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Environmental risk assessment for the use of liquid swine manure as soil fertilizer

Avaliação do risco ambiental para uso de dejetos líquidos de suínos como fertilizante de solo

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ABSTRACT: Liquid Swine Manure (LSM) has being recognized as a potential fertilizer for agriculture, but excessive and/or prolonged applications of high doses in agricultural systems may cause soil and water pollution. The present paper presents the proposition of a multicriteria model that aims to identify and classify agricultural areas that receive LSM as soil fertilizers, according to the degree of potential risk of contamination of surface waters. The proposal is based on the knowledge of experts, use of Geographic Information Systems (GIS) and the modelling of a decision support system. The determination of environmental risk criteria was performed based on a literature review and its weighting was defined through consultation with specialists from various institutions, research, educational and environmental of the State of Santa Catarina. The model, called SMRISK (Swine Manure Risk), was applied within a watershed with intensive pig farming located in Southern Brazil and proved to be more restrictive compared to the legal regulations used for the environmental licensing of pig farming in the State of Santa Catarina.

Keywords: Pig Farming; Animal Waste; Geographic Information Systems.

RESUMO: O dejeto líquido de suínos (DLS) apresenta reconhecido potencial fertilizante para a agricultura, entretanto aplicações excessivas e/ou prolongadas de altas doses em sistemas agrícolas podem causar poluição do solo e da água. O presente trabalho apresenta a proposição de um modelo multicritério que visa identificar e classificar áreas agrícolas que recebem DLS como fertilizante de solo, de acordo com o grau de risco potencial de contaminação das águas superficiais. A proposta fundamenta-se no conhecimento de especialistas, no uso de Sistemas de Informações Geográficas (SIG) e na modelagem de um sistema de suporte à decisão. A determinação dos critérios de risco ambiental foi realizada com base em revisão de literatura e sua ponderação foi definida mediante consulta a especialistas de diversas instituições de ensino, pesquisa e meio ambiente do Estado de Santa Catarina. O modelo, denominado de SMRISK (Swine Manure Risk), foi aplicado em uma bacia hidrográfica com produção intensiva de suínos localizada no sul do Brasil e demonstrou ser mais restritivo em comparação com as normativas legais utilizados para o licenciamento ambiental da suinocultura no Estado de Santa Catarina.

Palavras-chave: Suinocultura; Dejetos Animais; Sistemas de Informação Geográfica.

INTRODUCTION

Brazil ranks fourth in the world ranking of pig meat production, with an animal stock of 39.95 million heads, with 49.9% of this amount concentrated in the Southern Region, standing out the State of Santa Catarina with 6.88 million (Instituto Brasileiro de Geografia e Estatística, 2019). The modernization of the pig production system in the country allowed increased productivity and scale gains, but consequently, the increase in the concentration of animal waste (Ito et al., 2016). Due to the important amount of nutrients in waste, its use as fertilizer in agriculture is a widespread practice and its management is done predominantly in liquid form (Seganfredo, 2007). However, excessive and/or

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prolonged applications of high doses of LSM in agricultural systems increase the concentration of nutrients in the surface layers of the soil (Girotto et al., 2010; Hart et al., 2010), in particular phosphorus (P). In agricultural areas, high soil P levels can be a source of diffuse pollution for water bodies (Estatistical Office of the European Union, 2018). This process is influenced by climate factors, land use and management and physical and environmental aspects. In view of this scenario, we propose a simplified model of environmental risk assessment for the use of LSM as soil fertilizers, with the objective of identifying and classifying agricultural areas according to the degree of potential risk of surface water contamination, based on the knowledge of specialists, the use of Geographic Information Systems (GIS) and the modelling of a decision support system.

