WATER QUALITY EVALUATION OF THE LOWER SÃO FRANCISCO RIVER, SERGIPE, BRAZIL

Maria Nogueira Marques[1], Álvaro Marcio de Oliveira Santos[2], Adnívia Santos Costa[3], Felipo Obed Correia[4], Suelem Santos Gomes[5], Jose do Patrocínio Hora Alves[6]

ABSTRACT

The São Francisco River basin is of major hydrological and economic importance for Northeast Brazil. It is responsible for 95% of the streamflow of the rivers that cross the State of Sergipe, and the catchment is the most important source of water for human supply in the State. The objective of this study was to perform the first evaluation (according to the Brazilian National Water Agency) of the water quality in the sub-basin of the lower São Francisco River in Sergipe using the Water Quality Index (WQI). The index uses nine water quality parameters, each assigned with a specific weighting established by the National Sanitation Foundation (NSF). Samples were collected in 2009 and 2010, at three month intervals, at five sites along the sub-basin. Of the 39 water samples evaluated, 72% were of good quality, 13% were acceptable, and 5% (each) were bad, very bad and excellent. These data represent an important baseline for future studies.

KEYWORDS: WQI, environmental assessment, monitoring**.**

1 – INTRODUCTION

Water is a raw material that is fundamental to life and to the maintenance of environmental equilibrium, as well as a resource that is irreplaceable in diverse human activities. The dramatic increase in the population has resulted in a huge increase in consumption of the planet's water reserves. The use of water can be characterized as taking two forms, either with derivation or without derivation. The use of water for dilution, transport and disposal of sewage, preservation of fauna and flora, cattle raising, hydroelectric power generation, recreation and fluvial navigation is characterized as use without derivation. Water used to supply urban areas, industries, rural areas, irrigation and aquiculture is characterized as use with derivation. Derivation almost always implies a greater possibility of conflicts between uses, since it results in a lower return flux of water, with measurable net losses that vary according to use and circumstances, together with changes in water quality of variable magnitude (SIGRH, 2000; Cotrim 2006; Marques *et al.*, 2007a).

Anthropic interference in the aquatic environment has been responsible for most of the recent perturbations of hydric resources. Over many years rivers have become waste repositories, and the natural state of the aquatic environment has been profoundly altered. Changes in water quality are some of the best indicators of the impact of human activity on the biosphere (Porto, 1991). Water quality is a term that is not restricted only to the purity of water, but also considers the characteristics that are desirable for its various uses. The physical, chemical and biological characteristics of the water can all be altered; these alterations in the aquatic system can lead to damage to the regional economy, with impacts ranging from reduced fish catch to increased costs of water extraction and treatment (Gradvohl & Aquino, 2008).

The use of a water quality index (WQI) aids the integrated assessment of a water body, as well as communication with the lay public, since it offers a higher level of significance compared to the use of isolated parameters, in addition to providing an average of different variables within a single number. Nonetheless, the use of a single parameter is disadvantageous in that information on individual variables is

[1] Researcher, DCR – CNPq, Instituto Tecnológico e de Pesquisas do Estado de Sergipe –ITPS, Rua Campo do Brito n° 371, Bairro São José, Aracaju, SE, CEP 49020-380, maria.marques@itps.se.gov.br;
[2] Researcher, DTI – FAPITEC, ITPS, Rua Campo do Brito n° 371, Bairro São José, Aracaju, SE, CEP 49020-380, alvaroquimica@ig.com.br;
[3] Master's student, Universidade Federal de Sergipe - UFS, Av. Ivo Prado n° 612, Jardim Rosa Elze, São Cristóvão, SE, CEP 49015-070;
[4] Researcher, ITPS, Rua Campo do Brito n° 371, Bairro São José, Aracaju, SE, CEP 49020-380, felipo.obed@yahoo.com.br;
[5] Researcher, ITI – FAPITEC, ITPS, Rua Campo do Brito n° 371, Bairro São José, Aracaju, SE, CEP 49020-380, suelemgomes@ymail.com;
[6] Director and President, ITPS, and Associate Professor, UFS – DIQ-LQA, Rua Campo do Brito n° 371, Bairro São José, Aracaju, SE, CEP 49020-380, patrocinio@itps.se.gov.br.

lost, together with any ability to interpret the effects of interactions between them (CETESB, 2008; Marques *et al.*, 2008). The quality parameters that contribute to the WQI calculation principally reflect the contamination of water bodies arising from the discharge of domestic sewage, and it is also important to emphasize that the index was developed to assess water quality mainly from the perspective of public supply and the need to treat the water used for this purpose (CETESB, 2003).

