resolution of 30 meters.

Table 1 - Score relationship according to the depth of the water table.

Depth (m)	**Values**
<1.5	100
1.5 – 4.6	90
4.6 – 9.1	70
9.1 – 15.1	50
15.1 – 22.9	30
22.9 – 30.5	20
>30.5	10

Source: Adapted from Ribeiro (2005).

For the aquifer material (Parameter A), the wells were divided into scores based on the material found (Table 2). This variable was identified by crossing local geological information, according to the CPRM database (2006). Thus, sandstone and basalt materials were identified as constituents.

Table 2 - Classes of Aquifer material (A) and their respective values.

Aquifer Nature	**Value**	**Regular**
Clay shale (Claystone)	1 - 3	20
Metamorphic/igneous rock	2 - 5	30
Altered metamorphic/igneous rock	3 - 5	40
Glacial till	4 - 6	50
Sandstone, limestone and stratified mudstones	5 - 9	60
Massive sandstone	**4 - 9**	**60**
Massive limestone	4 - 9	80
Sand and basalt	4 - 9	80
Basalt	**2 - 10**	**90**
Karsified limestone	9 – 10	100

Source: Adapted from Ribeiro (2005).

For parameter R (recharge), the classification follows the values presented in Table 3. In the study area, sandstone and basalt were present as geological formations. Thus, for basalt, the value proposed by Hausmann (1995) was used, considering an average recharge of 125 mm/year, corresponding to a score of 80. For sandstone, an average annual recharge of 222 mm/year was considered, according to studies by De Melo et al. (2012), corresponding to a score of 60.

Table 3 - Aquifer recharge classes (R) and their respective values.

Recharge (mm/ano)	Value
< 51	1
21 - 102	3
102 - 178	6
178 - 254	8

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> 254	9

Source: Adapted from Ribeiro (2005).

For the topography variable (T), a mosaic of scenes with Shuttle Radar Topography Mission (SRTM/USGS, 2022) images was created, with a spatial resolution of 30 m. The scenes used were denoted as SH-22-Z-A; SH-22-Y-B; SH-22-X-C; and SH-22-V-D. The scores for this variable are presented in Table 4.

Table 4 - Topography Classes (T) land use and their respective values.

Slope (%)	Value
< 2	100
2 - 6	90
6 - 12	50
12 - 18	30
>18	10

Source: Adapted from Ribeiro (2005).

For LU (Land Use), a multispectral image from the OLI sensor, dated 13/03/2021, with a spatial resolution of 30 meters, cloud-free (NASA, 2021) was used. In the Raster Classification tool, an automatic classification of the image was performed, considering the following categories: pastures and agroforestry areas, water bodies, forests and semi-natural areas, and urban areas, and their respective scores (Table 5).

Table 5 - Land use classes and their respective values.

LU parameter	
Land occupation	***Value***
Agricultural areas	
Agroforestry, heterogeneous agricultural areas	50
Artificial areas	
Continuous urban areas, airports	75
Natural areas	
Aquatic environments	50
Forests and semi-natural areas	0

Source: Adapted from Ribeiro (2005).

According to Ribeiro (2005), for the IS method, Equation 1 was applied using the GIS raster calculator S. Finally, the IS result was classified according to Table 6. Therefore, all vector cartographic information in polygon format was rasterized at a spatial resolution of 30 meters and SIRGAS2000 coordinate system, as well as the data interpolation and land use classification results.

$$\mathbf{IS} = (0.186*D) + (0.212*R) + (0.256*A) + (0.121*T) + (0.222*LU) \qquad \textbf{\textit{Equation 1}}$$

Table 6 - Contamination susceptibility classes

Value	Susceptibility
> 90	Extremely vulnerable
80 - 90	Very high
70 - 80	High
60 - 70	Moderate to high

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50 - 60	Moderate to low
40 - 50	Low
30 - 40	Very low
< 30	Extremely low

Source: Adapted from Stigter et al. (2006).

III. RESULTS AND DISCUSSION

DEPTH OF THE GROUND LEVEL

In the evaluated area, the depth of the water table varied from values less than 1.5 m to greater than 30.5 m (Figure 4). The shallower an underground reservoir, the more susceptible it is to pollution. This is because contaminants are closer to the groundwater flow, facilitating the contamination passage into the aquifer (BORBA et al., 2016). The lighter areas in Figure 4 represent points with shallower depths, indicating higher scores and susceptibility to contamination. This is due to the shallower water table, making the aquifer more vulnerable to surface pollution load.

