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Determination of Maximum Water Infiltration Areas in Vacacaí-Mirim Basin in Southern Brazil

Determinação das Áreas de Infiltração Máxima de Água na Bacia Hidrográfica do Rio Vacacaí-Mirim no Sul do Brasil

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Abstract

Determining the rates of water infiltration into the soil is of extreme importance, because it does not only determine the recharge of aquifers, but also estimates the vulnerability to soil contamination. Considering this, the present study aims to determine the rate of water infiltration into the soil using the DRASTIC method in the Vacacaí-Mirim basin in Rio Grande do Sul state, Brazil. To determine these rates, the analysis of physical parameters was obtained in the soil physics laboratory at the Federal University of Santa Maria, campus of Frederico Westphalen, in the state of Rio Grande do Sul. The ease infiltration rates in the years 2010 and 2011 ranged from 10 (slightly cracked areas) to 30 (areas with high drilling). Regarding the areas of maximum infiltration in 2010, 24% of the basin area showed this condition, and in 2011, the percentage decreased to 18.55%. According to the results, the methodology is proven to be significant to determine the infiltration rates of water in the Vacacaí-Mirim basin. The areas that stood out with the highest infiltration rates are in the floodplains of the river basin, where rice cultivation prevails. Therefore, it is incredibly important to preserve these areas to maintain the local quality and quantity of the groundwater.

Keywords: Infiltration; DRASTIC; Land uses

Resumo

A determinação das taxas de infiltração de água no solo é de fundamental importância, pois além de determinar a recarga de aquíferos, estima a vulnerabilidade à contaminação do solo. Com base nisso, o presente trabalho tem por objetivo determinar o índice de infiltração de água no solo pelo método DRASTIC na bacia hidrográfica do rio Vacacaí-Mirim, no estado do Rio Grande do Sul. Para a determinação desses índices, as análises dos parâmetros físicos foram obtidas no laboratório de física do solo da Universidade Federal de Santa Maria, *campus* de Frederico Westphalen-RS. Os índices de facilidade a infiltração nos anos de 2010 e 2011 variaram de 10 (áreas pouco fissuradas) a 30 (áreas com altas perfurações). Com relação as áreas de infiltração máxima, no ano de 2010, 24% da área da bacia apresentou tal condição, já para o ano de 2011, esse percentual caiu para 18,55%. Com base nisso, a metodologia se mostra interessante para a determinação das taxas de infiltração de água na bacia hidrográfica do rio Vacacaí-Mirim. As áreas que mais se destacaram com as taxas de infiltração máxima localizam-se nas várzeas da bacia hidrográfica, onde predominam o cultivo de arroz, sendo assim é de fundamental importância a preservação de tais áreas com vista a manutenção da quali/quantidade da água subterrânea no local.

Palavras-chave: Infiltração; DRASTIC; Usos do solo

1 Introduction

Increasing the availability of water for agricultural crops is an alternative way to increase food production around the world. This must occur rationally, aiming at techniques that avoid excessive consumption and properly use the resource. Thus, several studies report the relationship between water use and production systems (Avelino & Dall'erba 2020; Flörke, Schneider & McDonald 2018; Jiang et al. 2017; Xinchun et al. 2017; Ye et al. 2018). The major contribution to the preservation of water resources is the advancement of water and soil management systems that contribute to increasing the efficiency of water use, aiming at better use of rainwater (Spohr et al. 2007).

The infiltration process is the passage of water into the soil profile. The descent of water gradually changes soil moisture, although natural precipitation tends to saturate only the layers close to the surface (Santos 2011. In addition, this process can be influenced by several factors such as changes in the physical properties of the soil and the removal of the vegetal layer on the ground surface. Such a surface, for example, can become impermeable due to various reasons: traffic, excessive trampling, continuous cultivation, and others. Another determining factor for infiltration is the existence of layers that can hinder permeability, affecting the infiltration rate (Lima 2008).

Several authors refer to water infiltration and/or percolation as the main aquifer recharge processes. These processes are regulated by environmental variables and factors that can have high spatial variability. Making areas with the potential to generate recharge is also spatially differentiated (Santos & Koide 2011).

The characteristics of the permeable media (the porous media where leakage occurs) are determined by the soil type, texture and structure, and the amount and type of clay (Lima 2008). There are several methods to determine water infiltration in the soil, among which the DRASTIC method described by Oliveira & Ferreira (2002) stands out. This method considers several factors such as land cover, topography, land use, and occupation, and has already been used effectively by several investigations (Bevilacqua 2015; Kemerich, Ritter & de Borba 2014; Linhares 2012).

Oliveira & Ferreira (2002) justified this method using fixed limits that make the definition of maximum infiltration areas always dependent on the verification of these limits. It is useful to have a way to unite all the parameters under analysis and obtain a scaling of areas that are more and less favorable to infiltration, using fixed limits that can result in a given region not having any areas of maximum infiltration (Oliveira & Ferreira 2002).

Thus, the present study aims to determine the maximum infiltration areas presented in the Vacacaí-Mirim Basin in the state of Rio Grande do Sul, Brazil, using the DRASTIC method.

2 Methodology

2.1 Characterization of the Study Area

The Vacacaí-Mirim Basin is located in the central part of Rio Grande do Sul, between latitudes 29º 36' 55" S and 29º 39' 50" S and longitudes 53º 46' 30" W and 53º 49' 29" W, covering a total area of 1,145.7 km^2 (Casagrande 2004). It consists of three large geomorphological compartments, with distinct morphological and geological characteristics: North-Rio-Grandense Plateau, Central Depression, Sul-Rio-Grandense Plateau, and Coastal Plain.

The Norte-Rio-Grandense Plateau covers the state's highest elevation zone, between 300 and 480 m, and consists of Mesozoic flows from the Serra Geral, covered by large desert extensions formed by older sandstones (Marion, Hendges & Andres 2018). This region is characterized by the presence of an undulating and gently undulating relief, resulting from fluvial dissection processes on the surface of the plateau. River drainage has a dendritic pattern, with V-type or flat-bottomed valleys (De Nardin & Robaina 2005).

The Central Depression has a slightly wavy relief stretching from least to west between the Plateau North Rio Grande and the Plateau South Rio Grande. As stated by Simielli (2009), it consists of sediments, Cenozoic rocks deposited at an altitude ranging between 100 and 200 m, where the Jacuí River and its tributaries are located, including the Caí, Sinos, and Taquari Rivers.

The Plateau Sul-Rio-Grandense represents the crystalline shield. It consists of ancient plutonic and metamorphic rocks, dating back to the Pre-Cambrian. The relief is formed by rounded hills due to prolonged exposure to erosion and isolated areas with an altitude above 300 m (Simielli 2009).

