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Methodological proposal for the allocation of water quality monitoring stations using strategic decision analysis

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Abstract In order to fill a gap in the monitoring of water quality in Brazil, the objective of this study was to propose a methodology to support the allocation of water quality monitoring stations in river basins. To achieve this goal, eight criteria were selected and weighted according to their degree of importance. It was taken into account the opinion of water resources management experts. In addition, a decision support system was designed so that the methodology could be used in the allocation of water quality monitoring stations by researchers and management bodies of water resources, to be fully implemented in geographic information system environment. In order to demonstrate the potential of the proposed methodology, which can be used in places that have or not existing monitoring networks, it has been applied in the Minas Gerais portion of the Doce river basin. Because the area already has a monitoring network with 65 stations in operation under the responsibility of the Minas Gerais Water Management Institute (IGAM), an expansion of the network was suggested and a simulation of a scenario was performed considering that the study area did not have an established network. The results of the analyses consisted of maps of suitability, indicating the locations with greater and lesser suitability for the establishment of the stations. With the application of the methodology, seven new sites were proposed so that the study area had the density recommended by the National Water Agency (ANA), and it was verified that the Caratinga River Water Resources Management Unit (UGRH5 Caratinga) has the most deficiency of stations among the six units evaluated in the Minas Gerais portion of the Doce river basin. In the simulated scenario considering the non-existence of a network, the adequacy map obtained was compared with the existing monitoring network and it was possible to classify the stations according to the purpose for which they were established, such as monitoring environments under anthropic activities or establishing benchmarks for the water bodies. Overall, the proposed methodology proved itself robust, and although the results were specific to one basin, the criteria and decision support system used are fully applicable to other areas of study.

Keywords Brazilian watershed · Monitoring network · Multi-criteria decision analysis · Water pollution

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Introduction

Agricultural expansion and rapid population and industrial growth along with the use of water resources has resulted in the generation of a large amount of effluents that, most often, are released into water bodies without prior treatment and in larger amounts, superior to its potential for self-purification (Ajorlo et al. 2013; Barakat et al. 2016; Dupas et al. 2015; Muangthong and Shrestha 2015). As a result, water quality tends to decrease and sometimes drops below the standards set by environmental legislation and can cause serious damage to the ecosystem and compromise the health of the living beings (von Sperling 2014).

Given this fact, the pollution of water bodies has become a global problem and its control is one of the major challenges of water resources management. Especially in Brazil, the need to diagnose factors that affect water quality and predict future impacts from human activities is becoming more and more urgent. Several studies on water quality in river basins in Brazil have been observing an increasing pollution and pointing out the release of domestic effluents without proper treatment as the main source of pollution (Avila et al. 2016; Calazans et al. 2018a, 2018b; Costa et al. 2017; de Oliveira et al. 2018; Oliveira et al. 2017; Pessoa et al. 2018; de Souza and do Gastaldini 2014; Vargas et al. 2018). This fact is a result of the critical situation of the Brazilian population in relation to the sanitary sewage, where the precarious waste collection and wastewater treatment in Brazilian cities have resulted in a significant amount of pollution load reaching water bodies, causing negative consequences to the multiple uses of water resources (ANA 2017).

Taking into account that the impact of the discharge of effluents in the water bodies is evaluated due to changes in water quality variables, qualitative monitoring is the first step for the development of a reliable and appropriate database for planning purposes and management of water resources (Shrestha and Kazama 2007; Simeonov et al. 2003). Given this fact, issues related to the project of monitoring networks and improvements of the methodologies used have been a objects of study of several researchers (Chang and Lin 2014; Chilundo et al. 2008; Karamouz et al. 2009a, 2009b; Memarzadeh et al. 2013; Ouyang 2005; Park et al. 2006; Pourshahabi et al. 2018; Telci et al. 2009).

In Brazil, the existing monitoring networks make it possible to monitor the changes in the physical, chemical, and biological characteristics of water resulting from anthropic activities and natural phenomena, subsidizing control instruments of environmental pollution, as well as the formulation of environmental policies (ANA 2013a). Despite the growing importance of water quality monitoring networks, many water resources management bodies in Brazil still rely on experiential knowledge and subjective judgments to determine the location of monitoring stations, which may be leading to a waste of human, financial, and logistics resources. Ideally, monitoring programs must adopt methodologies that have already been accepted and standardized (Strobl and Robillard 2008).

In 2010, the National Water Agency (Agência Nacional de Águas—ANA) launched in Brazil the National Water Quality Assessment Program (Programa Nacional de Avaliação da Qualidade das Águas—PNQA), which aims to provide an integrated monitoring system, with standardized collection and analysis procedures in every state allowing the monitoring of the evolution of water quality throughout the national territory in a systematic way (ANA 2012).

As the main component of the PNQA, the National Water Quality Monitoring Network (Rede Nacional de Qualidade de Água—RNQA) has as one of its objectives the allocation of water quality monitoring stations based on goals such as taking into account the density of stations in each region (ANA 2013b). However, the methodology proposed by the program of allocation of the stations takes into account only the water availability in the region and the flow required to dilute the effluents released into the water bodies (Avila et al. 2016), without taking into account several other relevant criteria in the allocation of monitoring stations. Therefore, despite the efforts being conducted by the PNQA, there is still a lack of methodologies applied to the Brazilian conditions that support planning and qualitative management of water resources in order to provide water management bodies proper tools that can guide them in the decision-making process.

Based on the above considerations, the objective of the present study was to propose a methodology to support the allocation of water quality monitoring stations using strategic decision analysis, developed in function of relevant criteria for monitoring water quality and applicable to the Brazilian river basins. The proposed methodology was applied in the Minas Gerais portion of the Doce river basin due to its great importance in the national context, as well as the lack of studies related to it. Since the basin already has an existing monitoring network, sites with potential for the establishment of new stations were identified and it was performed a simulation of a scenario where it was considered the non-existence of the current monitoring network.

Materials and methods

Structure of the methodological proposal

This methodological proposal for the allocation of water quality monitoring stations consists of a MCDA (Multi-Criteria Decision Analysis) method, which aims to classify a series of alternatives taking into account multiple criteria in the same decision system (Walker et al. 2015). In the planning and management of water resources field, several studies can be found using MCDA (Calizaya et al. 2010; Kuang et al. 2015; Montazar et al. 2013; Weng et al. 2010).

The methodology was elaborated so that it could be implemented in GIS (geographic information system) environment, in order to make the management and analysis of the spatial data easier, given the possibility of combining and simultaneously evaluate the criteria and their factors within the set of decision and evaluation rules (Sánchez-Lozano et al. 2013). The reproducibility of the analyses can also be guaranteed over time, since when working in GIS platform, the database can be updated frequently. In the most recent literature, several studies can be found integrating GIS with MCDA methods (Aires et al. 2018; Fraga et al. 2018; Kabak et al. 2018; Karlsson et al. 2017; Lorentz et al. 2016; Neji and Turki 2015; Owusu et al. 2017; Tang et al. 2018; Villacreses et al. 2017).

