



A system for environmental monitoring of hydroelectric reservoirs in Brazil

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ABSTRACT

Environmental monitoring of aquatic systems is an important tool to support policy makers and environmental managers' decisions. Long-term, continuous collection of environmental data is fundamental to the understanding of an aquatic system. This paper aims to present the integrated system for environmental monitoring (SIMA), a long-term temporal series system with a web-based archive for limnological and meteorological data. The following environmental parameters are measured by SIMA: chlorophyll-*a* (μgL^{-1}), water surface temperature ($^{\circ}\text{C}$), water column temperature by a thermistor string ($^{\circ}\text{C}$), turbidity (NTU), pH, dissolved oxygen concentration (mg L^{-1}), electric conductivity ($\mu\text{S cm}^{-1}$), wind speed (ms^{-1}) and direction ($^{\circ}$), relative humidity (%), shortwave radiation (Wm^{-2}) and barometric pressure (hPa). The data were collected in a preprogrammed time interval (1 hour) and were transmitted by satellite in quasi-real time for any user within 2500 km of the acquisition point. So far, 11 hydroelectric reservoirs are being monitored with the SIMA buoy. Basic statistics (mean and standard deviation) and an example of the temporal series of some parameters were displayed at a database with web access. However, sensor and satellite problems occurred due to the high data acquisition frequency. Sensors problems occurred due to the environmental characteristics of each aquatic system. Water quality sensors rapidly degrade in acidic waters, rendering the collected data invalid. Data is also rendered invalid when sensors become infested with periphyton. Problems occur with the satellites' reception of system data when satellites pass over the buoy antenna. However, the data transfer at some inland locations was not completed due to the satellite constellation position. Nevertheless, the integrated system of water quality and meteorological parameters is an important tool in understanding the aquatic system dynamic. It can also be used to create hydrodynamics models of the aquatic system to allow for the study of meteorological implications to the water body.

Keywords: Environmental monitoring, Database, time series, reservoirs.

Sistema para monitoramento ambiental de reservatórios hidrelétricos no Brasil

RESUMO

O monitoramento ambiental de sistemas aquáticos é uma importante ferramenta para subsidiar as tomadas de decisão e o gerenciamento ambiental. Séries temporais de longo prazo de dados contínuos são fundamentais para a caracterização desses sistemas aquáticos. O

objetivo deste trabalho é o de apresentar o sistema integrado de monitoramento ambiental (SIMA), um sistema que amostra séries temporais de dados limnológicos e meteorológicos e os armazena em um sistema baseado na *web*. As variáveis ambientais amostradas pela boia SIMA são: clorofila-a (μgL^{-1}), temperatura da superfície da água ($^{\circ}\text{C}$), temperatura da coluna d'água por uma cadeia de termistores ($^{\circ}\text{C}$), turbidez (NTU), pH, concentração de oxigênio dissolvido (mg L^{-1}), condutividade elétrica ($\mu\text{S cm}^{-1}$), velocidade do vento (ms^{-1}) e direção do vento ($^{\circ}$), umidade relativa (%), radiação incidente de ondas curtas (Wm^{-2}), pressão atmosférica (hPa). Os dados são amostrados em um intervalo de tempo pré-determinado (1 hora) e são transmitidos por satélite em tempo quase real para qualquer usuário que esteja a um radio de até 2500 km do local de aquisição dos dados. Atualmente estão sendo monitorados 11 reservatórios hidrelétricos via boia SIMA. Uma estatística básica (média e desvio padrão) dos dados e exemplo de séries temporais de alguns parâmetros são apresentados. Entretanto, problemas relacionados aos sensores e ao satélite de coleta de dados foram identificados devido à alta frequência amostral de aquisição dos dados. Os problemas relacionados aos sensores ocorrem devido às características ambientais de cara sistema aquático em monitoramento. Em águas ácidas os sensores de qualidade de água se degradam com maior rapidez, e os dados coletados se tornam inválidos. Outro problema é a infestação de perifíton nos sensores, o que pode causa erro de leitura. Os problemas relacionados ao satélite envolvem a recepção do dado, o qual ocorre somente quando o satélite passa sobre a antena da boia SIMA. Contudo, devido a posição da constelação de satélites algumas localizações não estão totalmente cobertas. O sistema SIMA é uma importante ferramenta para o monitoramento da qualidade da água e dos parâmetros meteorológicos, que pode inclusive contribuir para a caracterização da dinâmica de sistemas aquáticos. Os dados também podem ser utilizados para alimentar modelos hidrodinâmicos, e avaliar os efeitos de eventos meteorológicos no sistema aquático.