MATERIAL AND METHODS

The design of the model is supported by the concept of risk, understood as a probability of occurrence, which can be defined as the potential product of contamination and vulnerability (Aven, 2016). The estimate or the potential degree of environmental risk by the use of LSM as soil fertilizers in agricultural areas is given by the integration of multidimensional indicators that relate the management of the agro ecosystem with the characteristics of the physical environment, and its result is expressed on a qualitative scale. The model (Figure 1) was called SMRISK (Swine Manure Risk) and uses the Hierarchical Process Analysis method - AHP (Saaty, 1990) as support for decision-making with multiple quantitative and qualitative criteria. The conceptual model started from the selection of criteria based on: 1. Reliability (scientific validity and/or theoretical consistency); 2. Practicality (cost/benefit correlation - time, availability and/or ease of detection in the field); and 3. Utility (simplified complexity, public domain, and multiscale). The construction of SMRISK followed a hierarchical organization of levels based on the fundamental analytical principles of the AHP method, which are: 1 - Establishment of hierarchies (structuring of the problem, criteria and their respective classes at hierarchical levels, grouping them into independent sets, but relatable to each other); 2 - Definition of importance of criteria and classes (the determination of the importance of each criterion and its classes was based on the paired comparison through equal judgment of priority, individually defining each comparative weight and its respective importance, obeying a numerical scale (Saaty, 1990) ranging from 1 (equal importance) to 9 (extreme importance), according to the judgment of each of the specialists participating in the evaluation of the criteria/factors of the model; 3 - Consistency model logic (the evaluation is given by the inconsistency index (CI), accepting maximum values of 10.0% to ensure the logical consistency of the model (Saaty, 1990). The validation of the criteria and the respective risk classes was determined by judgment and weighting of importance, carried out from consultation with specialists from various educational institutions (UFSC, UDESC, UFFS, IFC), research (Embrapa, EPAGRI/CIRAM) and environmental agencies (IMA/FATMA) in the Santa Catarina State, through a digital form. Thirty-one specialists were consulted from April to July 2019, obtaining feedback from 17 evaluators. In the preparation of the form sent to the specialists, the weighting method used to determine weights of importance followed the fundamental scale (Saaty, 1990).

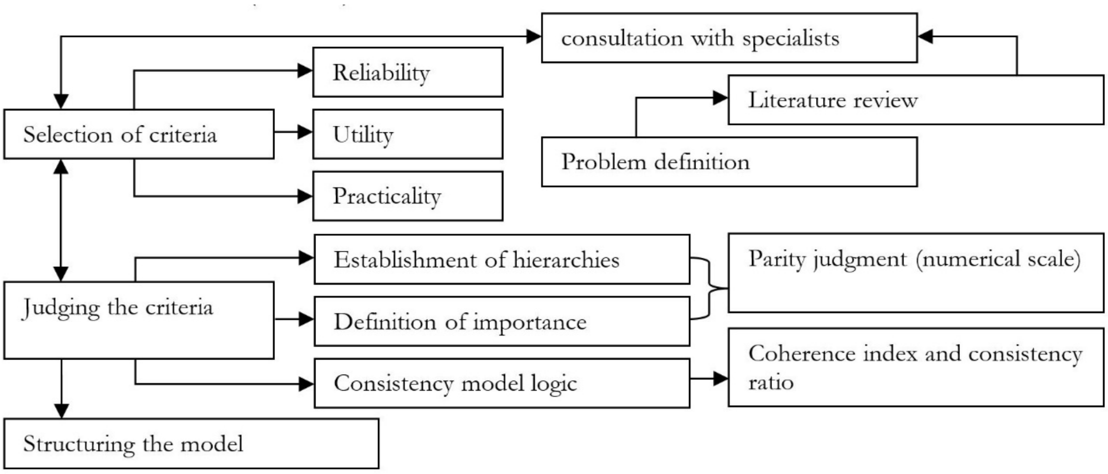

Figure 1: Conceptual structuring of the simplified environmental risk assessment model for the use of liquid swine manure as soil fertilizers (SMRISK).