The methodology was structured to be applied in places that have or not an established water quality monitoring network, and the difference between the two analyses is the weighting of one of the used criteria. The flowchart of the methodological proposal is shown in Fig. 1. The following topics detail the main steps for applying the methodology.

Definition of the adopted criteria

Defining the location of water quality monitoring stations requires, first, the definition of the objectives to be achieved with the network, so it will produce relevant information about the study area (Park et al. 2006; Telci et al. 2009) and, consequently, to support actions of planning and management of water resources. In Brazil, most of the monitoring networks still operate in the characterization of the general state of water quality, with few networks that work with a specific objective.

After a literature research, it was found that the standard objectives for determining the network design can be summarized in the following: (a) detecting and understanding the spatial and temporal variations of water quality; (b) identifying sources of pollution that affect water quality; (c) detecting violations of water quality standards established by the legislation; and (d) evaluating the effectiveness of water quality recovery actions (ANA 2013b; IGAM 2017; Khalil and Ouarda 2009; Strobl and Robillard 2008; Telci et al. 2009).

In the PNQA, ANA describes some criteria for the location of the monitoring stations: (a) strategic sites: located in border region, state borders, or in large

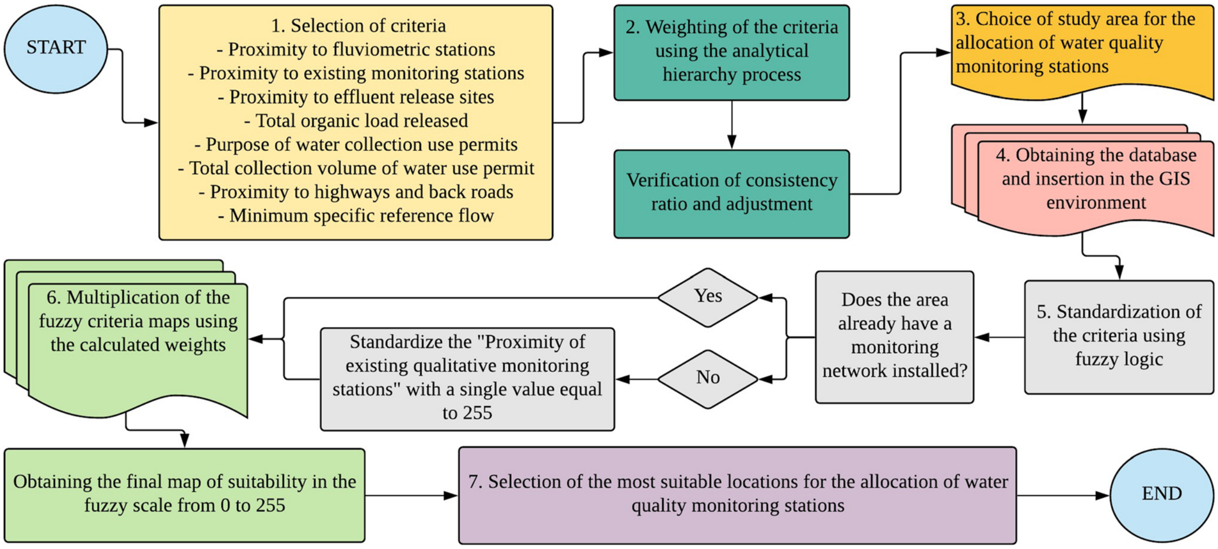

Fig. 1 Flowchart of the methodological proposal for the allocation of water quality monitoring networks in river basins

companies; (b) impact points: located in environment under impact of potentially polluting anthropic activities; and (c) reference points: located in an environment with low anthropic activities' impact, aiming to establish reference standards for the water body under analysis (ANA 2013b).

Therefore, the choice of the criteria used in the methodology took into account the standard objectives found in the literature and the recommendations obtained in the PNQA for the installation of water quality monitoring networks (ANA 2013b), which resulted in the selection of eight criteria considered of high importance (Table 1).

Weighting of the criteria used

Considering that the selected criteria contribute with different weights in the decision-making process of choosing a new location for the establishment of monitoring stations, it was necessary to carry out a weighting according to the importance of each one in the analysis. Thus, the weight of each criterion was estimated with the AHP (Analytical Hierarchy Process) method, developed by Thomas Saaty (Saaty 1990).

The AHP is a MCDA method based on a paired comparison used to define the relative priority of the analyzed criteria (Shahsavari and Khamehchi 2018). In

Table 1 Selected criteria for the methodology of the allocation of qualitative monitoring stations and their respective considerations

Criteria and considerations
•Proximity to fluviometric stations: This criterion aims to bring closer the qualitative monitoring and the quantitative monitoring, associating the water quality values with the water flow values. Therefore, it should be considered that the closer to fluviometric stations, the greater the suitability of the site for the installation of a qualitative monitoring station
•Proximity to existing qualitative monitoring stations: The proximity to existing water quality monitoring stations can be understood as a negative factor, since sites without monitoring should be prioritized. Therefore, it should be considered that the more distant from an existing water quality monitoring stations, the greater the suitability of the location for the installation of a new station
•Proximity to effluent release sites: This criterion represents one of the main impacts that human activities have on water quality, such as the discharge of domestic sewage into water bodies, which, as found in the literature, represents the main source of pollution in river basins in Brazil. Therefore, it is considered that the closer to effluent discharge points, the greater the suitability of the site for the establishment of a monitoring station.
•Total organic load released: In order to emphasize the importance of the discharge of effluents in the water bodies, the total organic load released must also be taken into account, since the higher this value, the greater the flow required to dilute the effluent. So it is considered that, the higher the organic load released, the larger the need to establish a monitoring station in that area
•Purpose of water collection use permits: This criterion considers that the location for establishing a point of water quality monitoring should be influenced by the purposes of water collection use permits in the river basin analyzed, so that the most important uses have a greater weight and, therefore, prioritized, for example sites for the establishment of monitoring stations
•Total collection volume of water use permitted: In order to consider the quantitative issue of the collection volume of water use permitted, it is considered that the larger the total amount granted, with consequent reduction of the self-purification capacity of water bodies, the greater the need to establish a monitoring station in the area. This criterion has high relevance in the identification of areas where irrigation permits for the use of water are the majority, since in most cases they correspond to the largest water volumes permitted
•Proximity to highways and back roads: This criterion aims to facilitate access to monitoring points, since the logistical issue must be taken into account (Strobl and Robillard 2008). Therefore, it is considered that the closer to the highways and back roads, the greater the suitability of the site for the establishment of a monitoring station
•Minimum reference flow: This criterion considers the water production of the area under study, taking into account that larger flows can dilute larger volumes of effluents. It is desirable that the flow rate used in the calculation of water availability corresponds to a minimum reference flow value (Avila et al. 2016). Thus, it is considered that the greater the minimum reference flow value of reference, the lower the need to establish a station in the area, since greater flow rates can dilute a larger amount of wastewater, reducing the risks of water quality reaching levels lower than the standards set by environmental legislation

other words, this technique is based on a square matrix "n x n," where the lines and the columns correspond to "n" analyzed criteria. Thus, the value "aij" represents the relative importance of the criterion of line "i" in relation to the criterion in column "j." Since this matrix is reciprocal, only the bottom triangular half needs to be filled out, since the other half derives from the first half and the main diagonal assumes values equal to 1 (Zambon et al. 2005).