Ribeiro et al. (2005) report that the inherent susceptibility of the aquifer is defined by two factors: intrinsic (which considers only geological characteristics); and specific (which takes into account the specific pollutant).

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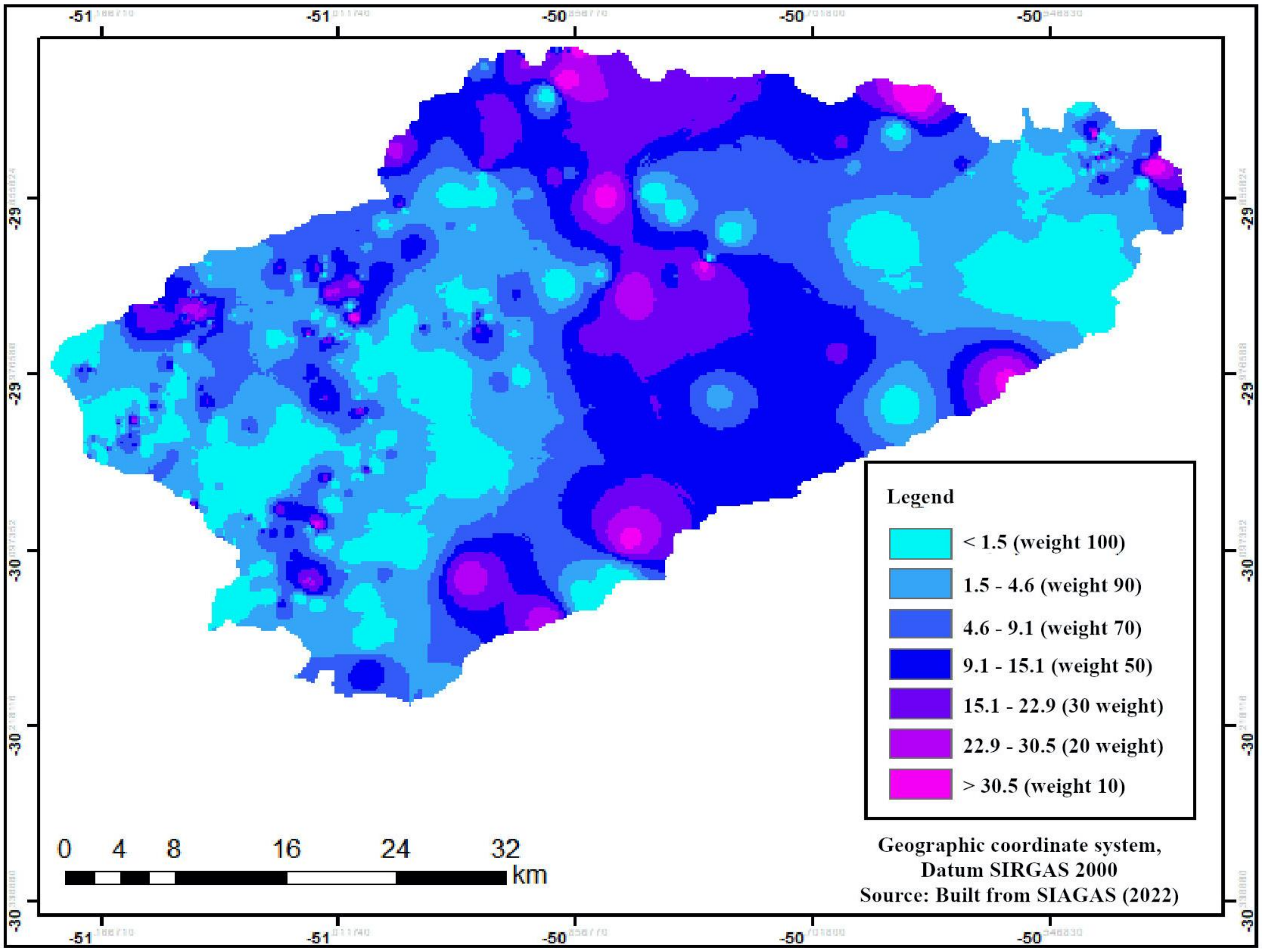

Figure 4 - Variation in the water table in the Gravataí River Basin - G10. Source: SIAGAS (2022).