The Structure of the SMRISK (Table 1) used the grouping of four criteria judged, evaluated and analysed by the experts, being: Criterion 1 - Slope (slope of the surface of the terrain in relation to the horizontal, being the difference of height between two points and their respective distance). The classes that correspond to this criterion were adapted according to: Melland et al. (2007); Dall'Orsoletta, (2018); Criterion 2 - Distance from the water body (average distance between the edge of the agricultural area to the nearest body of water, taking into account the direction and drainage flow in the terrain). The determination of the distance variations of this class were adapted based on: Bechmann et al. (2005); Beegle et al. (2007); Melland et al. (2007); and the legal provisions of Law 12.651/2012; Criterion 3 - Method of application (method of application of swine liquid manure in agricultural areas), adapted from: Andersen & Kronvang, (2006); Bechmann et al. (2005); Mallarino & Haq (2015), considering the available technological models; Criterion 4 - Critical Environmental Phosphorus Limit - CEL-P (expresses the maximum P extractable content by the Mehlich-I method admitted to the soil layer 0–10cm (Gatiboni et al., 2015). The determination of the values of the final weights derived from the weighting made by the group of experts showed a consensus of 78.3% and consistency of 3.8%.

Table 1: Criteria, weights, classes, degree of risk and class score of the simplified environmental risk assessment model for the use of liquid swine manure as soil fertilizers (SMRISK).

Criterion	Weight	Category	Risk	Score
1 - Declivity	0.455	>20.1%	High	0.640
		10.1-20%	Medium	0.265
		0-10%	Low	0.095
2 - Distance from the water body	0.164	<30m	High	0.561
		30.1-50m	Medium	0.255
		>50.1m	Low	0.184
3 - LSM Application Method	0.097	Surface not incorporated	High	0.752
		Surface incorporated	Medium	0.167
		Injected >5cm soil	Low	0.081
4 - Environmental Critical Phosphorus Limit (CEL-P)	0.284	>40+CC>20%[3]	High	0.644
		>40+CC<=20%[2]	Medium	0.291
		<=40+CC[1]	Low	0.065

Legend: [1]<=40+CC: value less than or equal to 40 plus soil clay content (expressed as a percentage); [2]>40+CC<=20%: value greater than 40 plus clay content up to 20% above the limit; [3]>40+CC>20%: value greater than 40 plus clay content above 20% of the limit (Gatiboni et al., 2015).

SMRISK follows an additive approach, where factors are multiplied by a weighting value and its score, summed together to result in a risk index, from a weighted linear combination, according to the equation (Equation 1):

$$R = \sum_{i=1}^{n} wi.xi \tag{1}$$

Where: R = Risk; wi = weight of criterion i; xi = score i; n = number of criteria. The scale of the degree of risk was defined as: low (model values <= 0.241), medium (values >= 0.242 and <= 0.412) and high (values >= 0.413).

The spatial cut out of SMRISK analysis is the Watershed of Lajeado Clarimundo - MBHLC (27°12'6.57"S; 52° 8'9.07"W), located in the northwest portion of the municipality of Concordia, State of Santa Catarina, Brazil. The MBHLC has an area of 236.5 ha, the land profile is characterized by small farmers, with an average of 9.3 ha per property and the main economic activity developed is pig rearing, with animal stock of 4675 finishing pigs and 792 sows, with all production developed under contractual agreement with agro-industries in the region. The choice of this unit for the case study was determined by means of three criteria: 1 - Use of the concept of watershed as a territorial unit of analysis and management of natural resources; 2 - Geographical area with representativeness in the regional and national context, in terms of intensive pig production; 3 - Availability of socioeconomic and environmental data and information of the areas and pig farmers, and, collection of geospatial data. Altogether, ten temporary cultivation areas (L1 to L10 – Figure 2) located in MBHLC were selected.