In order to make the analysis easier, the criteria were first ordered according to their degree of importance and then compared in pairs using the Saaty scale, according to the values presented in Table 2 (Karlsson et al. 2017; Saaty 2008).

To assign the degree of importance to each criterion, 10 management and planning of water resources experts were invited to answer a weighing questionnaire. According to Behmel et al. (2016), decision-making process always requires consultation with subject matter experts, and this is a crucial step. It was also found that a large amount of experts is not a requirement to the AHP method (Alwaer and Clements-Croome 2010; Karlsson et al. 2017; Montazar et al. 2013), since the opposite can result in a high degree of inconsistency because of the possibility of arbitrary answers among the interviewees (Cheng and Li 2002).

First of all, the consultation was made with five experts from the Minas Gerais Water Management Institute (Instituto Mineiro de Gestão das Águas—IGAM). IGAM is a water resources management body in Minas Gerais, all of which work directly with the "Waters of Minas Project" (Projeto Águas de Minas). This project has been monitoring the quality of surface water in the state of Minas Gerais since 1997. Subsequently, five water quality experts working in the academic environment were consulted, all professors with a doctorate degree and coming from different universities in Brazil.

The questionnaires were sent by email and the experts were given 2 weeks to respond before a polite reminder was made. In the questionnaire, we asked the experts to put the criteria in order of most important to least important and then perform the comparison by pairs using the Saaty scale of degree of importance, as shown in Table 2. Of the ten questionnaires sent, all returned properly completed.

After considering the preferences and judgments of the experts, the comparison matrix was made using the WEIGHT module of the IDRISI Selva software. After that, it was verified, the consistency of the decisions taken by calculating the CR (consistency ratio). CR values ≤ 0.1 indicates a good level of consistency. CR values > 0.1 indicates that the comparison values should be revised, since the judgments are considered inconsistent (Saaty 1990).

Study area

The methodological proposal was applied in the Minas Gerais portion of the Doce river basin, which corresponds to approximately 87% of the total area of 82,427 km^2 (ANA 2018a). In the state of Minas Gerais, the Doce river basin is subdivided into six Water Resources Management Units (Unidades de Gestão de Recursos Hídricos—UGRHs), which correspond to UGRH1 Piranga, UGRH2 Piracicaba, UGRH3 Santo Antônio, UGRH4 Suaçuí, UGRH5 Caratinga, and UGRH6 Manhuaçu (CBH-Doce 2016a).

In the Minas Gerais portion of the Doce river basin, the water quality monitoring began in 1997 through the "Waters of Minas" project under current responsibility of the IGAM, water resources management body of the state of Minas Gerais. In the current monitoring network, the Minas Gerais portion of the Doce river basin contains 65 stations in operation, which four annual campaigns are held on quarterly frequency for the monitoring stations located outside the riverbed of the Doce river and 12 annual campaigns on a monthly basis for those located in the riverbed of the Doce river (IGAM 2016). Figure 2 shows the spatial distribution of the 65 IGAM monitoring stations as well as the division of the basin per UGRH.

The basin comprises 228 municipalities, whose territories are totally or partially inserted in it, 200 in Minas Gerais and 28 in Espírito Santo (CBH-Doce 2016b). There are 209 city offices located in the basin territory,

Table 2 Saaty scale of importance degree

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely Less important	Very strongly	Strongly	Moderately	←Equal→	Moderately More important	Strongly	Very strongly	Extremely

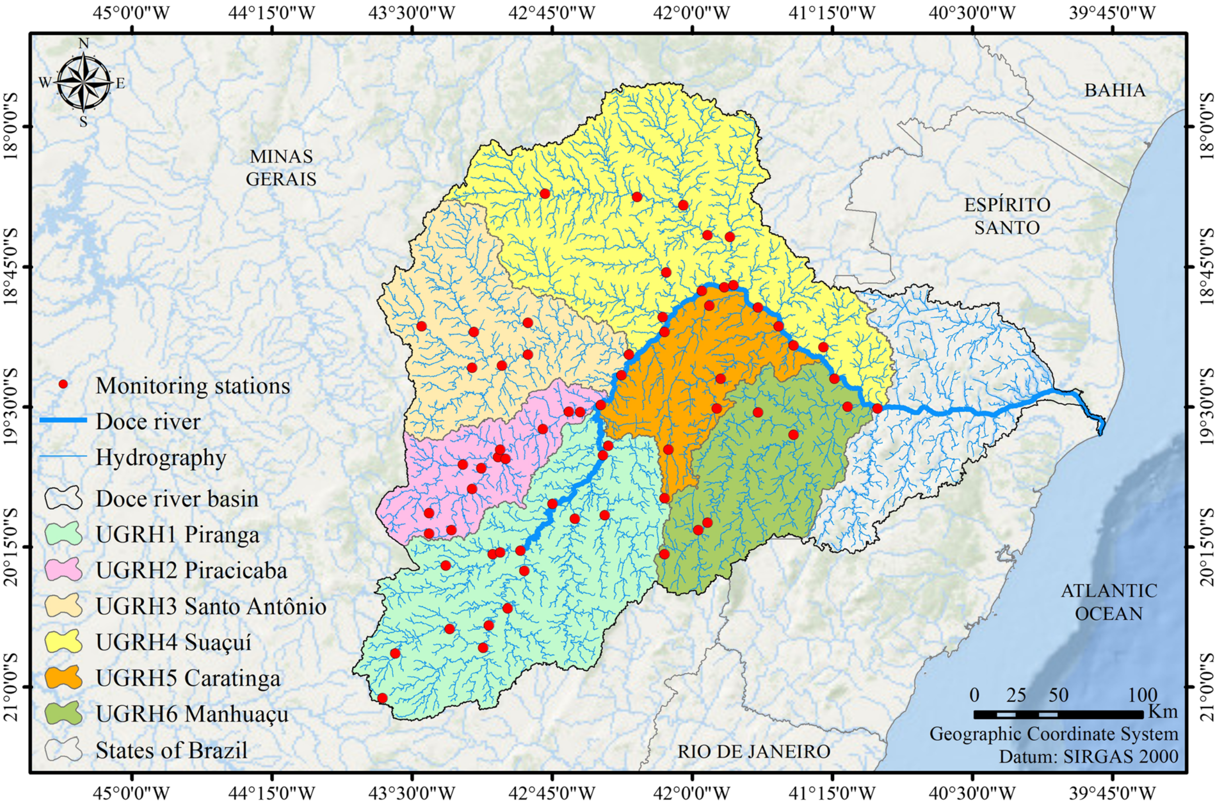

Fig. 2 Spatial distribution of the water quality monitoring stations of the IGAM in the Minas Gerais portion of the Doce river basin

with a population of approximately 3.6 million inhabitants (IBGE 2010). In the context of water quality, these values have negative consequences due to precarious treatment of domestic sewage, one of the main problems encountered in the basin. The negative impact of the discharge of effluents on the quality of the waters is observed in some rivers of the basin, especially in its tributaries. In the main channel of the Doce river, this impact is minimized by the increase in the available flow (ANA 2016).