RECHARGE

In a specific period, the amount of water that infiltrates the surface and crosses the area with an unsaturated zone is called recharge; water enters the land through direct precipitation flows, groundwater flow, and surface soil infiltration (MCGUFF; MCMULLEN, 2004). In this case, considering that the higher the recharge, the more risk of aquifer contamination (LIMA et al., 2017), as water movement is greater, and consequently that of a possible contaminant.

In Figure 5, it can be observed that in the studied area, two values for recharge were found. A smaller proportion of the basin area has recharge values of 125 mm/year, indicating that this portion of precipitation recharges the aquifer. The basalt areas of the basin are included in this area. On the other hand, a larger portion of the river basin has a recharge of 222 mm/year, represented by sandstone areas.

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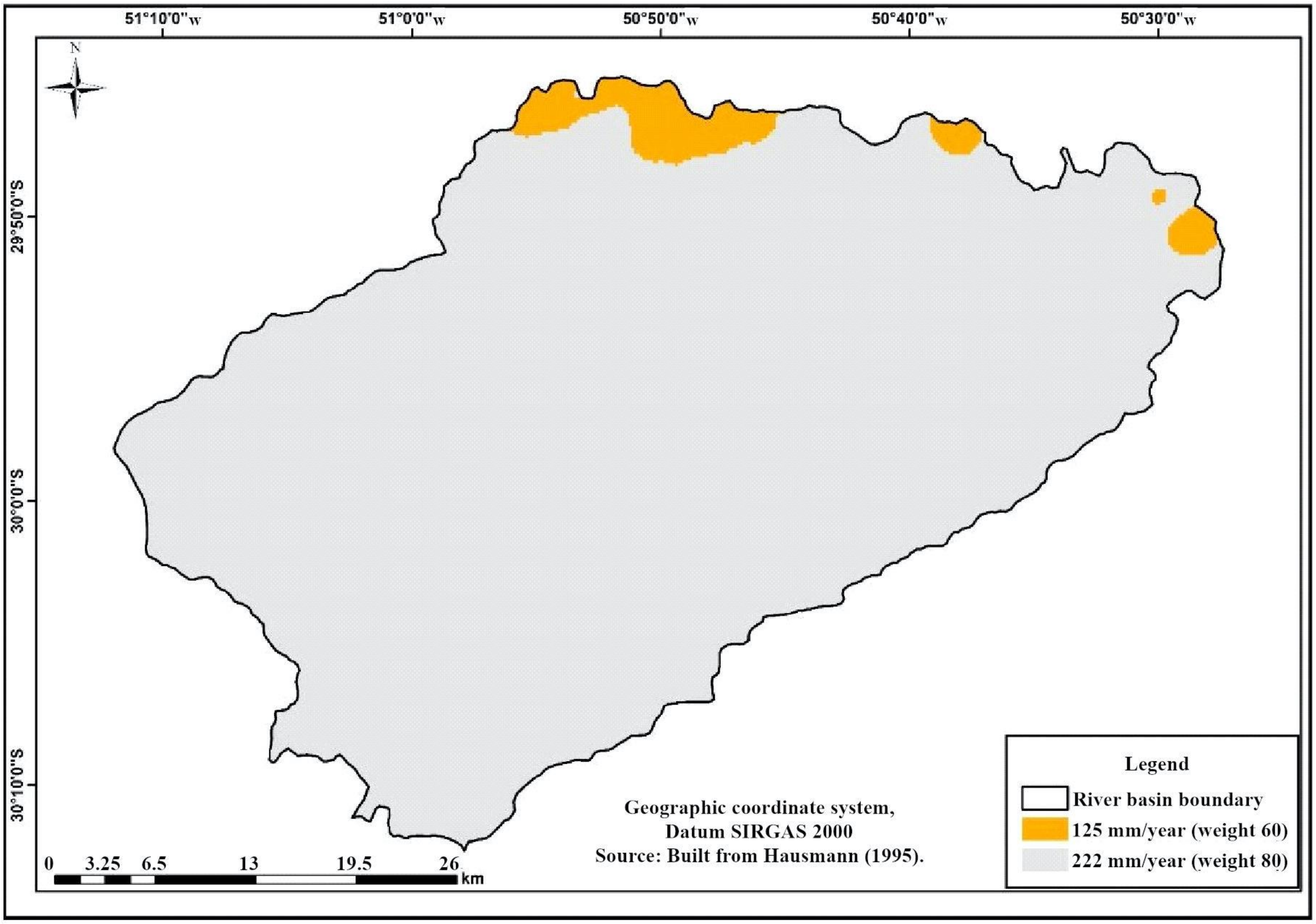

Figure 5 - Recharge in the Gravataí River Hydrographic Basin - G10. Source: Hausmann (1995) and De Melo et al. (2012).