Palavras-chave: Monitoramento ambiental, Bando de Dados, Séries Temporais, Reservatórios.

1. INTRODUCTION

Reservoirs, or man-made lakes, are usually built to store water for later use, water supply, flood control or power generation (Casamitjana et al., 2003). There are approximately 31 hydroelectric reservoirs in Brazil, though the reservoirs have multiple uses, They have a volume of more than 1 billion cubic meters and were built by electric sector. The hydroelectric sector is responsible for 97% of energy generation in the country and is considered the largest hydroelectric system in the world (Kelman et al., 2002). The damming of these waters, however, causes great environmental, social and economic impacts (Tundisi, 1994).

The monitoring of water quality in these environments is necessary not only for the quality of the environment but also for the quality of life of the population. Tundisi et al. (2012) pointed that the search for ecological indicators is a relevant task for environmental managers. However, the authors also pointed out that many good ecological indicators are difficult to find. Studies of water quality in most of the aquatic environments have been based primarily on datasets obtained at different sites or along track lines in cruises (Jerosch et al., 2006). Nevertheless, this approach does not consider the different scales of temporal variability of biological and environmental parameters, which is a requirement for any basic ecological study. However, sampling efforts must be carefully considered since misleading conclusions may arise from less intensive data collection, while large sampling programs considerably increase the costs of data acquisition.

Ideally, temporal collection of data from aquatic systems is accomplished by automatic stations capable of autonomous monitoring of limnological and meteorological variables (Glasgow et al., 2004; Stech et al., 2006). With the installation of an associated telemetric link, the constant surveillance provided by these systems makes it possible to quickly detect changes and trends in critical indicators (Glasgow et al., 2004).

Long-term, continuous, time-series collection of environmental data data is fundamental to identify and classify sudden changes and to determine their effect on aquatic systems. According to Roland et al. (2012), hydrological pulses and changes in land use can regulate functioning and interaction between biotic and abiotic components in Brazilian aquatic systems. These pulses can be natural or induced for antropic activity, frequent, seasonal or intermittent, with variable magnitude and both direct and indirect effect (Tundisi et al., 2004). Comprehension of functions and characterization of controlling factors, however, normally arise after the collection of large data sets at different time scales, which allows one to identify and differentiate short and long-term variability.

Effective water quality monitoring has become critical for water resource management programs, as water quality perturbations related to escalating human population growth and industry pressures continue to increase in inland areas. Government personnel and scientists show increasing interest in understanding the processes occurring in these environments (Glasgow et al., 2004). However, the main problem is the lack of a consistent long term series of collection of water quality data.

The acquisition of meteorological data is also important for water quality monitoring since the intensity of precipitation events determines runoff intensity and the transport of organic and inorganic elements from the soils to the aquatic ecosystems (Johnson et al. 2008). In this way, changes in the intensity and frequency of precipitation may contribute to higher input of nutrients and consequently enhance the eutrophication process. This process results in excessive algal growth which is a public-health issue, since cyanobacteria blooms, in addition to degrading water quality, can produce toxins harmful to human health (Chorus and Barthram, 1999).

The long term series collection of water quality and meteorological data is essential for environmental studies of aquatic systems. The goal of this paper is to present a system for long-term time series collection of environmental data as well as a data-based data storage system with web access.

2. MATERIALS AND METHODS

2.1. Integrated System for Environmental Monitoring - SIMA

SIMA is a set of hardware and software for data acquisition and real-time monitoring of hydrological systems (Stech et al., 2006). It is an independent system formed by an anchored buoy in which sensors, data storage systems, a battery and a transmission antenna are fixed (Figure 1).

The data are collected in preprogrammed time intervals (1 hour) and are transmitted by satellite in quasi-real time for any user within a range of 2500 km of the acquisition point. The selection of the environmental parameters measured by SIMA took into account factors such as: relevance as an environmental index (i.e. the variables that respond consistently to alterations in the functioning of the aquatic system) and technical suitability for data acquisition and transmission from automatic platforms.