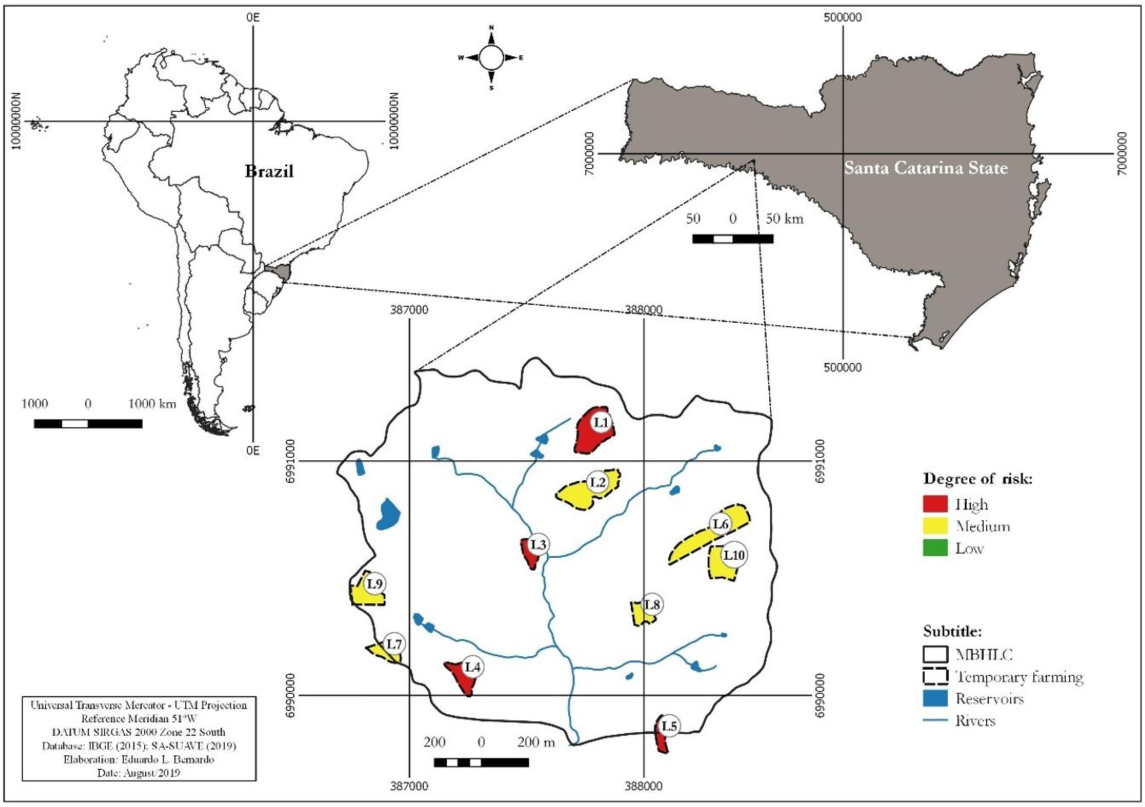

Figure 2: Location map of the study area and application of the simplified environmental risk assessment model for the use of liquid swine manure as soil fertilizers (SMRISK).

Field data for phosphorus (mg/dm^3) and clay (%) from random stratified sampling in the 0-10cm layer, forming four composite samples (3x1) for each area. Phosphorus content in the soil was analysed by the Mehlich-1 method and the clay content by the densimeter method (Teixeira et al., 2017). These data are part of the project database: Evaluation of indicators and strategies for valuation of environmental services in hydrographic basins with intensive production of animals (SA-SUAVE), of the thematic line: Environmental services in the rural landscape (arrangement AS), Macroprogama 2, of the Brazilian Agricultural Research Company - Embrapa, held at the National Center for Research in Swine and Poultry - CNPSA (2015/2019). Data regarding the delimitation of agricultural cultivation areas and the criteria of the water body distance and slope model were extracted from the orthorectified database of the State of Santa Catarina. The distance from the water body was determined by buffering 30 and 50 meters from the water bodies in the MBHLC area. The slope was obtained through geoprocessing techniques from the Digital Terrain Model (DTM). The information of the method of application of the LSM in each sampled area was obtained from a questionnaire applied to the pig farmers who own the sampled areas.