The Doce river basin plays an important economic role in the southeastern region of Brazil. Besides comprising the largest iron ore complex in Latin America, some of the important economic activities in the basin are farming (reforestation, traditional crops, coffee, sugarcane, livestock), the agribusiness (sugar and ethanol), mining (gold, bauxite, precious stones, etc.), industry (pulp and dairy), trade and support services of the industrial complexes, and electricity generation (ECOPLAN-LUME 2010). As well as the discharge of effluents, those activities result in enormous environmental impacts along the Doce river, including deforestation, erosion, siltation, and pollution of rivers and soil (Oliveira and da Quaresma 2017).

Obtaining the database and insertion of the criteria in GIS environment

In Table 3, the source of the data used can be observed, taking into account the study area and the criteria chosen for the implementation of the methodology.

The data of purpose of water use permits and water volume use permitted were obtained through the water

Table 3 Database used in the study

Data base	Source
Hydrography and Otto basins	ANA (2018a)
Purpose of water use permits	IGAM (2018a)
Total volume of water use permitted	IGAM (2018a)
Inventory of effluent release points	ANA (2017)
Total organic load released	ANA (2017)
Inventory of qualitative monitoring stations	IGAM (2018b)
Minimum reference flow	Elesbon et al. (2014a)
Fluviometric station inventory	ANA (2018b)
Highways and back roads	MMA (2018)

collection use permits granted by IGAM until the year 2018. The minimum flow rate used by Elesbon et al. (2014a) was $Q_{7,10}$, since this is the reference flow adopted in the state of Minas Gerais for permits for the use of water purposes. For the effluent release points and total organic load released, the data provided in the study "Sewage Atlas: River Basins Depollution" (Atlas Esgoto: Despoluição de Bacias Hidrográficas)" by ANA (2017) was considered, referring only to the domestic load, since the Minas Gerais portion of the Doce river basin does not have a system to register the permits for the use of water to discharge effluents.

All the obtained data were transformed into information layers in GIS environment using the software ArcGIS 10.5/ArcMap, which originated a database for the proposed of allocation of water quality monitoring stations. However, the multi-criteria analysis was performed on the IDRISI Selva 17 software, since it has a wide range of resources essential for the execution of the methodological proposal.

Standardization of the criteria used

In this methodological proposal, the fuzzy concept (Zadeh 1965) was used to give the criteria a standardized and representative value of the degree of adequacy of sites for the allocation of the monitoring stations. Therefore, the original data of the criteria were standardized on a continuous scale, ranging from 0, less suitable, till 255, more suitable, resulting in individual maps of suitability for the allocation of the stations.

In fuzzy logic, the standardization should take into account the differences presented between the criteria (Romano et al. 2015), and it is necessary to construct a decision rule executed through the membership function to the fuzzy set. Thus, for the continuous criteria (distances, for example), the fuzzy concept was applied through the Sigmoid function. As for the qualitative criteria (total domestic organic load released, for example) or those involving nominal scales (purpose of water use permits, for example), the values were assigned manually, being also adopted the same scale from 0 to 255.

For the standardization of the continuous criteria, a decision rule was elaborated and performed by means of the FUZZY routine on the IDRISI Selva software. For this, it was chosen to classify as continuous criteria for all those that involved the distance factor. Figure 3 shows the adequacy functions used in the methodological proposal.

For the increasing sigmoid function, it is considered that the suitability decreases the closer it gets to "a." As for the decreasing sigmoid function, the adequacy is considered to increase the closer it gets to "a." In Table 4, the limits used in the adequacy functions for each criterion analyzed are made available.

In the standardization of the qualitative criteria or the ones that involve nominal scales, the standardization was performed using the Otto basin vector data of the Doce river (ANA 2018a), which represents the smallest unit of the basin area, according to the classification of river basins developed by the engineer Otto Pfafstetter. Therefore, it was first applied a type of statistic in each of the eight criteria, which resulted in maps with discretized values per Otto basin for each one of them. The statistics applied in each criterion can be observed in Table 5.

For the criteria "total organic load released," "total volume of water use permitted," and "minimum reference flow ($Q_{7,10}$)," the values discretized per Otto basin

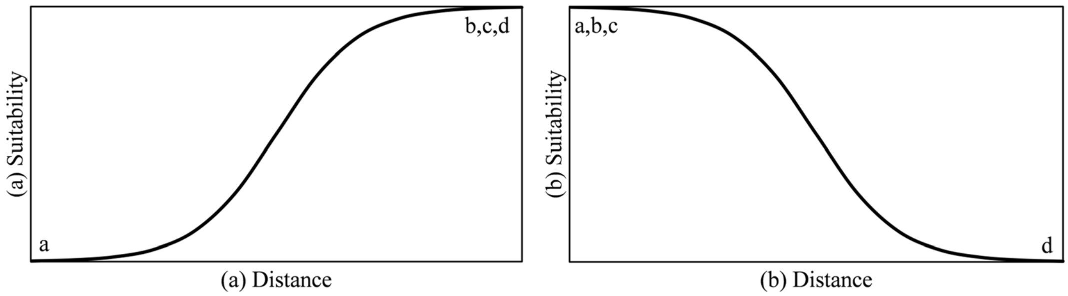

Fig. 3 Increasing sigmoid function (**a**) and decreasing sigmoid function (**b**) used in the methodological proposal for standardization of the continuous criteria

Table 4 Limits of suitability functions for each analyzed criterion

Function	Criteria	Limits (m)			
		a	b	c	d
Increasing Sigmoid	Proximity to existing qualitative monitoring stations	7000	Max.	Max.	Max.
Decreasing Sigmoid	Proximity to effluent release points	3000	3000	3000	Max.
	Proximity to fluviometric stations	5000	5000	5000	Max.
	Proximity to highways and back roads	7000	7000	7000	Max.

were divided into 30 categories with equal range of values and standardized in the fuzzy scale according to the considerations shown in Table 1. Such division makes each range have a different degree of importance. Although the fuzzy scale ranges from 0 to 255, it was chosen to standardize the criteria in the range of 110 to 255 with values varying every 5 numbers.

For the criterion "purpose of water collection use permits," the values in the fuzzy scale were obtained from the same questionnaire that was prepared for the weighing of the criteria. Thus, this step also had the opinion of 10 experts in the area and the fuzzy value used in the standardization of each purpose was the mean value of the answers.

Aggregation of the criteria used and acquisition of the final map of suitability

In the process of aggregation of the criteria, the WLC (weighted linear combination) method was used, which consists of an analytical method used when several criteria must be taken into account in the analysis (Blachowski 2015; Lorentz et al. 2016; Romano et al. 2015) being often used due to its easy implementation in GIS environment (Al-Adamat et al. 2010; Blachowski 2015; Muhsin et al. 2018; Tang et al. 2018).