The environmental parameters measured by SIMA are: chlorophyll-*a* (μgL^{-1}), water surface temperature ($^{\circ}\text{C}$), water column temperature by a thermistor string ($^{\circ}\text{C}$), turbidity (NTU), pH, dissolved oxygen concentration (mg L^{-1}), electric conductivity ($\mu\text{S cm}^{-1}$), wind

speed (ms^{-1}) and direction ($^{\circ}$), relative humidity (%), short wave radiation (Wm^{-2}), barometric pressure (hPa). The characteristics of the sensors are shown in Table 1.



Figure 1: Photo of the SIMA installed at Tucuruí floodplain, Brazilian Amazon.

Table 1: Characteristics of the limnological and meteorological sensors in SIMA.

Sensor	Manufacture	Range	Accuracy	Depth/Height
Chlorophyll- <i>a</i>	Yellow Spring	0-400 μm	0.1 μm	-1.30 m
Water Temperature	Yellow Spring	-5-60 $^{\circ}\text{C}$	$\pm 0.15^{\circ}\text{C}$	-1.30 m
Thermistor String	Yellow Spring	-5-60 $^{\circ}\text{C}$	$\pm 0.15^{\circ}\text{C}$	4 depths
Turbidity	Yellow Spring	0-1000 NTU	0.1 NTU	-1.30 m
pH	Yellow Spring	0-14	0.01	-1.30 m
Dissolved oxygen	Yellow Spring	0-50 mg L^{-1}	0.01 mg L^{-1}	-1.30 m
Electric Conductivity	Yellow Spring			
Wind	R.M. Young	0-100 ms^{-1}	$\pm 0.3 \text{ms}^{-1}$	3 m
Humidity	Rotronic	0-100 %	$\pm 1.5 \%$	3 m
Short wave	Kipp & Zonen CM21	0-1500 Wm^{-2}	$\pm 1-3\%$	3 m
Barometric pressure	Vaisala	500 -1100 hPa	$\pm 0.3 \text{hPa}$	3 m

2.2. Monitored Hydroelectric Reservoirs in Brazil

So far 11 hydroelectric reservoirs are being monitored using the SIMA buoy. The characteristics from each reservoir are described in Table 2. Figure 2 shows the location of each SIMA in Brazilian reservoirs.

Table 2. Hydroelectric reservoirs monitored using the SIMA buoy.

Reservoir	Damming Area	Total Volume	Dam's Maximum height
Tucuruí	2850 km ²	45.5 billions m ³	78 m
Corumbá	65 km ²	1.5 billions m ³	90 m
Estreito	46.7 km ²	1.418 billions m ³	92 m
Furnas	1440 km ²	22.95 billions m ³	127 m
Manso	427 km ²	7.3 billions m ³	140 m
Itumbiara	778 km ²	17 billions m ³	106 m
Funil	40 km ²	8.9 billions m ³	85 m
Serra da Mesa	1784 km ²	54.4 billions m ³	154 m
Itaipu	1350 km ²	29 billions m ³	196 m
Três Marias	1040 km ²	21 billions m ³	75 m
Xingó	60 km ²	402,800 m ³	141 m

The first reservoir monitored was Tucuruí and the last SIMA installed was in Xingó (see Figure 2 for location). The first reservoir is located in the Brazilian Amazonian region and the last is in the Brazilian Scrub Savanna in the Northeast. The Itumbiara hydroelectric reservoir is located in an area between Minas Gerais and Goiás States (Central Brazil) that was originally covered by tropical grassland savanna. The damming of the Parnaíba River flooded its main tributaries: the Araguari and Corumbá Rivers. The basin's geomorphology resulted in a lake with a dendritic pattern covering an area of approximately 814 km² and a volume of 17.03 billion m³ (Alcântara et al., 2010a).

The Serra da Mesa Reservoir is located in the Upper Tocantins River Basin, northern Goiás State. The Serra da Mesa Reservoir is the largest in Brazil in terms of water volume flow. During maximum flow the reservoir contains 54.4 billion m³ and measures 1,784 km² (Guimarães et al., 2004).