The São Francisco is Brazil's longest river, at around 2700 km, and is of national importance. Its source lies in the Serra da Canastra mountain range, in Minas Gerais State, and it discharges into the Atlantic Ocean at the frontier between the States of Alagoas and Sergipe. Its hydrographic basin occupies 638,323 km^2 (8% of the area of Brazil), and its water is used for almost all possible purposes. The network of waterways is extensive and complex, and drains parts of six Brazilian States (Minas Gerais, Goiás, Distrito Federal, Bahia, Pernambuco, Alagoas and Sergipe). This hydrographic area is divided into four physiographic regions, the Upper, Middle, Lower-middle and Lower zones of the basin. The State of Sergipe is located in the Lower São Francisco region, and includes 1.1% (7,024 km^2) of the overall area of the basin (MMA, 2006). According to the final report of the classification of watercourses in Sergipe, the São Francisco basin in the State contains 8 locations where surface water is extracted for public supply, of which 7 are on the São Francisco River and one is on the Nossa Senhora River in Japoatã. The water main from the São Francisco is responsible for 60% of the supply to the city of Aracajú (SEMARH, 2003).

The objective of this work was to assess the quality of the water in the São Francisco River hydrographic basin in the State of Sergipe, using the water quality index and measuring the the physico-chemical and biological parameters from which it is derived.

2 – METHODOLOGY

2.1 – Study area

The hydrographic basin of the São Francisco River is located in the north of Sergipe State, at the frontier with the State of Alagoas, and corrresponds to 33% of the area of the State (Figure 1). The total annual discharge of the rivers that flow through Sergipe or along the frontiers with other States is of the order of 58,765 million cubic meters, of which 95% is attributed to the discharge from the São Francisco River, giving an idea of its importance for the development of the State (SEMARH, 2003).

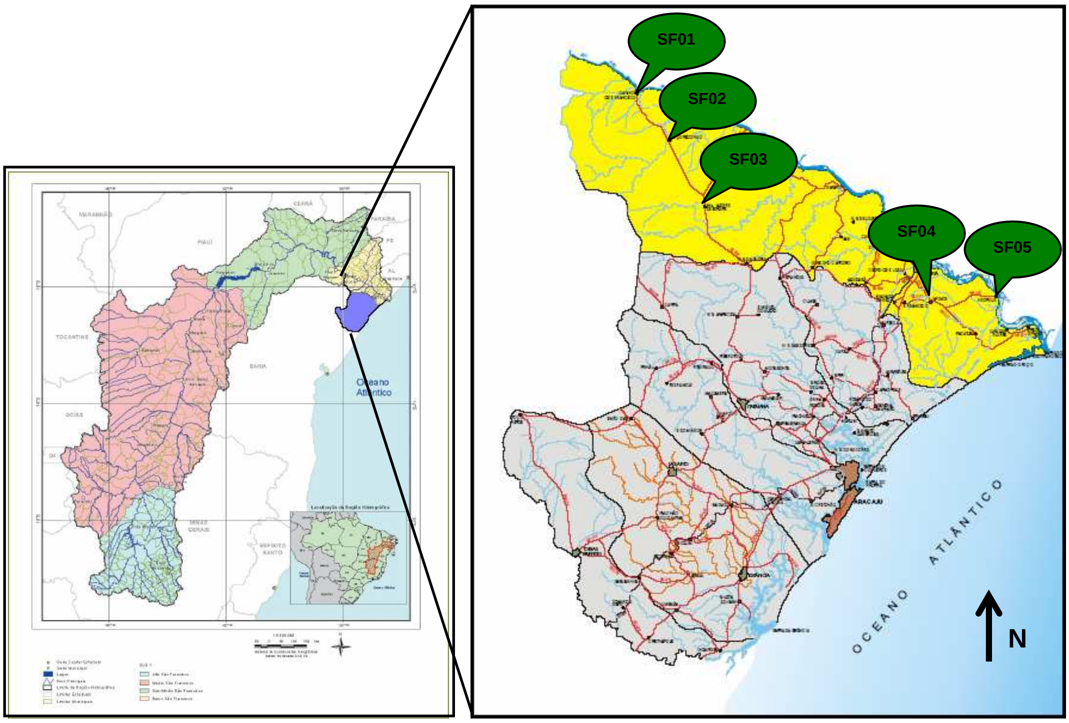

Figure 1 – Location of the hydrographic basin of the São Francisco River in the State of Sergipe, and the collection points (adapted from MMA, 2006 and SEMARH, 2003).