RESULTS AND DISCUSSION

The areas of temporary crops sampled for the evaluation of SMRISK comprised 14.5 ha distributed in nine pig farmers, which have a history of using LSM as soil fertilizers for more than 10 years, representing these areas, 39.7% of the use class with temporary crops found in the watershed. The mean levels of phosphorus (P) in the sampled areas (Table 2) fall within the "very high" interpretation class as defined by the Rio Grande do Sul and Santa Catarina States Soil Chemistry and Fertility Commission (Sociedade Brasileira de Ciência do Solo, 2016). The high levels of P in the soil indicate applications of LSM in higher doses or imbalance with nutritional needs of the crops (Dall'Orsoletta, 2018; Seganfredo, 2007). High levels of P in the soil result in a decrease in its adsorption capacity and of receiving new P additions (Estatistical Office of the European Union, 2018; Gatiboni et al., 2015), in parallel with the increased risk of its transfer to water resources (Hart et al., 2010). Due to this imbalance in the relationships of adsorption and P desorption in the soil, research has been developed aiming at establishing safety limits for P levels in the soil (Dall'Orsoletta, 2018; Gatiboni et al., 2015). In the USA, several states have established critical limits of P in soil levels ranging from 50.0 mg/dm^3 for the States of Delaware to 200.0 mg/dm^3 for the States of Texas, Oklahoma, and Kansas, and the application of any P source should be stopped when they reach values above those established (Sharpley & Beegle, 2001). In the State of Santa Catarina, CEL-P was established, which indicates the maximum level of P admitted for the use of LSM as soil fertilizer. Applying the CEL-P for the areas of temporary crops analysed, it was observed that 20.0% of these areas (Table 2) have P levels above the CEL-P, which according to IN-11 (Fundação do Meio Ambiente de Santa Catarina, 2014), would prevent new additions of P from any source, whether organic or mineral. Although soil P content may be useful as a reference for the assessment of potential environmental impacts, it represents only one dimension or a variable of a set of factors that determine the environmental risks associated with this nutrient. Among the main factors described in the literature, the slope of the terrain stands out, due to its direct relationship with the movement of water, sediments and nutrients, especially on the soil surface (Bechmann et al., 2005; Beegle et al., 2007). Steeper areas present higher velocity and energy of water flows on the surface, increasing the potential for disaggregation and transport of soil particles during the surface runoff process (Dall'Orsoletta, 2018; Melland et al., 2007). The areas of temporary crops analysed even though they are located in the most favourable lands have an average of 18.4% of slope (Table 2). In an experiment carried out in the Southern Region of Brazil, Dall'Orsoletta (2018) evaluated the influence of slope and the dose of LSM applied in the soil on the amount of P lost by surface runoff, demonstrating that the increase in slope also increases P losses by surface runoff, especially in areas with LSM application, total P losses doubled with each increase of 20.0% in slope, but were independent of soil clay content. In Australia and the U.S. State of Virginia, for example, agricultural areas with decline greater than 15.0% are classified as "high risk" of loss of nutrients from soil to water (McDonald et al., 2012; Melland et al., 2007). In addition to the slope, the third criterion analysed individually was at a distance from the source areas of P in relation to surface water bodies, a factor recognized by the literature as an important indicator of environmental risk (Bechmann et al., 2005; Leytem et al., 2017). This criterion is used to classify the risk potential of P reaching a water body, considering that the closer an agricultural area is to a water body, the greater the probability that P reaches the water resource (Hensleigh, 2013). The distance from the source areas of P to a water body is a risk indicator widely used in P indices in the USA. For example, in Nebraska (Wortmann et al., 2012) the source areas of P with a distance of less than 30.0 m from the bodies of water are classified as "high risk" in Pennsylvania (Beegle et al., 2007) 45.0 m and in Idaho (Leytem et al., 2017), distances of less than 60.0 m. In Europe, in the case of Denmark (Andersen & Kronvang, 2006), with an extension of less than 45.0 m and in Australia (Melland et al., 2007) areas with a distance of less than 30.0 m. In Brazil, Law Nº. 12.651/2012 considers Permanent Preservation Area (PPA) for watercourses up to 10 meters wide marginal range of 30 meters. For the temporary tillage areas analysed in the MBHLC, only one area (L3) is in the range of 30 meters of a watercourse (Table 2). The fourth criterion analysed comprises the method of application of LSM, a risk factor for P losses widely addressed in the literature (Bechmann et al., 2005; Beegle et al., 2007; Leytem et al., 2017; McDonald et al., 2012; Wortmann et al., 2012). Worldwide, the predominant form of application has been superficial, mainly due to economic factor however, this form presents some inherent environmental risks, especially bad odours, ammonia volatilization and nitrous oxide emission, in addition to the greater potential for nutrient losses due to surface runoff (Seganfredo, 2007). Several tools for assessing the risk of P loss in agricultural areas consider surface application in the soil as "high risk", citing the Colorado P index (Sharkoff et al., 2012), Arkansas (Sharpley et al., 2010) in the U.S. and Ontario (Reid, 2011) in Canada. Because of this, it is recommended the practice of incorporation of fertilizers in the soil, thus significantly minimizing losses due to surface runoff (Risse, 2015). In Brazil, especially in the State of Santa Catarina, surface application is the predominant practice for the use of LSM as soil fertilizers. Although machines and equipment that enable the injection of LSM into the soil are available on the market, this technology is not used under the MBHLC. All temporary tillage areas in MBHLC apply LSM superficially without the practice of incorporation.