Tucuruí reservoir is located in Pará State, North Brazil and was created in November 1984 by damming the Tocantins River. The main purpose of the reservoir is hydroelectricity, although it has multiple uses, such as flood control, fisheries, and recreation. It is one of the largest reservoirs in the Amazon Basin (Novo et al., 2002).

The Manso reservoir is located in the State of Mato Grosso (Central-West Brazil), 100 km from its capital, Cuiabá. The reservoir was flooded between November 1999 and February 2000 and its flooded area is about 427 km² (Valério et al., 2012).

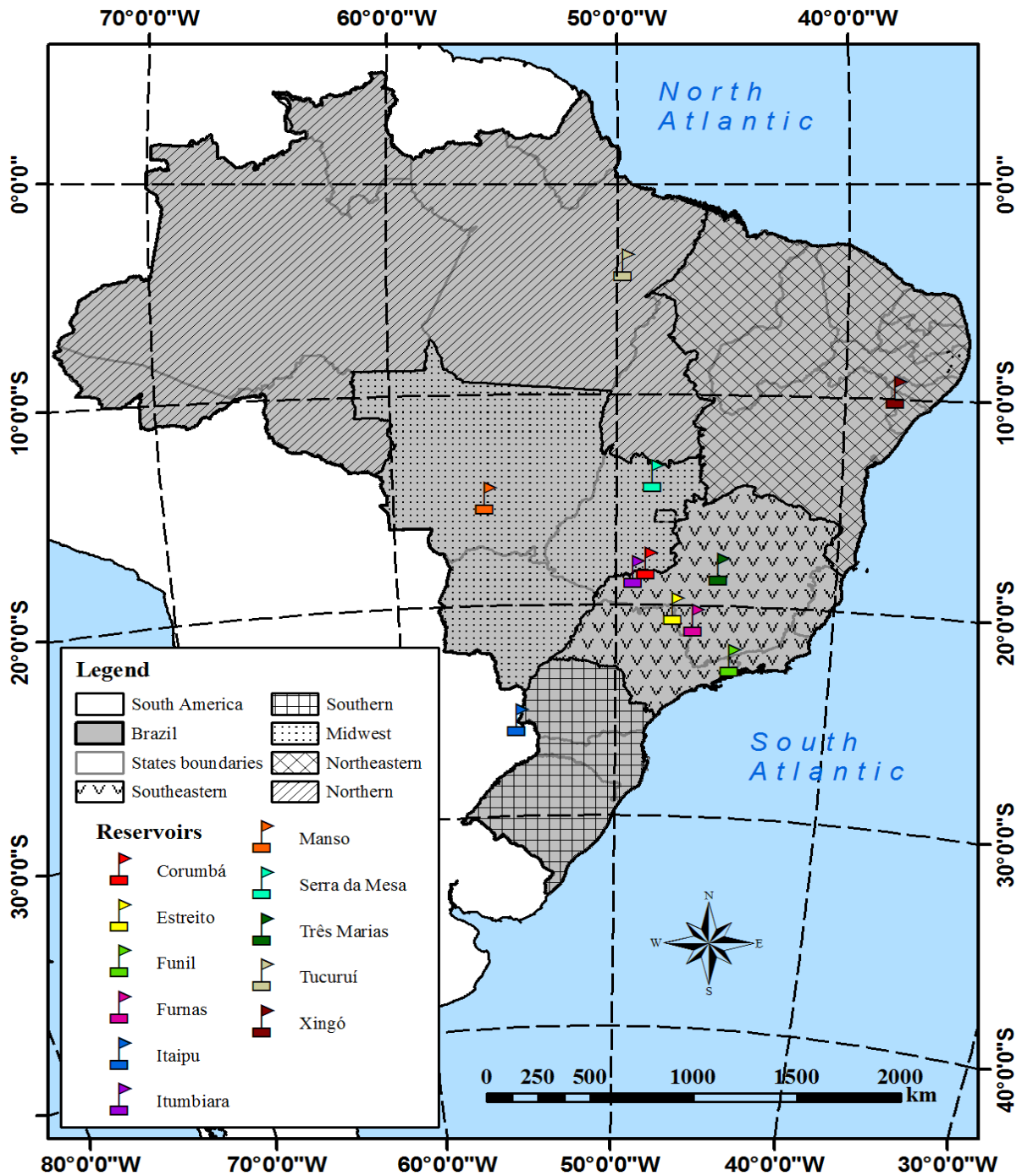


Figure 2: Location of the hydroelectric reservoirs monitored in Brazil.