The municipalities located in the basin include Amparo de São Francisco, Aquidabã (part), Brejo Grande, Canhoba, Canindé de São Francisco, Cedro de São João, Gararu, Graccho Cardoso, Ilha das Flores, Itabi, Japoatã (part), Malhada dos Bois (part), Monte Alegre de Sergipe, Neópolis, Nossa Senhora da

Glória (part), Nossa Senhora de Lourdes, Pacatuba, Poço Redondo, Porto da Folha, Propriá, Santana do São Francisco, São Francisco (part), Muribeca (part), Japaratuba (part), Pirambu (part), Feira Nova (part), Capela (part) and Telha. The population in the year 2000 was 229,819 inhabitants, with 105,116 persons resident in urban areas and 124,703 in rural areas. The main uses of water in the basin are public and industrial supply, transfer of domestic effluents, transfer of industrial and agro-industrial effluents, fisheries, irrigation and aquatic leisure and tourism (SEMARH, 2003).

Five collection points were selected along the river basin (Table 1), located on the São Francisco River in Canindé do São Francisco and Neópolis, on the Jacare River in Poço Redondo, on Cachorros Creek in Monte Alegre de Sergipe and on Pilões Creek in Japoatã. Photographs of the collection points are provided in Figure 2.

The final report of the classification of Sergipe's watercourses classifies the São Francisco River and Pilões Creek as class 2 fresh water bodies, and the Jacaré River and Cachorros Creek as class 1 brackish water bodies, according to the Brazilian National Environment Council (CONAMA) Resolution n° 20/86. This was replaced by Resolution n° 357/05 (CONAMA, 2005), which in Article 42 established that: *"While the respective classifications have not been approved, fresh waters will be considered to be class 2, and saline and brackish waters as class 1, unless current quality conditions are better, in which case the most rigorous corresponding class will be applied".*

Table 1 – Collection points and their geographical coordinates and altitudes.

Municipality	Code	River	Coordinates	Altitude
Canindé de SF	SF-01	S. Francisco River	S-09 38.458 / W-37 47.198	39 m
Poço Redondo	SF-02	Jacaré River	S-09 48.164 / W-37 41.266	177 m
Monte Alegre	SF-03	Cachorros Creek	S-10 05.268 / W-37 32.922	180 m
Japoatã	SF-04	Pilões Creek	S-10 22.060 / W-36 48.428	39 m
Neópolis	SF-05	S.Francisco River	S-10 18.499 / W-36 35.054	12 m

Point SF-01 – São Francisco River

Point SF-02 – Jacaré River

Point SF-03 – Cachorros Creek

Point SF-04 – Pilões Creek

Point SF-05 – São Francisco River

Figure 2 – Photographs of the collection points (photos by M. N. Marques).

2.2 – Sample collection

Samples were collected tri-monthly during the period March 2009 to November 2010 (a total of eight collections). The total number of samples was 39, since in March 2009 collection point SF-03 (Cachorros Creek) was dry. The samples were retrieved in the surface layer, using suitable vessels that had been pre-cleaned as required according to each type of analysis. The vessels were first rinsed two or three times with the water to be sampled. The samples were refrigerated at <4°C following collection and during transport to the laboratories, where they were stored in refrigerators prior to the analyses (with the exception of the samples used for dissolved oxygen determinations). All of the sample collection and preservation procedures obeyed the methodologies described in the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2005).

2.3 – Analytical methods

The following parameters were monitored: pH, turbidity, concentrations of phosphorus and nitrogen, total solids, dissolved oxygen, biochemical oxygen demand, thermotolerant coliforms and temperature. The methodologies used were those recommended by APHA (2005).

2.4 – Calculations of the water quality index (WQI)

The WQI used was the same as that adopted by the São Paulo State Environment Agency (CETESB, 2003, 2008) and the Brazilian National Water Agency (ANA, 2009), which is an adaptation of the WQI of the United States National Sanitation Foundation (NSF). The nine water quality parameters listed in Table 2 were used for the calculation.