Table 2: Phosphorus (P), clay, CEL-P, medium slope and distance of water bodies from temporary tillage areas analysed in the Lajeado Clarimundo Watershed - MBHLC, Concordia, SC, Brazil.

Temporary Farming	P Level (mg/dm^3)	Clay Level (%)	CEL-P[1]	Average Slope (%)	Distance to the water body (m)
L1	176.48	50	90	18.1	38.9
L2	93.88	45	85	18.4	77.5
L3	50.39	31	71	21.2	19.6
L4	57.57	42	82	23.7	50.4
L5	139.99	41	81	22.9	225.4
L6	90.43	49	89	16.2	242.9
L7	27.60	57	97	15.1	129.4
L8	37.94	34	74	19.1	153.8
L9	100.95	51	91	16.3	133.8
L10	20.22	55	95	13.5	240.7

Legend: [1]CEL-P = 40+CC (clay content of the soil expressed as a percentage).

The first factor analysed in relation to the degree of risk was the slope, for which the specialists attributed the greatest weight of importance (45.5%) in SMRISK. In the case of MBHLC, 30.0% of the temporary crop areas analysed fell into the “high” risk class, due to their average slope above 20.1%. The other areas are located on plots with average slope between 10.1 and 20.0%, thus classifying themselves as a “medium” risk degree. According to the literature, in areas with a slope greater than 10%, LSM should be injected into the soil rather than applied superficially (Risse, 2015). The second criterion analysed in relation to the degree of risk was the CEL-P, to which the specialists attributed 28.4% of importance in the SMRISK. Of the total temporary tillage areas of MBHLC, 50.0% had P levels below the CEL-P, which frames them as “low” risk, while 20.0% had levels above the CEL-P, thus classifying themselves as areas of “high” risk, which according to the legislation of the State of Santa Catarina (Fundação do Meio Ambiente de Santa Catarina, 2014) would prevent the use of phosphate fertilizers from any source. For the risk plots “medium” that fall within the range between the CEL-P and up to 20.0% above this limit, the dose of P to be applied to the soil should be limited to up to 50.0% of the recommended maintenance dose for the crop to be fertilized (Fundação do Meio Ambiente de Santa Catarina, 2014). The third criterion analysed in relation to the degree of risk was the distances of water bodies, a factor considered by specialists with 16.4% importance in SMRISK. Of the 10 agricultural glebes analysed in the MBHLC, 80.0% are more than 50.1m away from surface water resources, which classifies them as “low” risk. One of the areas of temporary crops was part of the class: >30.1 m and <50.0 m, categorizing itself as “medium” risk, and a glebe in the class <30.0 m of surface water bodies with “high” risk. There is consensus in the literature that the distance from a source area of P to a water body determines the risk of contamination, because as the distance decreases the risk of P contamination increases (Reid et al., 2018). It is also recognized that agricultural glebes with distances greater than 50.0 m present lower risk for nutrient transfer via surface runoff to water resources (Bērziņa & Sudārs, 2010). The fourth criterion analysed in relation to the degree of risk was the method of application of the LSM. The way LSM are applied to the soil has a direct influence on the potential for losses and/or movement of nutrients to the bodies of water, especially the P (Hensleigh, 2013; Leytem et al., 2017; Sharkoff et al., 2012). For this criterion, the experts attributed 9.7% of importance in the SMRISK. According to this criterion, all sampled areas fell under risk class “high”. After the assessment and classification of the degree of risk for each criterion that composes the SMRISK, the next step was the integration of individual assessments aiming at determining the overall degree of risk for each of the ten areas analysed (Table 3).