The Coastal Plain is a sandy strip formed from the Quaternary onwards through Cenozoic marine regressions and transgressions. The low altitude promoted the formation of marshes, lagoons, and lagoons, including Lagoa dos Patos, Lagoa Mirim, and Magueira (Hoffmann et al. 1997).

In the regions of the basin's headwaters, in its higher altitudes, there is the Serra Geral Formation. According to the Serviço Geológico do Brasil (2008), it consists of basic flows of volcanic rocks (basalts, containing SiO_2 between 45 and 52%) and acid rocks (rhyolite, rhodocytes with SiO_2 content between 52 and 55 %) (Leinz & Amaral 1989).

There is a superior acidic sequence with intermediate acid spillage of rhodic to rhyolite, mesocratic, microgranular to vitrophic rocks, with common spherulitic texture (Carijó type), strong tabular disjunction at the top of the spills, and massive in the central portion with flow and self-folds frequent violations, presence of vesicles filled predominantly by chalcedony and agate, source of gravel mines in the region. Serra Geral basalt spills with micro-granular texture, the common presence of centimetric milli vesicles with black opal, and eventually the presence of native copper (Serviço Geológico do Brasil 2008). Thus, the most important difference between these two units lies in the previous fracture pattern and acid rocks with a horizontal tabular pattern, while the basic one has a polyhedral pattern that favors spheroidal exfoliation and rainwater infiltration, both in the massive as in amygdaloids and in vertical developments (Serviço Geológico do Brasil 2008). Some of them are open and facilitate water infiltration and groundwater recharge.

In this unit, soybean crops, forest, and pasture areas are located. In the western region of the basin, there are regions of alluvial plains where rice cultivation prevails, which can be understood by the formation of quaternary sediments (sludge).

Sequences of sandy and clastic sedimentary rocks with different relationships between porosity and permeability occur in the Peripheral Depression of the state of Rio Grande do Sul, and in the region close to the city of Santa Maria, as described below:

a) Sanga do Cabral Formation occurs in elongated tabular or lenticular bodies deposited in a continental environment, braided fluvial, containing vertebrate fossils fragments of amphibians and reptiles. It consists of loopholes and intraformational conglomerates, rare siltstones, and mudstones. Serviço Geológico do Brasil (1994) affirm that this is a case of an aquitard that provides low flow in wells, being a good quality water.
b) Caturrita Formation consists of sandstones, conglomerates, clayey silt, and shale containing fossil tetrapods and trunks of conifers, deposited in fluvial and deltaic continental lacustrine environment.
c) Botucatu Formation consists of fine to thick sandstones, well rounded grains, and high sphericity, arranged in sets and large cross bedding cosets. The paleoenvironment of deposition was continental desert with the formation of wind and river dunes. According to Serviço Geológico do Brasil (1994), they were excellent aquifer reservoirs.
d) Santa Maria Formation is divided into Passo das Tropas Member and Alemoa Member. Passo das Tropas Member is formed by sandstones and conglomeratic sandstones with subordinate pellites containing elements of Flora *dicroidium*. Serviço Geológico do Brasil (1994) ranks its aquifer as the best in the region, with excellent flow rates and water classified as of good quality, but very vulnerable to pollution. The Alemoa Member consists of red siltstones, clay, massive, containing fossil tetrapod fauna and carbonate concretions (calcretes). The paleoenvironment is described as lacustrine. According to Serviço Geológico do Brasil (1994), these are not aquifers, but aquicludes which do not store nor transmit water.
e) Alluvial and fluvial terraces: Serviço Geológico do Brasil (1994) describes alluvial aquifers as continuous, with great extension and free. They consist of unconsolidated clastic sediments of small thickness (up to 10 m). They have high permeability and water of good quality, but very vulnerable to pollution. On the other hand, river terraces are constituted of conglomerates, medium to clayey sandstones, and sandy siltstones. The free irregular aquifer consists of low consolidated sediments and very clayey, with small thickness. The permeability varies from low to average. The water quality is good, and its exploitation is carried out by dug wells.

The climate in the basin area, considering the Köppen classification, is of the Cfa type (subtropical, with precipitation well distributed throughout the year) (Kuinchtner & Buriol 2001), and the predominant soils according to the World Reference Base al for-Soil Resources are the predominant Red-Yellow Aluminum Acrysols in the Plateau region, in some restricted locations associated with Leptsols. In the Central Depression, subtropical Planosols and Chernosols with rainfall well distributed throughout the year (Casagrande 2004) are found.

The natural vegetation in the Plateau zone consists predominantly of subtropical forest and the Central Depression of natural pastures. Isolated tufts of small and large forests are common along with fields (Secretaria de Estado do Planejamento 1986). To determine the maximum infiltration areas, parameters were used that maximize the infiltration on the surface, and later on into the subsoil (Oliveira & Ferreira 2002). Soil classes in the Vacacaí-Mirim River Basin are shown in Figure 1.

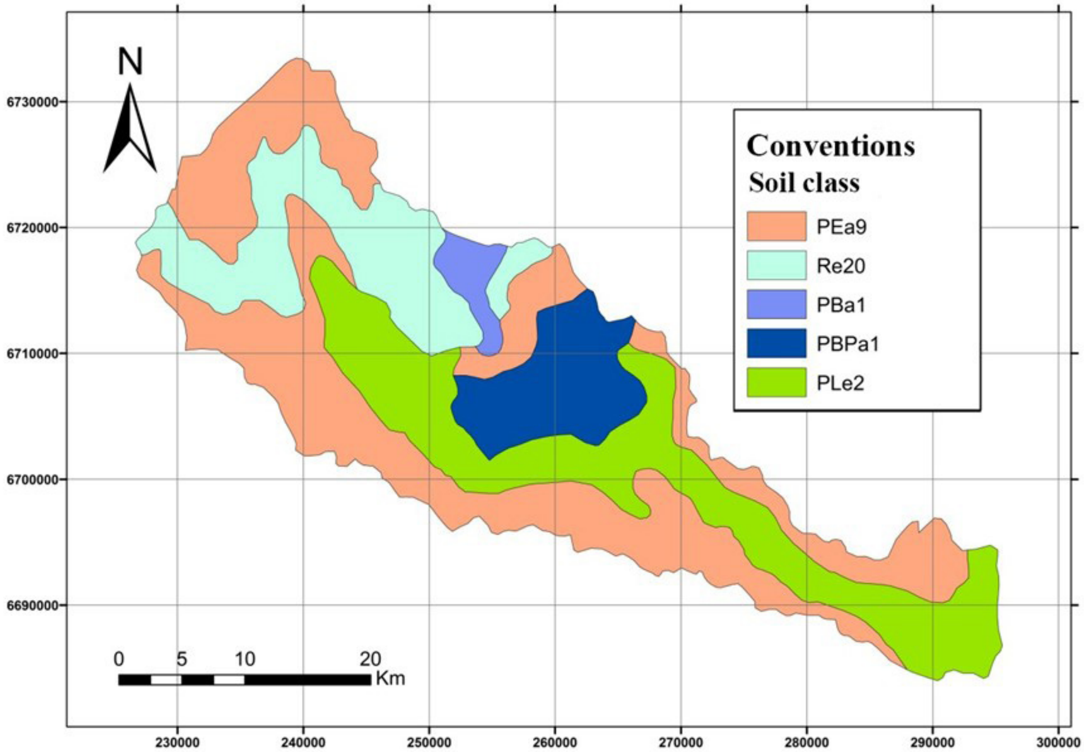

Figure 1 Land classes in the Vacacaí-Mirim river basin 2013.