In the WQI an averaged graph is provided for each quality parameter, plotting parameter values (*x*-axis) against the assigned quality rating (q_i) (*y*-axis). The quality rating has a scale of 0 (worst) to 100 (best). Each parameter is also assigned a weighting (w_i), representing its importance in terms of the overall WQI. This WQI mainly reflects the influences of sewage wastes and other organic materials, nutrients and solids (Almeida, 2007; CETESB, 2003, 2008).

The q_i value is multiplied by w_i, and the overall WQI value (on a scale between 0 and 100) is then obtained from the sum of the subtotals obtained for each individual parameter. The water quality is assigned to a category based on the WQI value (Table 3) (Almeida, 2007; Marques *et al.*, 2007b; Gradvohl & Aquino, 2008).

Table 2 – Units and weightings of the parameters used in the WQI.

Parameter	Unit	Weighting (w_i)
Thermotolerant coliforms	MPN 100mL^{-1}	0.15
pH		0.12
BOD_5	mg L^{-1}	0.10
Total nitrogen	mg N L^{-1}	0.10
Total phosphorus	mg P L^{-1}	0.10
Temperature difference	°C	0.10
Turbidity	NTU*	0.08
Total solids	mg L^{-1}	0.08
DO	% saturation	0.17

* NTU: nephelometric turbidity unit

The WQI may be defined by:

$$WQI = \prod_{i=1}^{n} q_i^{w_i} \quad (1)$$

Where, q_i is the quality value of the i^{th} parameter (a number between 0 and 100 obtained from the individual parameter quality variation curve) according to its concentration or measurement, and w_i is the weighting applied to the i^{th} parameter (a number between 0 and 1 attributed according to its importance for the overall quality evaluation), considering that:

$$\sum_{i=1}^{n} w_i = 1 \quad (2)$$

Where, *n* is the number of parameters used in the WQI calculation.

Table 3 – Scale of WQI values and the corresponding classification according to CETESB (2008).

Value	Category
80 ≤ IQA ≤ 100	Excellent
52 ≤ IQA ≤79	Good
37 ≤ IQA ≤51	Acceptable
20 ≤ IQA ≤36	Bad
IQA ≤ 19	Very bad

3 – DISCOVERIES AND DISCUSSION

3.1. Parameters evaluated

The thermotolerant coliforms parameter is used for the biological characterization of water, and indicates fecal pollution (and occasionally contamination) since it includes a group of bacteria present in the intestinal tracts of humans and other animals (Gradvohl & Aquino, 2008). CONAMA Resolution n° 357/05 sets a maximum permissible level (MPL) of 1,000 MPN (most probable number) per 100 mL for class 2 fresh waters and class 1 brackish waters. This is an important parameter for water quality evaluation, and its weighting in the WQI calculation is 0.15, a value that is exceeded only by that of dissolved oxygen (0.17).

Thermotolerant coliform values exceeded the MPL for 16 of the 39 samples analyzed, with the highest value ($1.6x10^5$ MPN $100mL^{-1}$) obtained for the sample collected in November 2009 at site SF-02 (Figure 3), indicating contamination of the water by fecal pathogens.