AQUIFER MATERIAL

In Figure 6, the aquifer material is represented, in which sandstone is predominant in the largest area. Sandstone may show a lower susceptibility index to contamination compared to basalt. This is because although sandstone is more permeable, contaminants can potentially be retained by the soil itself or its clay minerals. On the other hand, basalt may have fractures, providing a direct pathway for contaminants to reach the groundwater. According to Mcguff and Mcmullen (2004), the characteristics of the aquifer material are highly important regarding contaminants, including their absorption, reaction, and dispersion.

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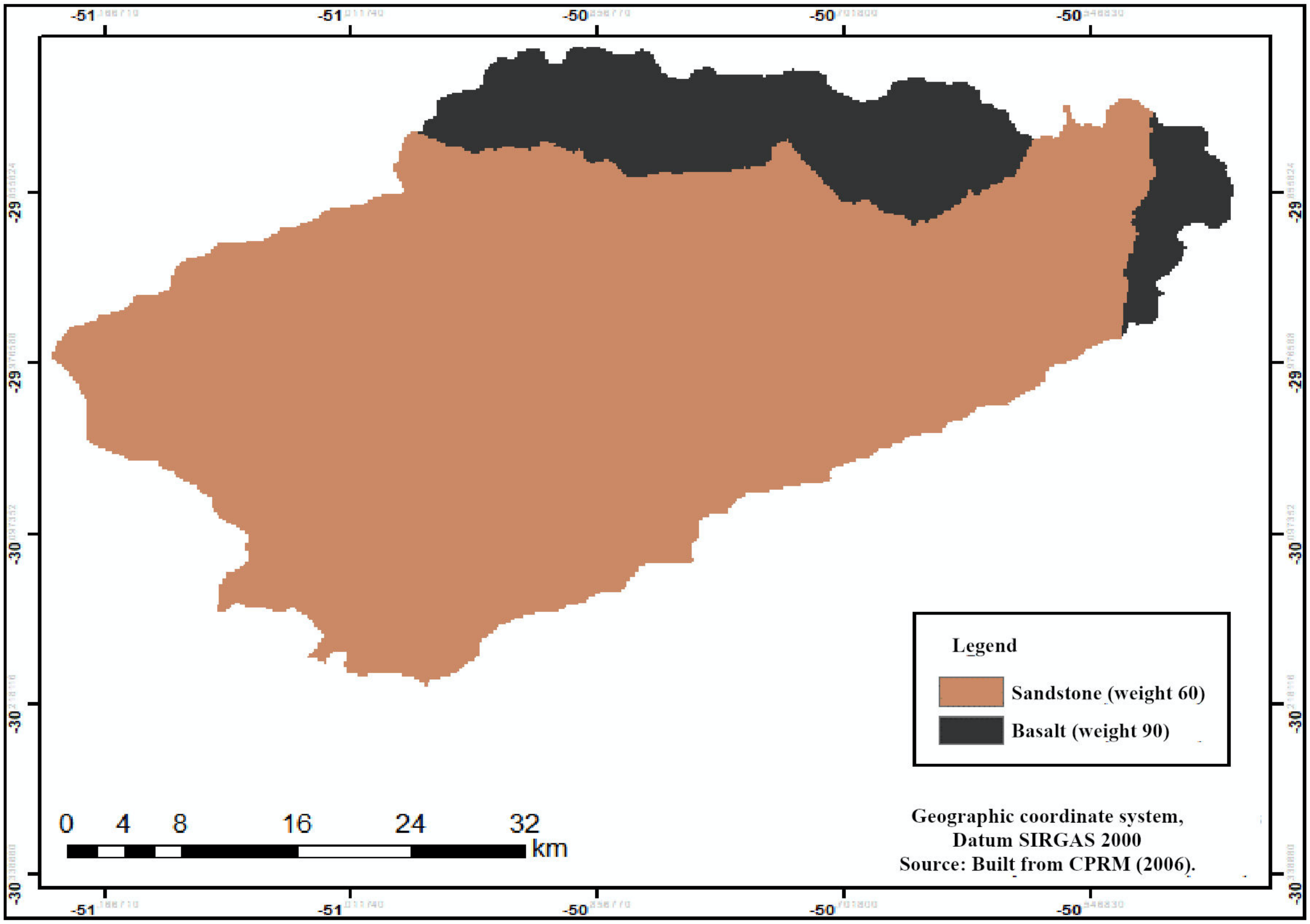

Figure 6 - Material from the aquifer Gravataí River Basin - G10. Source: CPRM (2006).