According to Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística 2002), soil classes of the study area can be characterized as:

a) PBPa1: Podzolic Bruno-gray Alic Planosols and dystrophic Ta to moderate and prominent, with medium/clayey texture and albaqualf eutrophic Ta to moderate, with medium texture/ clay gently wavy terrain and plan.

b) PBa1: Podzolic Bruno-gray Alic Ta, with clayey/ very clayey texture, stony and not stony phase, and dystrophic soils and alic litholic outstanding, with medium texture and clayey and chalky stony stage rhyodacites substrate, wavy relief, and strong wavy relief.

c) PEa9: Red-Dark Alic podzolic and dystrophic Tb, abrupt and not abrupt, with moderate texture, sandy, clay and medium clayey podzolic Bruno-Greying Alic Planosols Ta, average moderate clayey and red-yellow podzolic Alic Tb plinthic with average moderate clay texture and soft relief corrugated.

d) PLe2: eutrophic Planosols Ta, with sandy moderate texture and medium clay and relief plan.

e) Re24: Complex association litholic eutrophic soils chernozemic and moderate medium texture, chalky and rocky stage in a basaltic substrate Cambisols eutrophic Tb and Ta to moderate and chernozemic with clayey and medium texture, stony phase, reddish Brunizem with medium clayey and very clayey, stony phase and red earth, structured eutrophic moderate and chernozemic with clayey and very clayey in a strong relief, wavy and mountainous.

f) Re20: Complex association litholic eutrophic soils to chernozemic and moderate medium texture chalky and medium stony phase in a basaltic substrate with eutrophic Cambisols Tb and Ta to moderate and chernozemic, clayey and stony middle phase and reddish Brunizem with medium clayey and very clayey, stony phase and strong wavy relief.

According to Oliveira & Ferreira (2002), one of the available ways to classify soil permeability and infiltration ease is the soil hydrological classification based on the Soil Conservation Service, cited by David (1976), which comprises four different soil types (A, B, C or D).

The topography affects the direct flow of greater or lesser ease of infiltration probability. A horizontal ground surface facilitates the occurrence of leakage while a sloping terrain stimulates direct flow (Oliveira & Ferreira 2002). There have been various topography applications of the DRASTIC method to describe the groundwater pollution vulnerability, cited by Aller et al. (1987), according to Oliveira & Ferreira (2002).This method corresponds to a set of 7 parameters, one of which, the T parameter, refers to the slope of the terrain. The consideration of the topographic parameter has the same objective that applies here, i.e., to define areas where the possibility of surface leakage is increased, comparing areas where the possibility of direct flow is the highest. This method is used to divide the slopes into the following 5 classes: < 2%, 2% - 6%, 6% - 12%, 12% - 18%, and >18% (Oliveira & Ferreira 2002).

In this method proposed by Oliveira & Ferreira (2002), the maximum amount of soil water storage (AGUT) is a factor linked to the amount of water that can be removed from the soil by evapotranspiration. In conditions without evapotranspiration, the soil shows the minimum value that is given by soil retention (sr). Above this value groundwater flow by gravity can occur, while below this value, water is retained in the ground, without run-off. In the case of evapotranspiration, soil moisture can decrease to the minimum value given by the permanent wilting point of the plants (wp). The maximum depth at which evapotranspiration can occur is the depth reached by plant roots.

The higher the AGUT, the greater the amount of water retained in the soil (which can be renewed by the process of evapotranspiration followed by percolation), and the lower the deep infiltration (Oliveira & Ferreira 2002). Finally, below ground, the nature of the geological substrate will carry all runoff in the vadose zone until the water reaches the saturated zone. If there is no soil, outcrops of fractured geological formations facilitate infiltration. Also due to the geological substrate and its structure, areas with distinct aquifer potential are defined so that the definition of areas of maximum infiltration will only make sense if there are underlying underground water bodies of interest.

In the geologic context, the authors claim, what matters most is to known whether the geological formations are or not covered by the soil, and, if not, to know the degree of fracture or the existence of cavities that would facilitate the infiltration of surface water. In this case, only two classes are considered: (i) the existence of karstified or highly cracked media where the fractures are interconnected and continuous in-depth, or (ii) the remaining media as described by Hentges (2009).

To define the maximum infiltration areas, it is necessary to define the limit values for each parameter: soil type, topography, and AGUT. Once defined, the areas with parameter values over the threshold ones are selected. The areas in which the geological factor belongs to class A are also considered as areas of maximum infiltration (Table 1).

Table 1 Limit values for each class of soil type parameters, slope and AGUT to define the areas of maximum infiltration

Parameters	Class	Limit value
Soil type	A	10
	B	8
	C	4
	D	1
Slope (%)	< 2	10
	2 - 6 2 - 6	9
	6 - 12 6 - 12	5
	12 - 16 12 - 18	3
	> 18 > 18	1
AGUT (mm)	< 50	10
	51 - 100	9
	101 - 150	8
	151 - 200	7
	201 - 250	6
	251 - 300 251 – 300	5
	301 - 350 301 – 350	4
	351 - 400	3
	401 - 450	2
	> 450	1

Font: Oliveira & Ferreira (2002).

The Vacacaí-Mirim River Basin has a total area of 1,145.7 km^2, where the slope class < 2% is equivalent to 504.772 km^2, representing 43.80% of the total area, being distributed in the Centraland SE regions (Figure 2).

Figure 3 illustrates the types of soil present in the Vacacaí-Mirim Basin, which was used as one of the variables in the equation of the DRASTIC methodology. Type A soil is more prevalent in the basin, due to the high infiltration rate, even when they are wet.