Table 5 Statistics used in each qualitative criterion or that involves nominal scale to obtain maps with discretized values per Otto basins

Criteria	Applied statistics
Total organic load released	Sum
Purpose of water collection use permits	Majority
Total volume of water use permitted	Sum
Minimum reference flow ($Q_{7,10}$)	Average

The WLC was performed in the MCE (Multi-Criteria Evaluation) module of the IDRISI Selva software, with the criteria associated to their corresponding weights and the weighted linear combination was executed for each pixel of the study area. The last step of the WLC was to multiply the Boolean constraints, considered 0 for monitoring network projects, for everything that did not represent the hydrography. The result consisted of a final suitability map, where places with the highest suitability for the allocation of qualitative monitoring stations had values near 255 and places with less suitability had values close to 0.

Allocation of water quality monitoring stations

First, it was necessary to determine the number of new stations to be established. This procedure took into account the minimum density of stations defined by ANA (2013b) for the region in which the area of study is inserted. It is equivalent to the minimum of one station for each 1000 km^2 of area. The Minas Gerais portion of the Doce river basin has an area of 71,711 km^2 and a monitoring network with 65 stations in operation

Table 6 Density of water quality monitoring stations in the Minas Gerais portion of the Doce river basin

Analysis area	Area (km^2)	Number of stations	Density of stations/ 1000 km^2
Doce river basin	71,542.20	65	0.91
UGRH1 Piranga	17,578.80	16	0.91
UGRH2 Piracicaba	5682.46	13	2.29
UGRH3 Santo Antônio	10,767.60	7	0.65
UGRH4 Suaçuí	21,590.30	13	0.60
UGRH5 Caratinga	6712.79	8	1.19
UGRH6 Manhuaçu	9210.27	8	0.87

(Table 6), so it was suggested seven new monitoring points.

With the suitability map resulting from the WLC, it was possible to identify locations for the allocation of new water quality monitoring stations in the Minas Gerais portion of Doce river basin. To this end, it was selected the sites that had pixel value closer to 255, without distinguishing the UGRHs. Depending on the criteria established by the limiting factors used in the present methodological proposal, the new stations represent the locations with the highest suitability values, characterizing all of them as impact points.

Scenario simulation

In order to demonstrate the application of this methodological proposal to sites that do not yet have a monitoring network established, the simulation of the ideal suitability map for the Doce river basin was carried out. Thus, the entire procedure was redone using the criterion "Proximity to existing monitoring stations" standardized with a single value in the fuzzy scale, equals to 255 m, as shown in the flowchart (Fig. 1). In other words, for this criterion, the entire study area will have the same suitability for the establishment of a new station.

Results and discussion

Tables 7 and 8 show the results obtained from the AHP in the weighting of the criteria used for the allocation of the monitoring stations and the values obtained for the standardization of the purpose of water collection use permits in the fuzzy scale respectively. In order to obtain CR ≤ 0.1 in all matrices of the AHP, small adjustments were necessary in some values of degree of importance of the comparisons in pairs. However, it is important to emphasize that the order of importance of the criteria judged by the experts was maintained.

Table 7 Weights of the criteria obtained for the allocation of water quality monitoring stations in locations that already have an established network

Order	Criteria	Weight
1	Total organic load released	0.2311
2	Proximity to effluent release points	0.2204
3	Total volume of water use permitted	0.1525
4	Proximity to existing monitoring stations	0.1335
5	Proximity to highways and back roads	0.0797
6	Purpose of water collection use permits	0.0653
7	Minimum specific reference flow	0.0623
8	Proximity to fluviometric stations	0.0552

Table 8 Fuzzy scale used in the standardization of the purposes of water collection use permit

Order	Purpose of water collection use permits	Fuzzy value
1	Human consumption	255
2	Public supply	240
3	Animals thirst-quenching	195
4	Irrigation	180
5	Industrial use	170
6	Aquaculture	155
7	Mineral extraction	130
8	Other purposes	100

As can be seen in Table 7, the criteria related to effluent discharge obtained the highest weights among the eight criteria weighted by the experts. This result corroborates most of the studies found in the literature on water quality in river basins in Brazil, which highlights the release of domestic effluents without proper treatment as the main source of pollution. However, despite the domestic effluent being the main problem, the criteria used in the methodological proposal make no distinction as to the type of pollution source, so that all the entries can be inserted as a database in other analyses.

Regarding the standardization of the purposes of water collection use permits using the fuzzy scale (Table 8), the result demonstrated the knowledge of the experts as to the National Water Resources Policy, established in 1997 by the legislation No. 9433 (Brasil 1997). The legislation has as one of its foundations the multiple uses of water and claims that, in case of water scarcity, the priorities are human consumption and animals thirst-quenching.

Figure 4 shows the result of the standardization of the criteria using the fuzzy scale, with values varying from 0 to 255. As can be observed, the result covers the entire study area, since the multiplication of the results by the Boolean restraint was made