TOPOGRAPHY

In the case of parameter T, it was analyzed through the slope in percentage, as shown in Figure 7. In some areas with lower slopes, the chances of susceptibility to contamination are much higher compared to areas with steeper slopes. According to Aller et al. (1987) and Lnec (2002), this parameter and the slope of the site determine the probability of pollutants permeating the surface or remaining on it. This makes it more likely for pollutants to infiltrate the surrounding area. As shown in Figure 7, the central area of the Gravataí River basin exhibits more undulating regions (slope greater than 18%), while flatter relief can be seen in the north.

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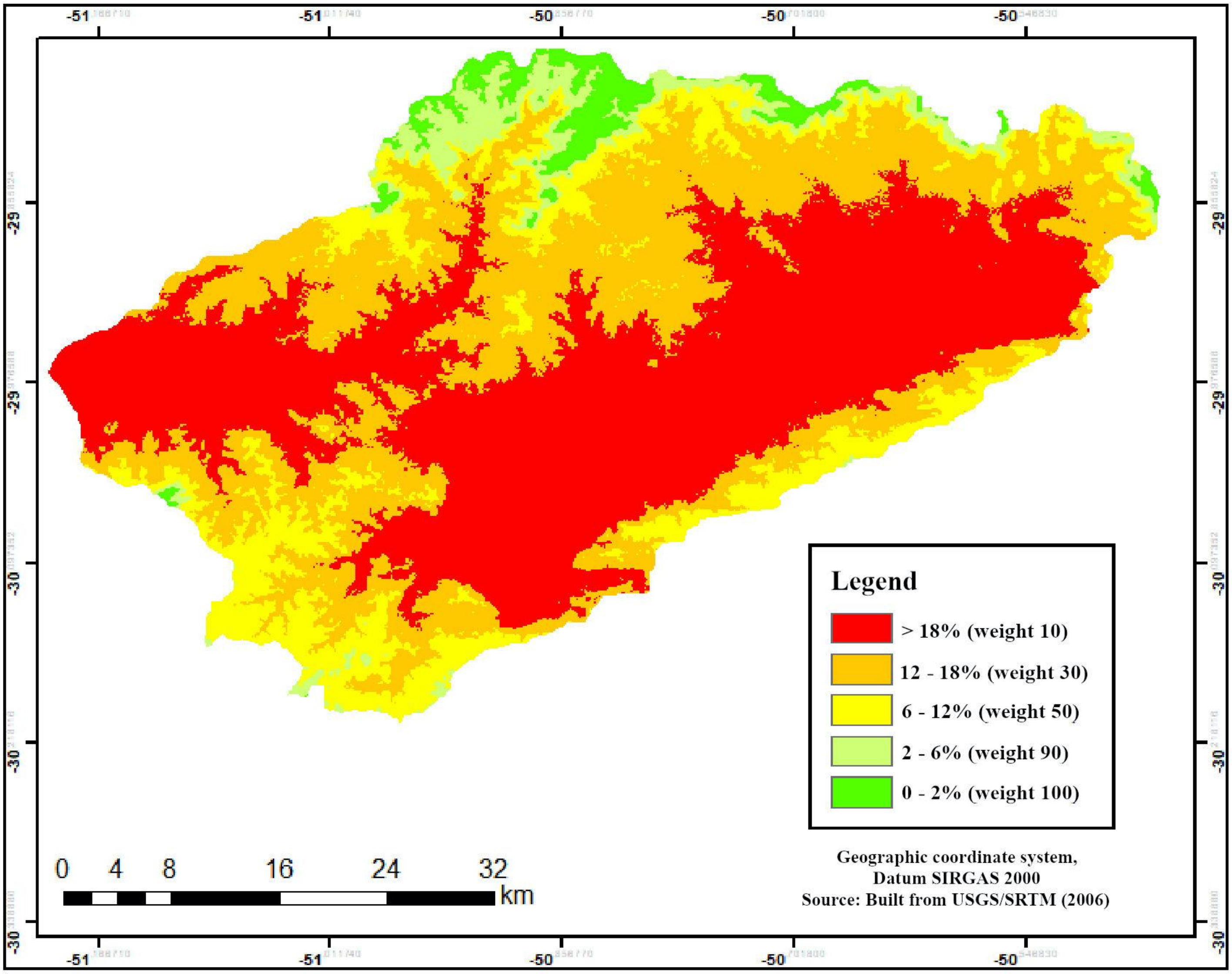

Figure 7 - Topography of the Gravataí River Basin - G10. Source: USGS/SRTM (2006).