In Figure 3, soil type-A and -Bhave 61.34% and 38.36 % of the basin area, respectively. As mentioned above, Type A soil has a low potential for direct flow and high infiltration intensities, even when completely wet. They mainly include deep areas with good or excessive drainage and have a high permeability. Type B, on the other hand, has below-average direct flow and moderate infiltration intensities when fully saturated. They include moderately deep soils with a moderately fine and coarse texture and well-drained soils.

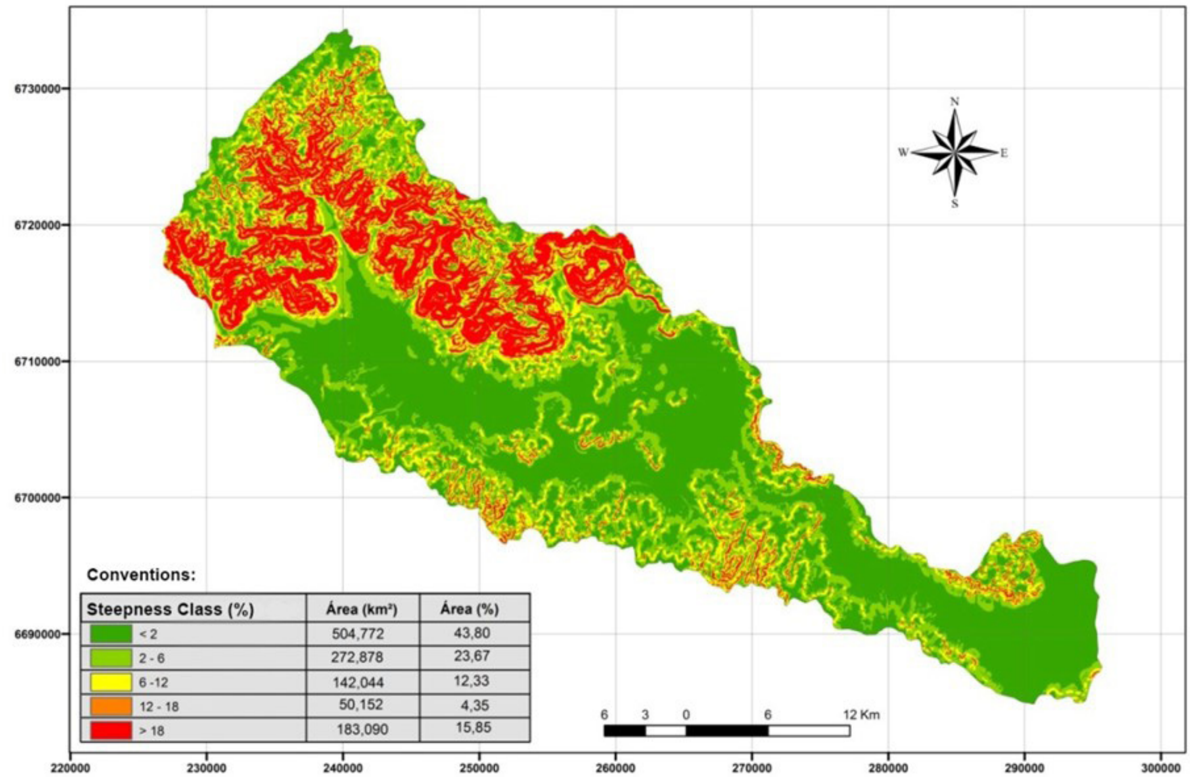

Figure 2 Slope Classes Map (%) in the Vacacaí-Mirim Basin.

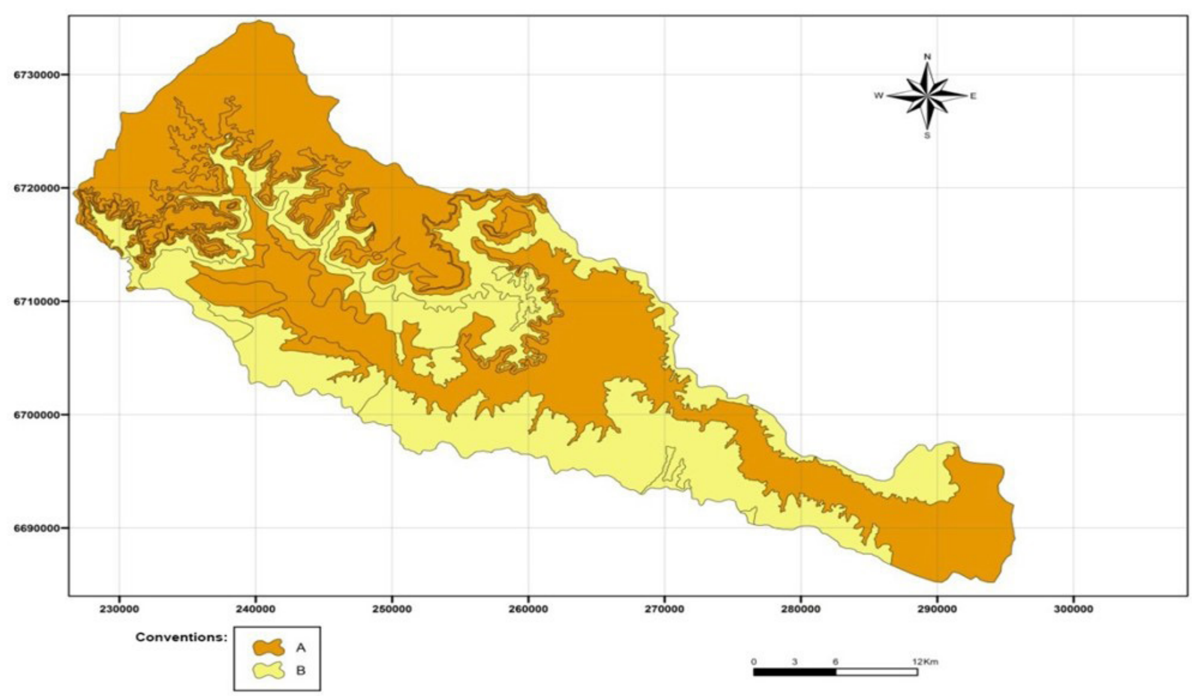

Figure 3 Soil Types presented in the Vacacaí-Mirim River Basin (David 1976).

2.2 Determination of Maximum Infiltration Areas

This step also followed the methodology proposed by Ferreira & Cunha (2002). Therefore, the creation of an infiltration index that gathers all the parameters and defines the maximum infiltration areas through a threshold value allows ordering the areas considering the ease of infiltration, and the standardization of the values obtained in different areas.