Table 3: Risk classification of temporary crop areas analysed in MBHLC according to the simplified model of environmental risk assessment for the use of liquid pig waste as soil fertilizers (SMRISK).

Temporary Farming	Criteria				
	1 - Declivity	2 - CEL-P	3 - Distance to the water body	4 - Application Method	Global Risk
	Risk Class				
L1	Medium	High	Medium	High	High
L2	Medium	Medium	Low	High	Medium
L3	High	Low	High	High	High
L4	High	Low	Low	High	High
L5	High	High	Low	High	High
L6	Medium	Medium	Low	High	Medium
L7	Medium	Low	Low	High	Medium
L8	Medium	Low	Low	High	Medium
L9	Medium	Medium	Low	High	Medium
L10	Medium	Low	Low	High	Medium

Analysing the results obtained for the areas of temporary crops using the SMRISK model, slope was the most weight factor in the definition of the risk classes of each agricultural glebe, reflecting the topographic profile of the MBHLC that has strong relief wavy. The distance factor of water bodies was not a determining criterion for any of the crops analysed, but it is highlighted that this behaviour is a specific characteristic of MBHLC and also by the low weighted value by the specialists. For the method of application of the LSM, all areas fit the risk class "high", the maximum in the classification. Regarding the CEL-P factor, the results obtained with the model (SMRISK) indicate that 80.0% of the areas would be suitable for the use of LSM as soil fertilizers. Comparatively, the overall risk obtained by the SMRISK model was more restrictive than the isolated use of CEL-P, which is explained by the fact that SMRISK considers other risk variables related to P accumulation and movement in the soil. The use of SMRISK under the MBHLC has proven to be a feasible model and stops environmental risk assessment in agricultural areas using LSM as soil fertilizers.

CONCLUSIONS

1. The analysis of environmental risk in the use of LSM as soil fertilizer by SMRISK in MBHLC allowed a faster and more comprehensive evaluation of agricultural glebes on a river basin scale.

2. The multicriteria approach used allows adjustments related to the evaluation and weighting of criteria, as well as changes in the class ranges of each factor, thus enabling its adaptation to each region according to its environmental characteristics and specific management.

3. The use of geographic information systems (GIS) was fundamental and facilitating in the process of evaluation and classification of agricultural areas, besides being the appropriate tool for obtaining much of the data and information of the environment being analysed.

4. The proposal presented is shown as an alternative for environmental risk assessment and support for environmental management in the use of LSM as soil fertilizer, configuring itself as a complementary tool in the identification and classification of areas that require a more accurate assessment of their potential for surface water contamination.

5. Comparatively, the overall risk obtained by the SMRISK model was more restrictive than the isolated use of CEL-P, which is explained by the fact that SMRISK considers other risk variables related to p accumulation and movement in the soil.

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Author contributions:

Eduardo Lando Bernardo: Development and application of the model, treatment and analysis of data (part of his doctoral thesis).

Claudio Rocha de Miranda: Supervision, monitoring and support in the development of the model and data analysis.

Sebastião Roberto Soares: Research support.

Paulo Belli Filho: Supervision and monitoring development of research (supervisor the doctoral thesis of Eduardo Lando Bernardo).