LAND USE (LU)

The land use classes in the Gravataí River Basin (Figure 8) show a large portion of the flooded area. According to FEPAM (2020), this is due to a high demand for agricultural activities, particularly involving the irrigation of rice crops. These activities are located in a more vulnerable region of the area (North).

The other areas classified by land use and occupation fall into forests and semi-natural zones, discontinuous urban areas, and annual crops. However, according to Guasseli et al. (2012), currently, the rice class in the large wetland is considered the most problematic area. This is because rice is found in areas that intersect between the swamp and its peak flooding periods.

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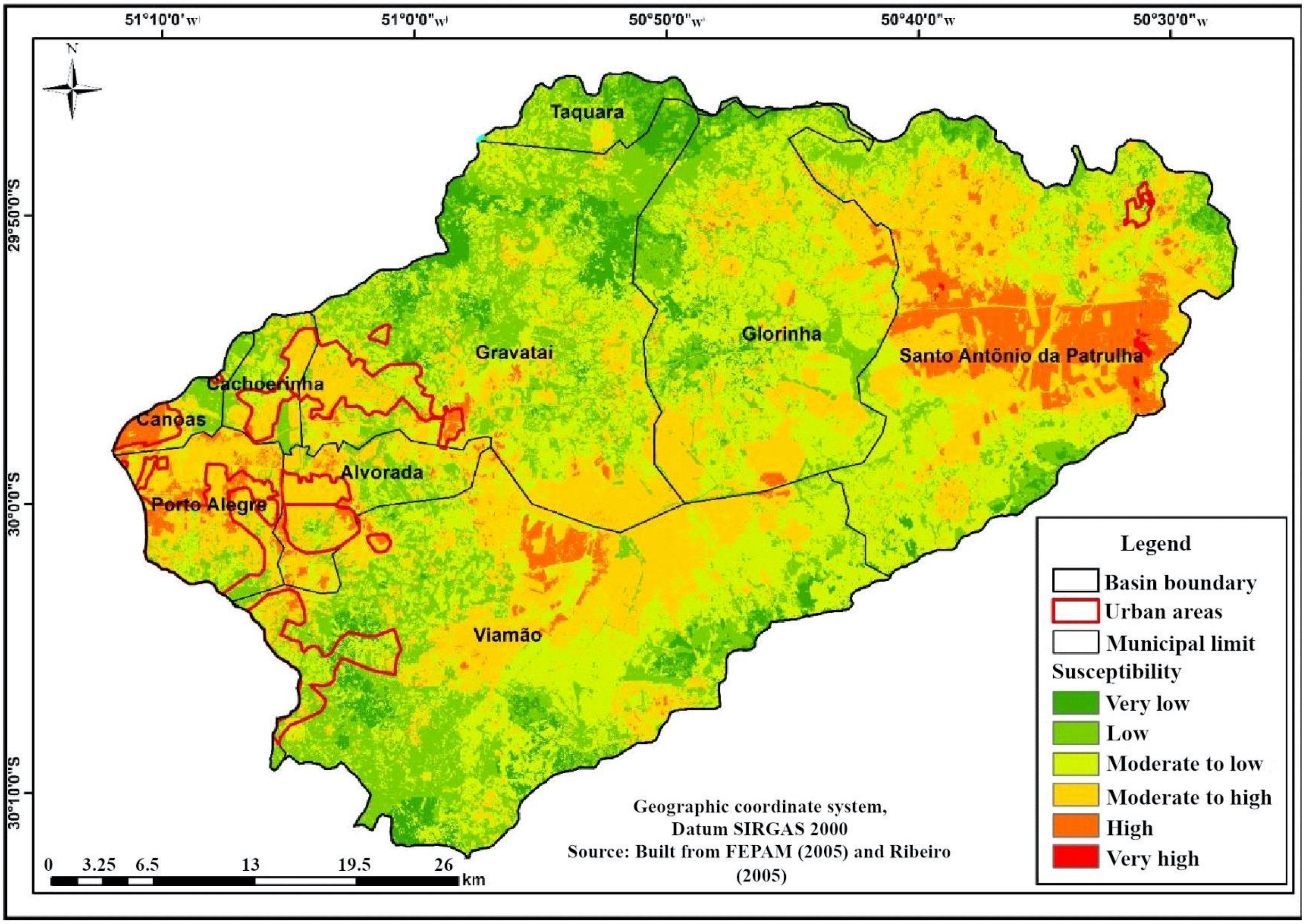