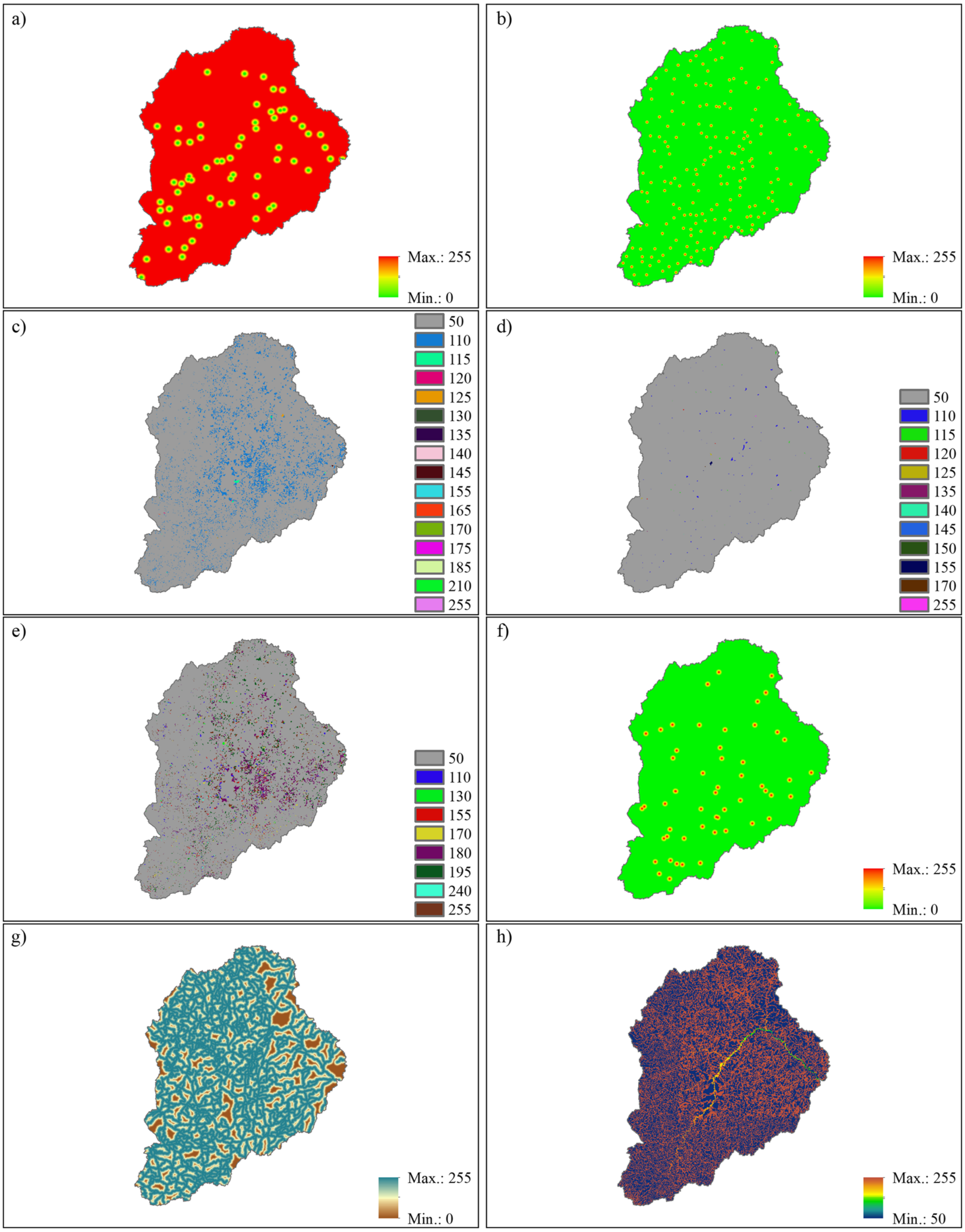

Fig. 4 Result of the standardization of the criteria using the fuzzy scale, being **a** proximity to existing monitoring stations, **b** proximity to effluent release points, **c** total volume of water use permitted, **d** total organic load released, **e** purpose of water collection use permits, **f** proximity to fluviometric stations, **g** proximity to highways and back roads, and **h** minimum reference flow ($Q_{7,10}$)

only at the end of the WLC. It is also possible to observe that in addition to allowing the transformation of the units of the criteria in an only measurement basis, the standardization ranked internally in each of the criteria, demonstrating how the suitability of the allocation of the qualitative

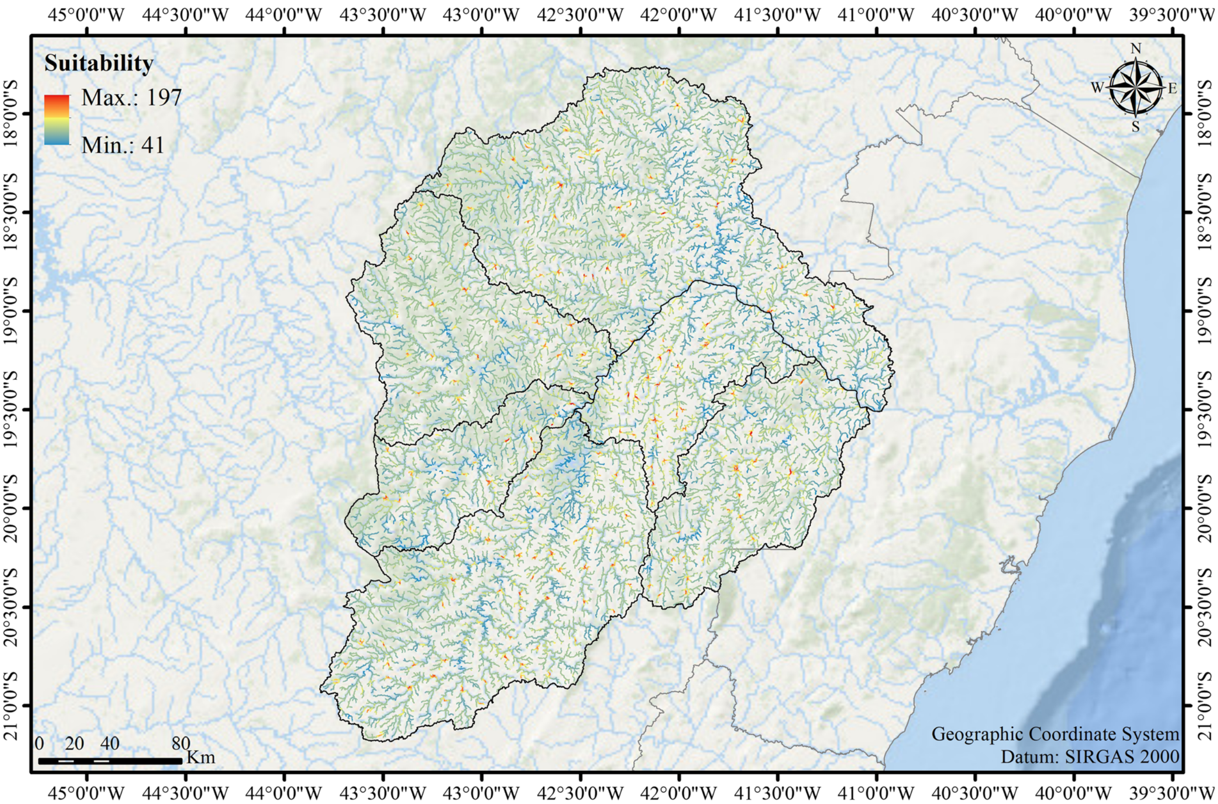

Fig. 5 Final map of suitability for the allocation of new water quality monitoring stations in the Minas Gerais portion of the Doce river basin

monitoring stations varies spatially in the study area.

The aggregation process of the criteria using the WLC method resulted in a map off suitability for the allocation of new monitoring stations in the Minas Gerais portion of the Doce river basin, with values ranging in fuzzy scale from 41, less suitable, to 197, more suitable. In Fig. 5, the map resulting from the aggregation of the criteria can be seen.

From Fig. 5, it is possible to observe that sites with greater suitability have characteristics that favor the allocation of new stations based on the limiting factors established by the criteria such as being less proximate to existing monitoring stations. It is important to highlight the high values of adequacy found in the UGRH5 Caratinga, showing that, despite the fact that it already has a density of stations higher than that one established by ANA (2013b) (Table 6), the area has a high anthropogenic intervention.

As from the map shown in Fig. 5, seven sites were identified that showed the greater suitability values. If the proposal is incorporated by IGAM, such sites may constitute new water quality monitoring stations in the Minas Gerais portion of the Doce river basin, causing the study area to have a minimum density of stations established by ANA (2013b). In Table 9, the information regarding the new monitoring points proposed for the study area is described.

Due to the minimum density of monitoring stations being below recommended, it was decided to propose only impact points, as suggested by Pérez et al. (2017). Additionally, areas with high potential for pollution will affect the water quality more significantly, so they should be prioritized (Do et al. 2012).

The exclusive choice of points of impact is also justified by the fact that water quality is one of the main aspects of vulnerability of the basin, since several determining factors in the occurrence of point and diffuse contaminations are observed, such as discharge of domestic effluents without treatment, inadequate disposal of solid waste, high generation of industrial effluents, and inadequate soil use (ECOPLAN-LUME 2010).