For an index definition, assigning values to each parameter is needed, as well as finding an expression which links the several parameters. The soil type can take four values, prevailing soils that facilitate the infiltration surface and penalizing soils that favor the direct flow. The topographic surface slope features in the same way as the parameter T (topography) in the DRASTIC method (Aller et al. 1987). The maximum amount of storable water in the soil which may be used for evapotranspiration (AGUT) is characterized by dividing the value assumed by the variable on 50-mm intervals. The calculations proposed by Oliveira and Ferreira (2002) were carried out:

$$IFI = TS + T + AGUT \quad \textbf{(1)}$$

where *IFI* is the infiltration facility index; *TS* refers to the value assigned to the type of soil; *T* assigned to slope; and *AGUT* assigned to the variable AGUT, wherein the greater the index, the greater the ease of infiltration. The ease of infiltration assumes values between 3 and 30.

To define the areas of the maximum infiltration from the IFIs it is necessary to set an index limit. Using the criteria above-mentioned, the areas of maximum infiltration correspond to:

$$|F| = 26 \text{ (amount TS } \epsilon \text{ } \{10.8\} \wedge \text{ amount T } \epsilon \text{ } \{10.9\} \wedge \text{ AmountAGUT } \epsilon \text{ } \{10.9\})$$

The maximum infiltration areas will occur when the F values are greater than 26, i.e., in the sum of the variables, TS values are between 8 and 10, and T and AGUT between 9 and 10.

To obtain the required parameters for the establishment of maximum infiltration areas on the basin aquifers of Vacacaí-Mirim River, the following methods and materials were used.

The clinographic map necessary to establish the land slope was obtained from topographic maps published by the Army, at 1:50,000 scale and contour lines every 20 m.

The evaluation of soils into types A, B, C and D of the hydrological soil classification from US-SCS was carried out by interpreting the characteristics of the mapped soils (Brasil 1973; Streck et al. 2002). The result of this interpretation will be a letter adapted to soils.

To estimate the AGUT soil samples located on aquifers were collected and then determined their sr and wp values. The obtained values were applied to the following Equation 2.

$$AGUT = rp\ (sr - wp) \quad \textbf{(2)}$$

where rp is the roots depth. To determine the rp, the soil use and occupation of the basin was mapped from satellite images firstly.

To generate this map, images from the Landsat TM 5 satellite (orbit point 223/81 and 222/81), available at INPE's image catalog - National Institute for Space Research were used. With the ArcGIS software version 9.3, the images were processed and georeferenced in the UTM coordinate system and SIRGAS 2000 was used as the datum reference.

The Landsat 5 TM satellite has a spatial resolution of 30 meters and temporal resolution of 16 days. In this study images of February 9th, 2010, and of February 5th, 2011 were used. These dates were chosen to facilitate the classification of targets, given that the phenological cycle of soybeans and rice has its greatest vegetative vigor in the study area between January and March.

After georeferenced images, the basin limit was designed. Using the tool "Extract by Mask" (extraction by infusion), images were cut to the edge of the basin. The classes chosen for the mapping considering the resolution of the images were soybean cultivation, rice cultivation, bare soil, forest, water, field/pasture, and urban areas, and these were manually vectored so as not to interfere in the calculation of the remaining ones. The proximity of the spectral response with bare ground.

With the cropped image, training areas were chosen, that is, the areas where the pixels of the defined classes were found. For image classification, the supervised classification method was used, in which the user defines the classes and not the automated software. Also, in the sample formation stage, the Minimum Distance Classifier was used, a supervised statistical method that quickly and accurately classifies each image pixel.

To generate the resulting image, ArcToolbox's "Create Signatures" tool was used. This tool creates a file of spectral signatures of predefined targets, in ASCII format. Later, with the generated signature file, the "Maximum Likelihood" (Maximum Likelihood) tool was used, which is also an ArcToolbox tool. In this tool, the image to be classified and the signature file generated previously was inserted and then the classification of the images was carried out.

The resulting image is a map format " shapefile " which were used to calculate areas and the respective percentage of each class by applying the Calculate Tool Geometry (the geometry calculation tool). All procedures were performed on both images (2010 and 2011).

3 Results and Discussion

3.1 Land Use and Occupation

The land use classes chosen for the study area in 2010 are shown in Table 2 and Figure 4.

The classes of Land use chosen for the studying area in the year 2011 are shown in Table 3 and Figure 5.

During the two years when the determination of use and occupation of the soil in Vacacaí-Mirim basin was held, only field/pasture decreased from 43.03% to 29.79%. The other uses showed an increase. Bare soil, urban area, rice cultivation, soybean cultivation and bodies of water increased from 11.28 % to 13.65 %, from 2.43 % to 2.51 %, from 23.76 to 28.67 % (the largest increase), from 8.31 % to 11.05 % and from 1.62 % to 1.81 %, respectively. The decrease in field/pasture areas may be related to an increase in short-cycle crop production areas, due to higher financial returns. Furthermore, the relationship between the reduction of pasture areas and the growth of urbanization should be highlighted, the latter being related to the expansion of urban centers and the need for more areas around cities.

The understanding of the dynamics of temporal fragmentation of the landscape in the studied area was possible through the classification of land use and occupation. Thus, the integration of studies, for example, the determination of areas of maximum infiltration, can help to create subsidies for managers in decision-making.

Table 2 Description of land use areas in Vacacaí-Mirim Basin for the year 2010

Class	Area (ha)	Area (%)
Bare soil	13,704.34	11.28
Urban area	2,953.56	2.43
Rice	28,858.24	23.76
Soy	10,102.65	8.31
Forest	11,304.24	9.55
Water blade	1,966.82	1.62
Field/Pasture	52,255.98	43.03