Figure 8 - Land use in the Gravataí River Hydrographic Basin - G10. Source: Zanaga et al. (2021).

SUSCEPTIBILITY INDEX

In the analyzed area, the IS presented seven classes ranging from very low (5.61%) to very high (0.08% of the area), with a predominance of moderate to low class (37.02%). The highest values are located in the riverbed area of the Gravataí River, which was altered to create a channelized middle section, a project used to increase rice production (GUASSELI et al., 2018). In the upper and middle regions of the river, there are mainly agricultural lands with rice plantations, while in the other region, the area is more densely populated and has industrial and urban areas near the lower part of the river (GUASSELI et al., 2018).

FEPAM (2016) states that the G-010 basin is the most sensitive area in the Guaíba Hydrographic Region, primarily because rice farms have depleted the swamps' capacity to regulate the water flow. Based on the study carried out by da Silva (2022), the Gravataí River floodplain is very close to Greater Porto Alegre, making it more susceptible to environmental damage caused by industrial activity in the city. Thus, Foster et al. (2002; 2006)

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state that industrial areas have the potential to generate a contaminant load in the soil ranging from moderate to high, depending on the type of activity carried out. Furthermore, urban areas without domestic sewage collection and treatment systems can also contribute to aquifer contamination. Analyzing Figure 9, it is clear that this area presents areas with susceptibility ranging from moderate to high and high when crossing information from the IS method.

As can be observed in Table 7 and Figure 9, the classifications of susceptibility levels in percentage resulted in approximately 37.02% moderate to low, 28.04% moderate to high, 22.72% low, 06.53% high, 05.61% very low, and 00.08% very high. Table 8 illustrates the results obtained in other research related to IS. It is clear that most studies conducted showed moderate to low predominant classes.

Table 7 - Susceptibility index classes

Class	Area (ha)	Area (%)
Very high	168,48	00,08
High	13.114,50	06,53
Moderate to high	56.274,93	28,04
Moderate to low	74.301,20	37,02
Low	45.595,01	22,72
Very low	11.259,01	05,61
Total	**200.713,47**	**100,00**

Source: Own authorship.

Table 8 - Results obtained in research involving IS.

Authors	**Local**	**Susceptiblity classes**	**Predominant class (Regarding the area of study)**
Borba et al. (2016)	Frederico Westphalen - RS	Low and very low	Moderate to low (55,00%)
Tassi et al. (2019)	Ijuí - RS	Very low to high	Moderate to low (50,12 %)
Borba et al. (2020)	Turvo River Basin - RS	Very low to very high	Moderate to low (56,01%)
Favaretto et al. (2020)	Aratiba - RS	Low to high	Moderate to low (47,24%)
Coelho et al. (2022)	Jaú - SP	Very low to very high	High (57,91 %)
Toniolo, Ventura e Silva (2022)	SABESP West Business Unit - SP	Extremely low to moderate-high	Very low

Source: Own authorship.

IV. Conclusions

This research determined the effectiveness of the method for estimating the susceptibility of the Gravataí River basin in the state of Rio Grande do Sul, which presented seven different susceptibility classes. It accurately identified zones with susceptibility ranging from low to high contamination, varying from very low to very high. These results, ranging from high to very high, are the most common classification.

Data on the method variables were collected, where 37% of the area had a susceptibility index below moderate. The areas most susceptible to contamination are located close to the urban areas of the metropolitan

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region, along with sandstone regions and shallower water tables. More in-depth research is needed when considering the location of potential contamination and its relationship to the subject being researched. This shows which areas are ideal for future development. This allows us to understand how water resources are contaminated, which is crucial for creating water resource maps. Considering the location of potentially contaminating agricultural activities and how this intersects with study results.

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