Table 9 Location of the proposed stations for the expansion of the water quality monitoring network in the Minas Gerais portion of the Doce river, with descriptions

UGRH	Station*	Water course	Coordinates (decimal degrees)		Description
			Lat.	Long.	
1	PI01	Casca river	− 20.22	− 42.65	Station to be established downstream of the municipality of Rio Casca, monitoring an area of 2080 km^2, which receives effluents from several municipalities
1	PI02	Matipó river	− 20.28	− 42.33	Station to be established downstream of the municipality of Matipó and the confluence of the Matipó river with the Santa Margarida river, one of its main tributaries
3	PI03	Guanhães river	− 18.90	− 43.08	Station to be established downstream of the municipality of Senhora do Porto, monitoring an area of 1594 km^2, which receives effluent from several municipalities and mining activities in the region
4	PI04	Suaçuí Grande river	− 18.37	− 42.60	Proposed station to monitor the pollution of effluents released from the municipality of São Pedro do Suaçuí and from the economic activities in the region
5	PI05	Caratinga river	− 19.37	− 42.10	Proposed station for the monitoring of the effluents released from the municipalities of Dom Cavati, Inhapim, and Ubaporanga, which, also includes a large area of agricultural activity
5	PI06	São Domingos river	− 19.40	− 42.01	Station to be established upstream of the confluence of the São Domingos river with the Caratinga river, making it possible to monitor the diffuse pollution originated from the agricultural activities in the region
5	PI07	Traíra river	− 19.75	− 42.03	Proposed station for the monitoring of the pollution of the effluents released from the municipalities of Engenheiro Caldas and Sobrália, as well as from the economic activities in the region

**PI*, impact point

According to results obtained by the monitoring campaigns, the main source of pollution that affects the quality of the waters of the Doce river basin is the release of domestic wastewater without treatment, with high values of violation mainly for thermotolerant coliforms (IGAM 2018b), according to the limits established by DN COPAM/CERH No. 01/2008. This legislation is about the classification of water bodies and environmental guidelines for their framework in the state of Minas Gerais.

From the results presented in Table 9, it is possible to observe that the UGRH5 presented the greatest need of expansion of the monitoring network, since three of the seven suggested stations are inserted in it. This is because the UGRH5 have characteristics that, due to the limiting factors set by the criteria, favor the allocation of new stations in it, among which: (a) high organic load values released from the municipalities, reflected by the high number of municipalities without collection and treatment of generated effluents; (b) large area of agricultural activity in the headwaters of the Caratinga river, resulting in a great number of permits for the use of water for animal thirst-quenching and irrigation purposes, which, have high values of suitability in the fuzzy scale; and (c) low values of minimum reference flow among all the UGRHs .

Figure 6 shows the final configuration of the monitoring network, including the seven proposed ones and the 65 existing ones that are already in operation. In total, 72 water quality monitoring stations are in the Minas Gerais portion of the Doce river basin. The spatial distribution of the stations proposed in the present study demonstrates that a monitoring network does not need to be homogeneously distributed throughout the river basin.

Although only points of impact were identified for the expansion of the monitoring network, it is emphasized that the methodology also allows the selection of reference points, since the low values of adequacy represent environments with little impact of anthropic activities; thus, such sites should be selected if the purpose of the stations is to establish reference standards for

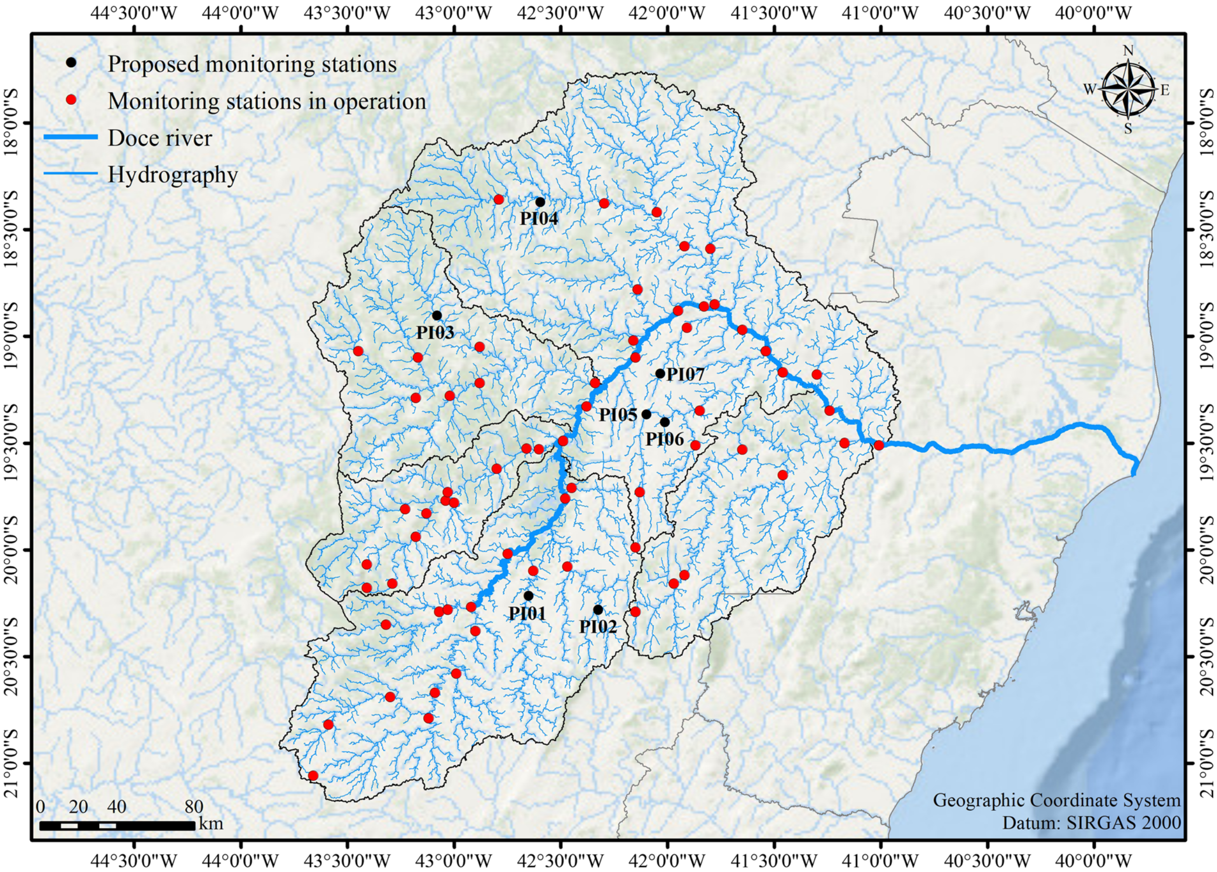

Fig. 6 Spatial distribution of the water quality monitoring net work in the Minas Gerais portion of the Doce river basin after proposing the allocation of the new stations

water bodies. As for the strategic points, it is not possible for the proposed methodology to get any information about them using the adequacy scale. However, as described in ANA (2013b), the location of the strategic points should be done in border regions, state border, and large companies.

Figure 7 shows the final result of suitability for the Doce river basin, considering the simulated scenario of non-existence of a monitoring network established in the study area. It is worth mentioning that the difference between analyses consisted only in the weighting of the criterion "Proximity to existing monitoring stations" and that the process of choosing sites for the stations also depends on the purpose of establishing the station or the monitoring network, as was done at the proposition of the new stations in the Minas Gerais portion of the Doce river basin.