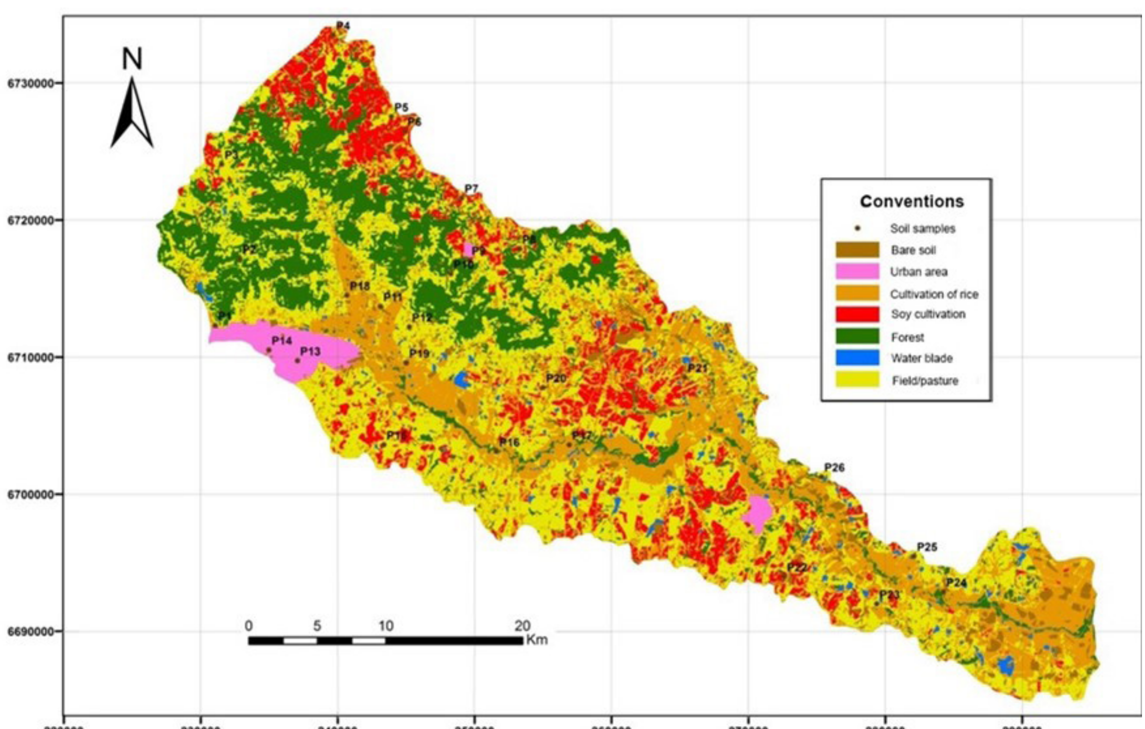

Figure 4 Map of land use and occupation in Vacacaí-Mirim Basin, RS, in 2010.

Table 3 Land use in Vacacaí-Mirim Basin in 2011

Class	Area (ha)	Area (%)
Bare soil	16,149.25	13.65
Urban area	2,974.73	2.51
Rice	33,916.32	28.67
Soy	13,076.29	11.05
Forest	14,811.09	12.52
Water blade	2,147.16	1.81
Field/Pasture	35,242.21	29.79

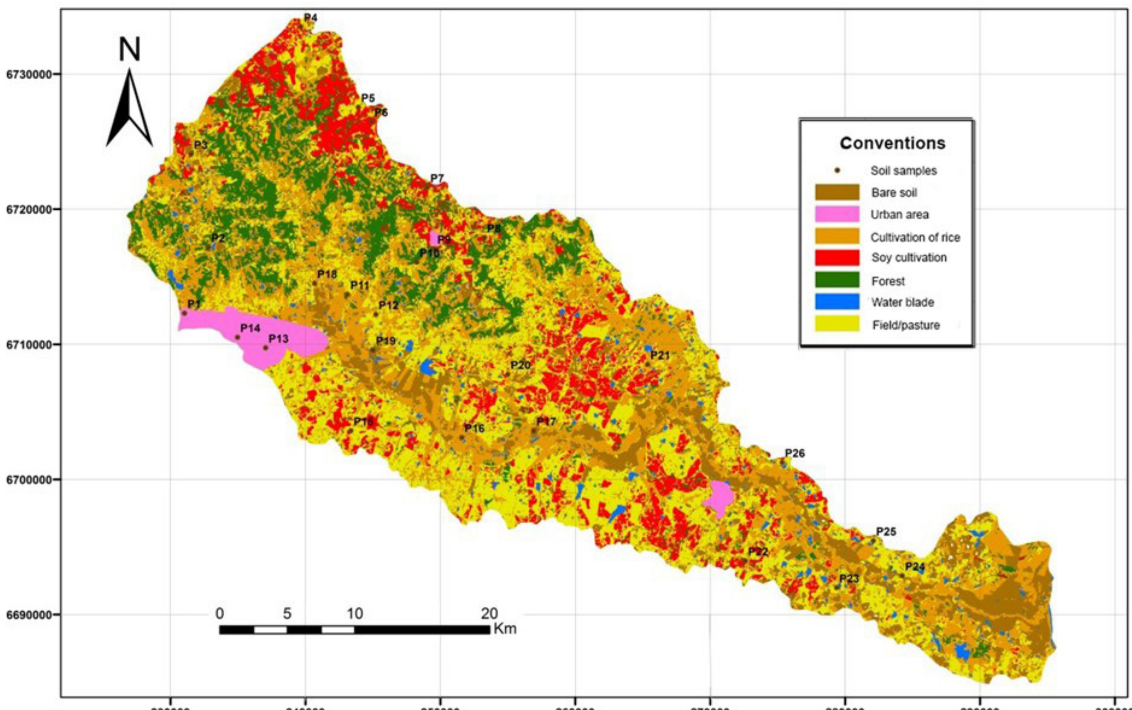

Figure 5 Map of land use and occupation in the Vacacaí-Mirim Basin, RS, in 2011.

3.2 Root Depth in the Different Classes of Land Use and Cover

According to the resolution of the used image, the following classes of land use and occupation were determined: bare soil, urban area, rice cultivation, soy cultivation, forest, water slide, field/pasture. Each class assumed a value for the root depth (Table 4).

Concerning deep roots, it is necessary to highlight the increase in the areas occupied by forests that have the greatest depth of roots among all the classes used (2,750 mm) and can increase the potential for water infiltration

Table 4 Value used to average depth of the roots

Use and ocupation of the soil	Depht of the roots – r_p (mm)
Bare soil	250
Urban area	0
Cultivationofrice	600
Soybean cultivation	600
Forest	2,750
Water blade	0
Field/Pasture	800

into the soil. However, the decrease in the area occupied by the field/pasture represents a decrease in the areas where the roots reach an average of 800 mm, thus reducing the infiltration potential of these areas.

3.3 Maximum Amount of Water in the Soil Available for Evapotranspiration

The AGUT values in the Vacacaí-Mirim basin ranged between 0 and 600 mm, and the highest values were observed in the western region, where the regions and higher soils occupied by areas of native forest in the river basin prevail (Figure 6). The lowest values were observed in the other regions.

The highest values were observed AGUT in Leptospires of the sand Acrisols the red S in the native forest. It can be explained by the low density of the soil at that time, which facilitates water infiltration along with the soil profile. Zwirtes et al. (2011), in a study on soil water infiltration under different land, uses, stated that native forest areas had a higher water infiltration rate, contrary to what happens in agricultural or pasture areas, which modify the physical properties of the soil.