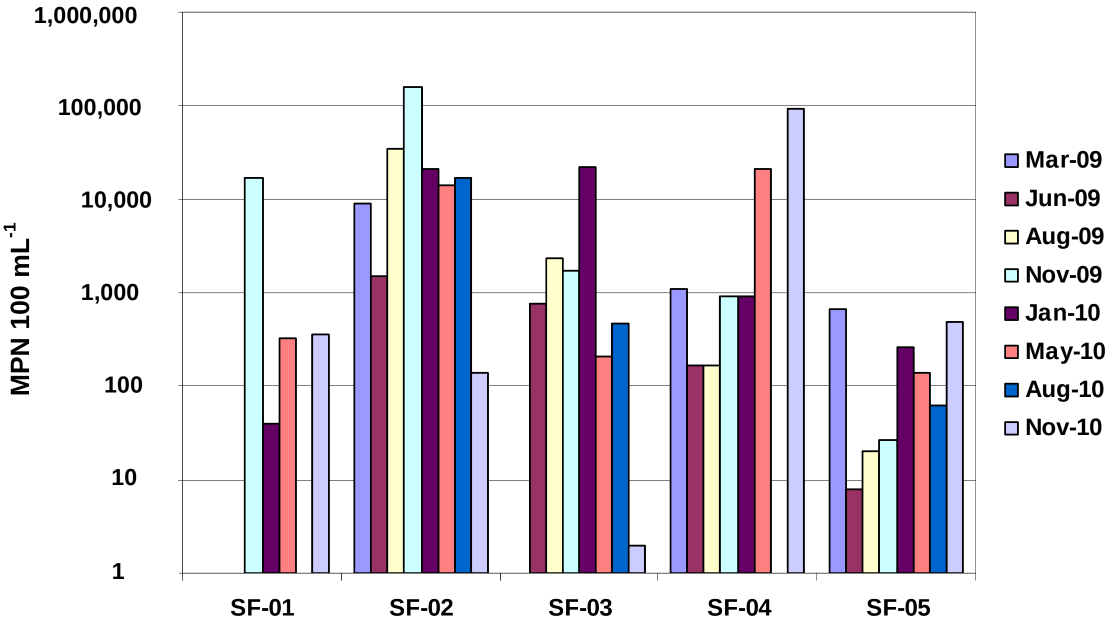

Figure 3 – Counts of thermotolerant coliforms in the samples (note logarithmic ordinate scale).

Site SF-02 (Jacaré River in Poço Redondo) was consistently the most impacted, since almost all of the samples (except that for November 2010) contained coliforms at levels that exceeded the MPL. Three samples exceeded the MPL at each of the sites SF-01 (São Francisco River in Canindé do São Francisco), SF-03 (Cachorros Creek in Monte Alegre de Sergipe) and SF-04 (Pilões Creek in Japoatã). The least impacted site, SF-05 (São Francisco River in Neópolis) was the only location where values were below the MPL for all samples. There were no obvious seasonal trends.

Descriptive statistics for the parameters pH, biochemical oxygen demand, total nitrogen, total phosphorus, turbidity, total dissolved solids and dissolved oxygen are presented in Table 4. The values in bold typeface indicate non-conformity with the limit values set by CONAMA Resolution n°357/05.

Table 4 – Descriptive statistics for the sample parameters pH, biochemical oxygen demand (BOD_5), total nitrogen, total phosphorus, turbidity, total dissolved solids (TDS) and dissolved oxygen (DO).

Class	Site	Parameter	Unit	CONAMA Res. n° 357/05	Mínimum	Mean	Standard deviation	Maximum
Fresh 2	SF-01 São Francisco River in Canindé do São Francisco	pH		6.0 to 9.0	7.34	7.59	0.18	7.91
		BOD_5	mg L^{-1}	≤5	1.00	3.32	1.80	**6.00**
		Total N	mg L^{-1}	-	0.06	0.25	0.18	0.56
		Total P	mg L^{-1}	≤0.1	0.01	0.06	0.04	**0.12**
		Turbidity	NTU	≤100	1.20	6.92	5.21	18.20
		TDS	mg L^{-1}	≤500	36.48	46.12	9.00	63.69
		DO	mg L^{-1}	≥5	6.35	7.99	0.98	9.15
Brackish 1	SF-02 Jacaré River in Poço Redondo	pH		6.5 to 8.5	7.46	8.23	0.52	**9.14**
		BOD_5	mg L^{-1}	-	4.90	**35.33**	39.63	**110.00**
		Total N	mg L^{-1}	-	0.62	4.88	4.78	13.18
		Total P	mg L^{-1}	≤0.124	0.08	**1.17**	1.26	**3.60**
		Turbidity	NTU	VA*	3.00	**244.48**	512.57	**1500.00**
		TDS	mg L^{-1}	500 to 30000	1380.60	4273.99	2747.37	8880.30
		DO	mg L^{-1}	≥5	6.42	10.07	3.74	16.80
Brackish 1	SF-03 Cachorros Creek in Monte Alegre de Sergipe	pH		6.5 to 8.5	7.35	8.10	0.45	**8.53**
		BOD_5	mg L^{-1}	-	2.70	**9.06**	3.61	**11.50**
		Total N	mg L^{-1}	-	0.45	1.34	0.58	2.24
		Total P	mg L^{-1}	≤0.124	0.12	**0.22**	0.17	**0.59**
		Turbidity	NTU	VA*	5.10	**168.01**	406.69	**1090.00**
		TDS	mg L^{-1}	500 to 30000	834.00	3660.06	1625.77	5612.00
		DO	mg L^{-1}	≥5	**4.59**	9.30	2.30	11.30
Fresh 2	SF-04 Pilões Creek in Japoatã	pH		6.0 to 9.0	7.72	7.97	0.17	8.16
		BOD_5	mg L^{-1}	≤5	0.50	**8.00**	5.03	**14.70**
		Total N	mg L^{-1}	-	0.22	0.46	0.23	0.90
		Total P	mg L^{-1}	≤0.1	0.04	0.06	0.02	**0.11**
		Turbidity	NTU	≤100	18.60	64.04	64.93	**206.00**
		TDS	mg L^{-1}	≤500	343.27	519.21	93.94	649.90
		DO	mg L^{-1}	≥5	5.46	7.79	1.32	10.10
Fresh 2	SF-05 São Francisco River in Neópolis	pH		6.0 to 9.0	7.50	7.72	0.19	8.11
		BOD_5	mg L^{-1}	≤5	2.70	5.73	2.22	**8.20**
		Total N	mg L^{-1}	-	0.06	0.55	0.46	1.51
		Total P	mg L^{-1}	≤0.1	0.02	0.09	0.06	**0.19**
		Turbidity	NTU	≤100	10.80	50.70	60.11	**189.50**
		TDS	mg L^{-1}	≤500	30.01	83.96	77.67	263.68
		DO	mg L^{-1}	≥5	5.19	8.03	1.95	10.70