The Xingó reservoir is located between Alagoas and Sergipe States (Northeast of Brazil), with an area of 60 km² that was originally covered by Scrub Savanna (Rosa et al., 2004). The Table 3 shows the start and end dates of each buoy's operation.

Table 3: Time series data available for each monitored hydroelectric reservoir.

Lat	Long	Reservoir	Start	End
-3.86°	-49.63°	Tucuruí	2004/04/27	2010/02/14
-17.77°	-48.56°	Corumbá	2005/01/25	2006/02/10
-20.15°	-47.26°	Estreito	2006/02/12	2007/01/30
-20.66°	-46.30	Furnas	2006/02/13	2007/02/06
-14.87°	-55.77°	Manso	2007/01/31	2008/11/06
-18.41°	-49.06°	Itumbiara	2009/03/28	Current
-22.53°	-44.56°	Funil	2011/10/24	Current
-13.84°	-48.30°	Serra da Mesa	2011/12/14	Current
-25.03°	-54.42°	Itaipu	2012/07/20	Current
-18.25°	-45.25°	Três Marias	2012/08/22	Current
-9.60°	-37.80°	Xingó	2012/10/20	Current

2.3. Data Base with web access

All time series collections are recorded in a data base with a web access. Through use of this web tool, it is possible to see data by time series, by buoy, by environmental parameter, and by time (see Figure 3). The user can also see basic statistical manipulation of the collected data. It is also possible to download selected data in a .csv format. The web platform can be accessed at <<http://www.dsr.inpe.br/hidrosfera/sima/en/index.php>>.

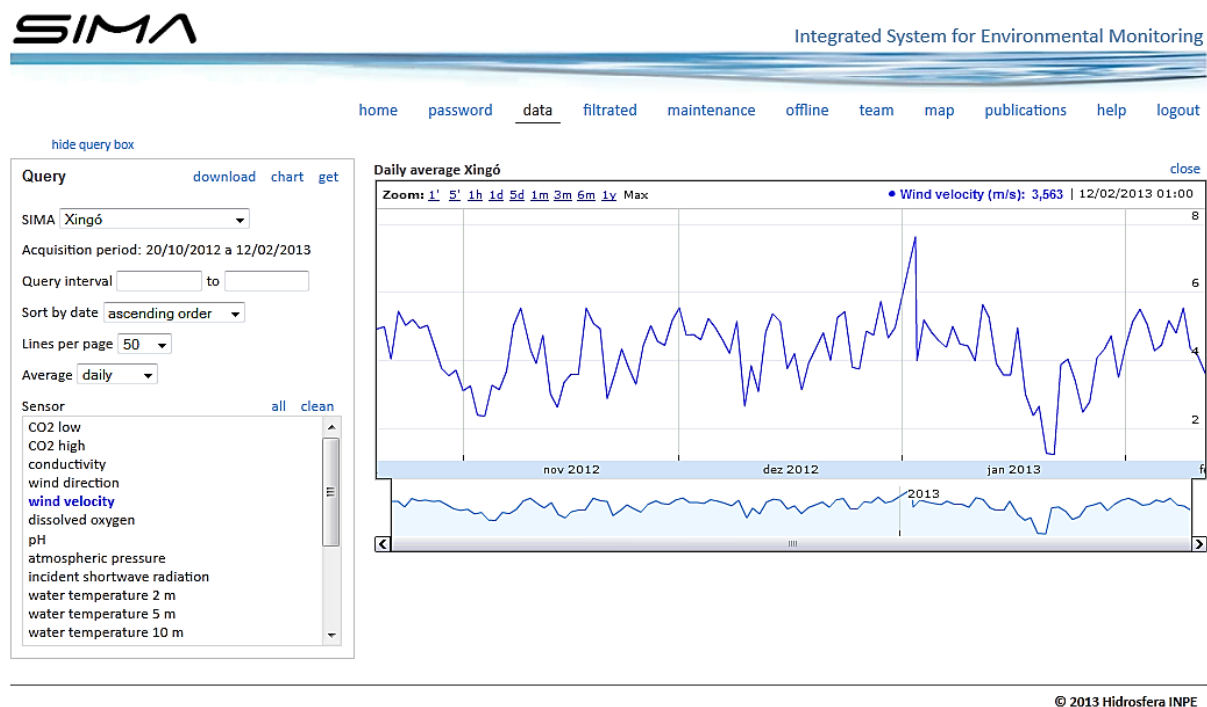


Figure 3: Web platform developed to record the time series.