3.4 Infiltration Easiness Index - I_{FI} (2010 - 2011)

The highest values of I_{FI} were in Planosols and red Acrisols (Figure 7). This may be related to the low clay content present in these soils, which facilitates the water infiltration along the soil profile. This parameter considers the conditions shown in Table 1, which is very dependent on the slope and soil type. Regarding the Planosol, several authors such as Bamberg et al. (2012) stated that it has low water permeation rate. According to Rosa et al. (2011) these soils have a very peculiar feature, the hydromorphism, which is stimulated by the predominantly flat terrain, combined with the presence of a clayey texture B horizon that waterproofs the soil, preventing water infiltration. However, when verifying in the equation that these areas are usually located in areas of lower slope (lowland areas of Vacacaí-Mirim) and have a high AGUT, a large infiltration rate was obtained in the present study.

Figure 8 shows the variation of the I_{FT} for the year 2011 obtained by the DRASTIC method. The I_{FT} values vary from 10 to 30, where the lowest values were observed in the highest regions of the basin, prevailing areas of native forest. The highest values were in the central, west, and lower regions where areas of lowland rice cultivation prevail.

The largest leakage values are mainly due to the occurrence of soil type A. They mainly consist of deep sand with good or excessive drain and have a high permeability according to David (1976) and Oliveira & Ferreira (2002). Another important factor is the topography of the land having less than 2% slope and containing an AGUT smaller than 50 mm. These three factors together provide conditions that cause greater water infiltration in the soil.

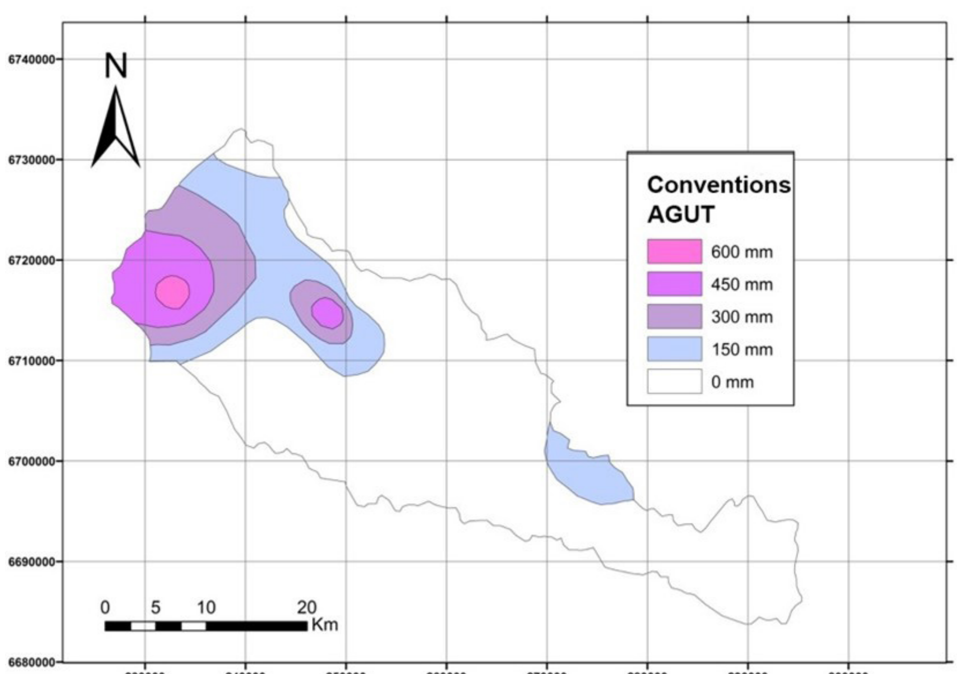

Figure 6 AGUT variation in Vacacaí-Mirim Basin in 2013.

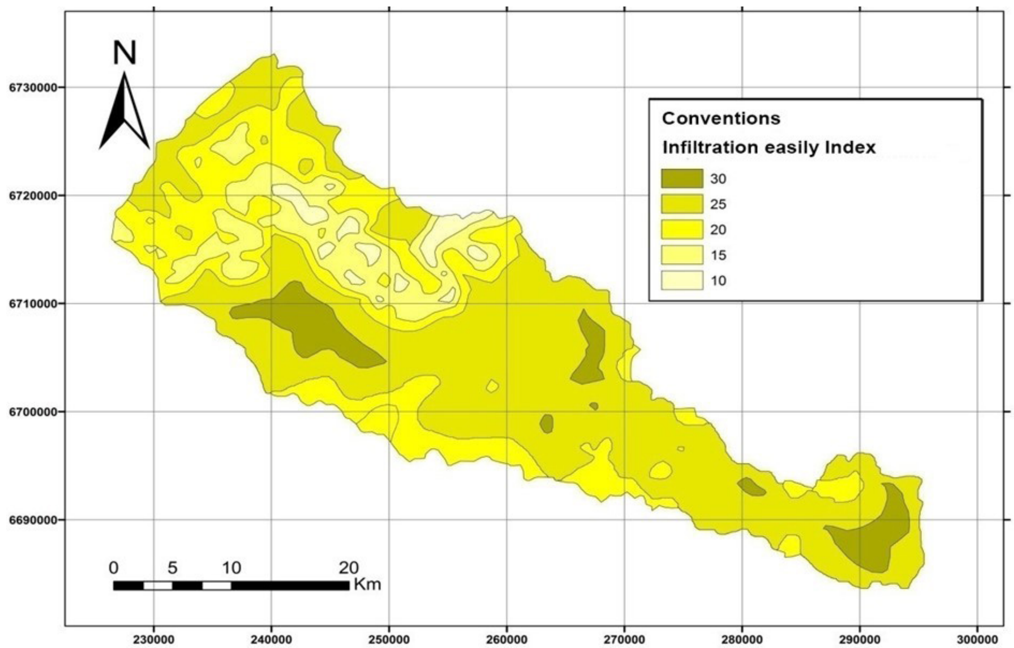

Figure 7 I_{FI} in Vacacaí-Mirim Basin in 2010.