* VA: virtually absent.

At site SF-01 there were two parameters (BOD and total phosphorus) for which at least one sample showed values that exceeded the MPL. Biochemical oxygen demand is a parameter that describes the quantity of oxygen needed to oxidize organic matter to a stable inorganic form by means of aerobic microbial decomposition. Excessive increases of BOD in a hydric body are normally caused by inputs of material having a predominantly organic origin. Phosphorus is a parameter that represents the excess of nutrients available for biological processes. Excess phosphorus present in sanitary wastes and industrial effluents leads to the eutrophication of natural waters (Almeida, 2007).

At site SF-02, almost all of the samples presented BOD and total phosphorus values that were in non-conformity with Resolution 357/05, indicating a high degree of eutrophication of the Jacaré River. Interestingly, the values obtained for dissolved oxygen were higher than the minimum permitted, with mean and maximum DO values of 10.07 mg L^{-1} and 16.80 mg L^{-1}, respectively. However, according to Piveli & Kato (2006) oxygen concentrations in eutrophicated water can greatly exceed 10 mg L^{-1}, even at temperatures higher than 20℃, characterizing a sit uation of supersaturation.

At this site (SF-02) the samples also presented very high values for total nitrogen, with a maximum of 13.18 mg L^{-1}. This parameter indicates the quantity of organic (biodegradable) matter arriving in the water body, which at elevated levels can provoke eutrophication and compromise many forms of aquatic life.

There were also signs of degradation of water quality at site SF-03, associated with medium-high values obtained for BOD, total phosphorus and turbidity. The latter parameter expresses the degree of interference in the passage of light through a liquid, and changes in light penetration result from the presence of material in suspension. High turbidity reduces photosynthesis in both rooted submerged vegetation and algae, and reduced plant development can lead, in turn, to lower productivity in fish populations. Hence, turbidity can influence the entire aquatic biological community (Almeida, 2006). CONAMA Resolution 357/05 states that turbidity should be virtually absent in class 1 brackish waters. However, the medium-high average value for turbidity at this site was due to the influence of the atypical sample collected in January 2010, which had a muddy appearance and gave a turbidity value of 1090 NTU.

At site SF-04 the average BOD value was 8.00 mg L^{-1}, with a maximum value of 14.70 mg L^{-1} in one of the samples, which considerably exceeds the MPL stated in Resolution 357/05. The turbidity value for the sample collected in June 2009 was 206 NTU, which also exceeds the MPL. At site SF-05, at least one of the samples presented values above the MPL for BOD (8.20 mg L^{-1}), total phosphorus (0.19 mg L^{-1}) and turbidity (189.5 NTU).

3.2. Water quality index

At sites SF-01 and SF-05 the WQI classification of the São Francisco River was good for most of the samples, with the exception of the November 2009 sample at SF-05 and the August 2010 sample at SF-01, which were classified as excellent.