In Fig. 7, it is possible to compare the adequacy map obtained, considering the non-existence of a network in the Minas Gerais portion of the Doce river basin, with the spatial distribution of the current IGAM monitoring network. This procedure makes it possible to conclude the purpose of the allocation of the stations. However, it should be pointed out that, since the current network was designed using methods different from the current methodological proposal, such analysis may present different results for which the monitoring stations were established.

The RD086 station (Fig. 7(a)), located in the Suaçuí Grande river, can be classified as a point of reference, since it is established in a place with a low suitability value, thus having low anthropic activity. From an environmental point of view, the allocation of monitoring stations in these locations makes possible to give greater support to the framework of water bodies, since the water quality at these sites tends to get closer to the natural conditions. The RD031 and RD034 (Fig. 7(b)) located before and right after the Piracicaba river receive

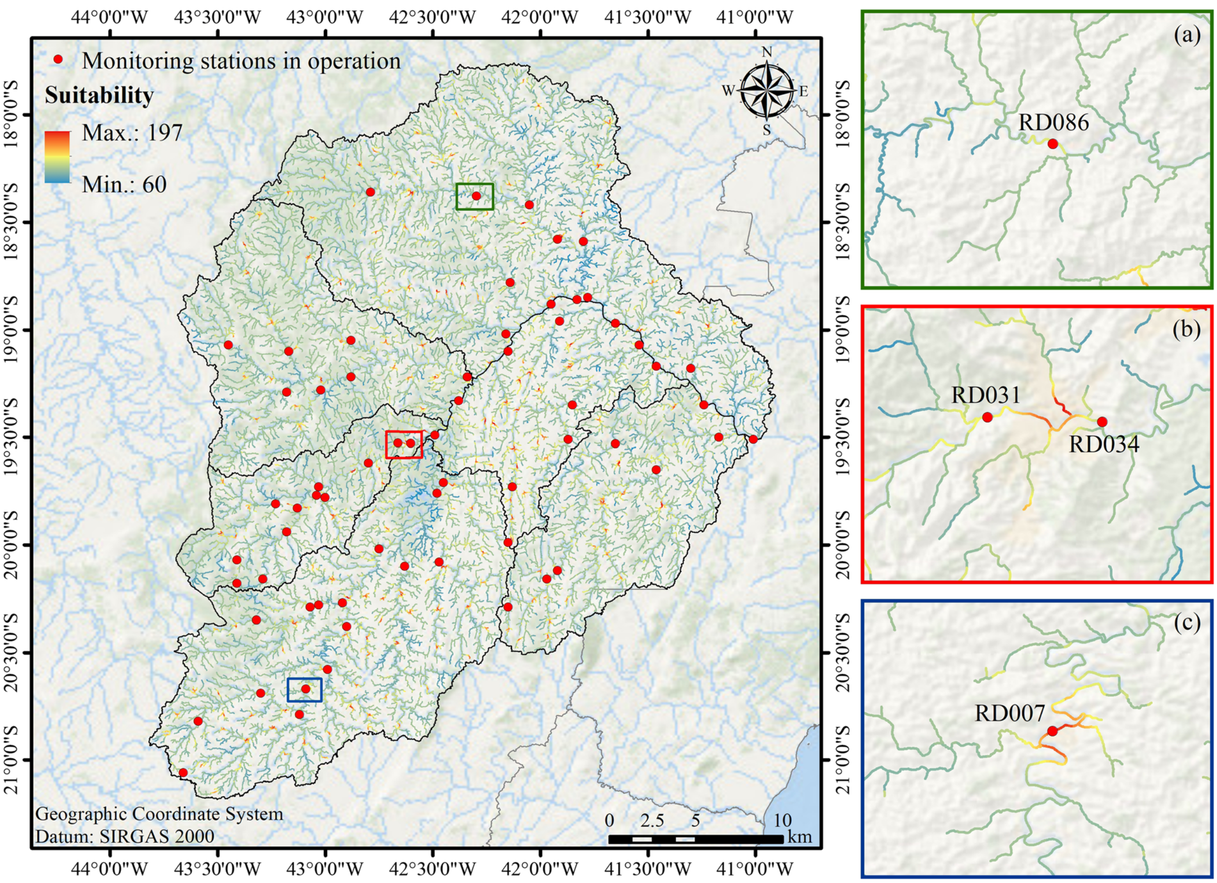

Fig. 7 Final map of suitability for the allocation of water quality monitoring stations in the Minas Gerais portion of the Doce river basin, considering the non-existence of a monitoring network, and distribution of the stations in operation

the effluents from the municipalities of Timóteo and Coronel Fabriciano respectively. Thus, it can be concluded that the stations were established with the purpose of evaluating the influence of the region on the water quality of the Piracicaba river, classifying them as reference point (RD031) and point of impact (RD034). The RD007 station (Fig. 7(c)) is located in the Piranga river, specifically in the urban area of the city of Porto Firme. Considering the methodology used, the site showed high suitability, which characterized it as point of impact.

Overall, it is clear that the current IGAM monitoring network was established to meet different goals that are inferred in this methodological proposal. Therefore, the methodological proposal developed can be used for the review and expansion of the current IGAM monitoring network in the Minas Gerais portion of the Doce river basin.

In contrast to previous studies (Chen et al. 2012; Mahjouri and Kerachian 2011; Mitrović et al. 2019; Varekar et al. 2015, 2016), the proposed methodology is presented as a robust and easy to apply method, since it uses criteria that are relevant to the monitoring of water quality and a database easily obtained by the water resources management bodies in Brazil. As for the abovementioned literature, they provide very specific and complex methodologies, in which the allocation of monitoring points is performed using extensive databases, not applicable to developing countries with limited financial resources (Alilou et al. 2018), such as Brazil.

Another advantage of the proposed methodology is its complete execution in GIS environment, which makes it easier to manipulate and update the database. In the Doce river basin, ANA (2017) already foresees a reduction of the organic load released by municipalities until the year 2035, while Elesbon et al. (2014b) presents a new proposal for allocation of fluviometric stations. Therefore, if there is any change in the database of any of the criteria, the analysis can be redone, and new decisions can be made by the water resources management bodies.

Conclusions

The proposed methodology, based on the selection of the weighed criteria and as a decision support system, proved to be robust and suitable to be used on the allocation of water quality monitoring stations by the water resources management bodies in Brazil.

The proposal of sites for the establishment of new monitoring stations in the Minas Gerais portion of the Doce river basin indicated that the Caratinga Water Resources Management Unit (UGRH5 Caratinga) has the most deficiency of stations.

When applying the methodology in the Minas Gerais portion of the Doce river basin, considering the nonexistence of the current monitoring network, it was possible to classify the stations in operation according to the purpose for which they were established.

Although the results were specific to one study area, the application of the proposed methodology is not restricted to the Minas Gerais Portion of the Doce river basin, since the criteria and decision support system used do not depend on the river basin and therefore applicable to other study areas.

The use of the methodology proposed in this study makes possible to design qualitative monitoring networks based on relevant criteria to the monitoring of water quality, being applicable to areas that have or do not have an established monitoring network.

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