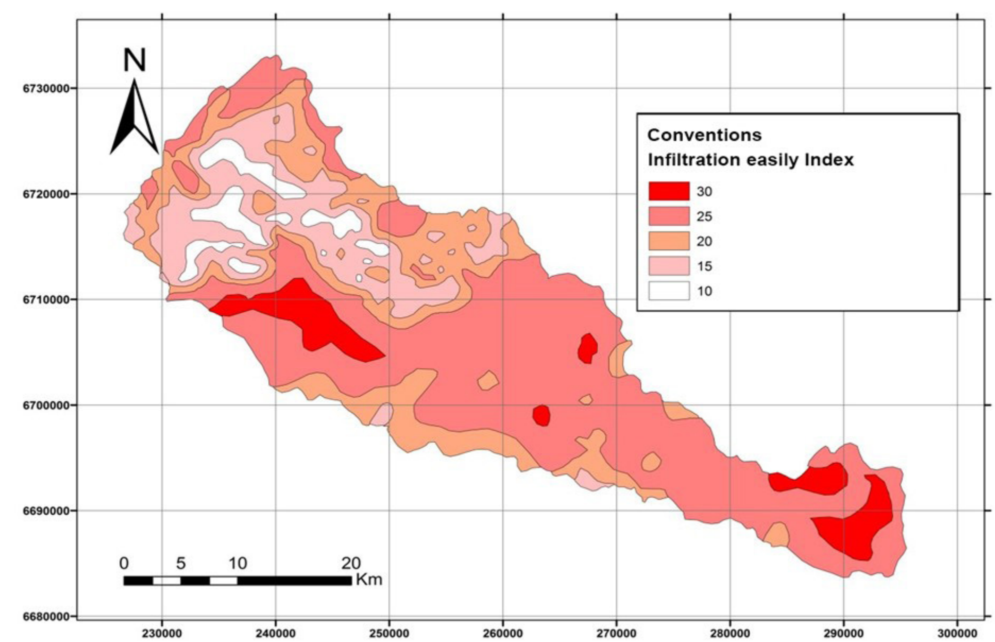

Figure 8 I_{FI} in the Vacacaí-Mirim Basin in 2011.

The areas of maximum infiltration correspond to 28,219.75 ha, i.e., 24% of the Vacacaí-Mirim basin total area (Figure 9), mainly in the central and eastern regions of the basin. The values of maximum infiltration were identified in native field, pasture, rice cultivation and urban areas. These areas can be related to the storage system and management of the soil (no changes in physical properties), leading to greater water infiltration along the profile. In this context, Silva et al. (2006) mentioned that a soil with good structural quality determines, in addition to a greater infiltration along its profile, a reduction of surface runoff and therefore a better control of erosion and entrainment of sediment.

Regarding the 2011 context, Figure 10 illustrates the maximum infiltration variation of the basin. The maximum infiltration occurred in 2,8823.50 ha (about 18.55% of the total area). The maximum infiltration occurred in rice cultivation, pasture, and native field spots in 2011, according to DRASTIC methodology.

In relation to 2010, the urban area did not show the maximum infiltration values. It may result from the growth of area partially or fully waterproofed, causing degradation in the properties of the soil and increasing the surface runoff. There was also an increase in relation to the total area (increment of 4.91%) of rice cultivation areas between 2010 and 2011. Melo, Cabral & Montenegro (2005) affirm that the process of waterproofing the soil, present in an urban area, reduces the amount of water infiltration, increasing the surface runoff, changing the roughness parameters and water retention in the soil.

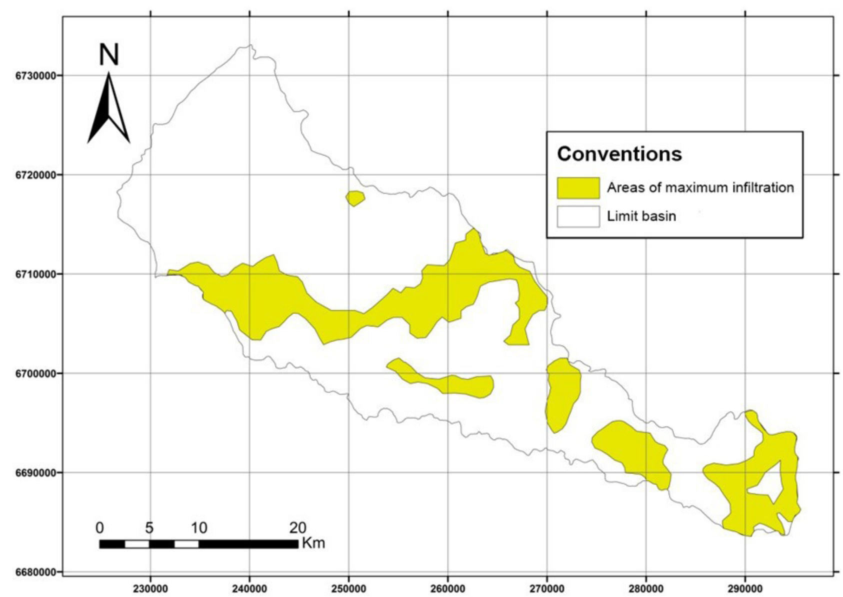

Figure 9 Changes in areas of maximum infiltration in Vacacaí-Mirim Basin in 2010.

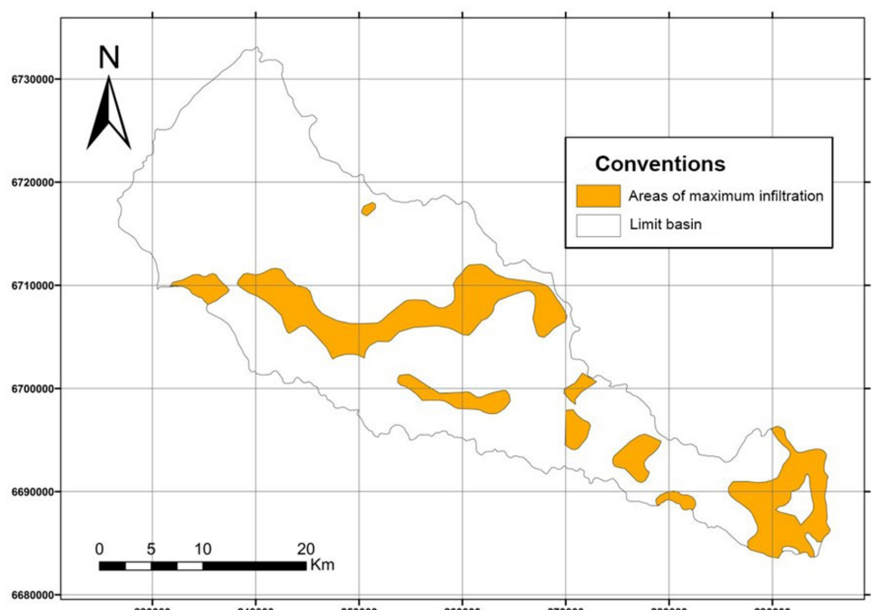

Figure 10 Changes in areas of the maximum infiltration in Vacacaí-Mirim Basin in 2011.

4 Final Remarks

Based on the application of the DRASTIC methodology, the Vacacaí-Mirim river basin has areas of large infiltration potential. Depending on the land use and occupation, contamination of the underground aquifer may occur. The land uses with the highest rates of maximum infiltration were pasture and rice cultivation. Such areas should receive much more attention from land managers, in view of preserving the quality/quantity of the aquifer and conservation of potential recharge areas.

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