During the high water period, the WQI at site SF-02, on the Jacaré River, varied between good (June 2009) and acceptable (September 2009, May 2010 and August 2010). During the dry period the classification was either bad (January and November 2010) or very bad (March and December 2009). Almost all of the samples from the Cachorro and Pilões creeks (sites SF-03 and SF-04) were classified as having a good WQI, with the exception of the January 2010 sample from site SF-03 and the November 2010 sample from site SF-04, which were rated as acceptable. The WQI values obtained in this work are presented in Table 5.

Table 5 – Water quality index values obtained for samples from the hydrographic basin of the São Francisco River in Sergipe State.

Municipality	Canindé do S. Francisco	Poço Redondo	Monte Alegre de Sergipe	Japoatã	Neópolis
Date/River	**SF-01 S. Francisco**	**SF-02 Jacaré**	**SF-03 Cachorro**	**SF-04 Pilões**	**SF-05 S. Francisco**
Mar/09	69	19	seco	62	69
Jun/09	66	59	61	57	72
Aug/09	68	44	58	65	73
Nov/09	60	11	59	67	80
Jan/10	78	38	39	64	71
May/10	76	48	58	52	58
Aug/10	92	42	63	79	74
Nov/10	77	36	66	42	74

WQI values: (0 – 19) very bad; (20 – 36) bad; (37 – 51) acceptable; (52 – 79) good; (80 – 100) excellent.

Of the 39 samples analyzed, two samples (5%) were rated as excellent quality. 28 samples (72%) were rated as good, with WQI values ranging between 52 and 74. Five samples (13%) were of acceptable quality, with WQI values of between 39 and 48, two samples (5%) were rated as bad, with WQI values of 36 and 38, and two samples (5%) were rated as very bad, with WQI values of 11 and 19 (Figure 4).

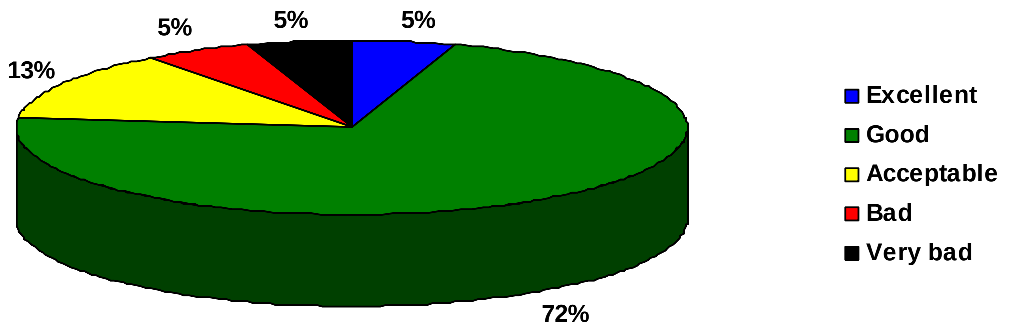

Figure 4 – Pie chart of the percentage distribution of WQI categories for samples from the hydrographic basin of the São Francisco River in Sergipe State.

From its source in the Serra da Canastra mountain range in Minas Gerais State, the São Francisco River basin drains seven Brazilian States, and along its course (a total drainage area of 638,323 km^2) all forms of water usage are encountered: electrical power generation, fluvial navigation, irrigation, fishing, tourism and leisure, dilution of domestic wastes and water supply to industrial and mining operations, amongst others (MMA, 2006). When the river finally enters the region of the lower São Francisco basin its water is still generally of good quality, and although there was strong evidence for anthropogenic impacts at the sites evaluated in the present work, this nonetheless demonstrates the considerable self-purification capacity of the river. An exception was the Jacaré River in the municipality of Poço Redondo, where water quality was consistently poor.

4 – CONCLUSIONS

The importance of this work is evidenced by the report of the Brazilian National Water Agency (ANA, 2009), in which the quality of the water in the São Francisco River basin is only evaluated for the State of Minas Gerais. In the present study, the quality of water in the hydrographic basin of the São Francisco River in the State of Sergipe was found to be generally good, although with evidence of contamination by domestic sewage, as shown by the data for the parameters thermotolerant coliforms, total nitrogen and total phosphorus. The exception was the Jacaré River in Poço Redondo, which was found to be highly impacted, with water quality indices varying between acceptable, during the high water period, and very bad, during the dry period.

An important finding is the high capacity of this hydric body for self-cleansing. Although its waters are used in diverse applications throughout its extensive drainage area, water quality is still good when the river reaches the municipality of Neópolis (site SF-05), close to its point of discharge into the Atlantic Ocean.

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