To enable the user to access the data is necessary to contact website administrator (see the information on the webpage) to request a login ID and password.

2.4. Data Processing

Two approaches were applied in order to overcome the problem of missing data in the time series: first, a simple moving average technique was used to fill small gaps (Box and Jenkins, 1994); second, during long periods of system malfunction, a synthetic series of data was computed by combining and averaging the available data.

For the majority of observations in the series, the synthetic time series can be considered as a four-year daily mean. The authors are aware that this approach precludes the understanding of the inter-annual variability; but, on the other hand, it allows for the analysis of a continuous series (Hipel and McLeod, 1994). However, the data available to researchers is original and unprocessed.

2.5. Observed Problems in the Time Series

The main problems observed occur with sensors and satellites. The sensors problems are due to the environmental characteristics of each water body. In acidic waters, water quality sensors rapidly degrade, rendering the collected data invalid. Infestation of periphyton in sensors is another problem.

The SIMA buoy collects data every hour, i.e., 24 readings per day. However, not all readings are received because the system requires satellites to be over the buoy antenna to complete the data transfer and, due to the positioning of some satellites, this does not occur long enough at some locations inland to complete all transmissions. This is most often the cause of missing data in the time series.

3. RESULTS AND DISCUSSION

The basic statistics for each reservoir for selected parameters are shown in Table 4. The table shows the mean and the standard deviation values for the entire period of operation of each reservoir. The Tucuruí reservoir has the warmest surface water and Itumbiara coldest.

Table 4: Basic statistics (mean and standard deviation) for each reservoir. “Temp” is the water surface temperature; “pH” is the hydrogenionic potential; “DO” is the dissolved oxygen; “Turb” is the turbidity and “Wind” is the wind velocity.

Reservoirs	Temp (°C)	pH	DO (mgL ⁻¹)	Turb. (NTU)	Wind (ms ⁻¹)
Tucuruí	29.4(±0.58)	7.23(±0.35)	1.96(±1.02)	316.88(±268.9)	2.45(±2.9)
Corumbá	26.4(±1.75)	6.9(±2.33)	5.7(±2.5)	119.7(±102.42)	1.93(±0.13)
Estreito	25.2(±2.12)	6.3(±0.75)	2.7(±1.48)	291.3(±209.4)	2.7(±0.21)
Furnas	24.6(±2.09)	9.3(±1.1)	6.2(±2.6)	174.7(±234.9)	2.7(±0.33)
Manso	28.96(±0.97)	7.5(±0.4)	6.5(±1.85)	1.51(±1.51)	2.6(±0.28)
Itumbiara	17.95(±10)	6.15(±3.6)	14.8(±11.52)	4.77(±2.47)	3.3(±2.58)
Funil	22.5(±5.7)	8.17(±1.36)	7.6(±7.7)	74.6(±117.44)	1.3(±0.68)
Serra da Mesa	22.02(±10)	6.9(±2.3)	8.2(±8.7)	147(±150.75)	2.1(±0.23)
Itaipu	23.53(±3.06)	7.63(±0.32)	3.13(±4.37)	6.9(±2.78)	3.4(±0.42)
Três Marias	19.32(±8.33)	6.32(±2.49)	8.21(±0.42)	1.97(±0.02)	2.38(±1.05)
Xingó	26.9(±0.8)	7.9(±0.3)	0.58(±1.12)	6.78(±6.27)	4.4(±0.34)

On average, the pH of Itumbiara, Serra da Mesa and Três Marias is acidic, and the other reservoirs are alkaline. The highest values of DO are found in Itumbiara reservoir and the lowest in the Tucuruí reservoir. Tucuruí also has the highest turbidity value and Manso reservoir the lowest. The highest mean value of wind velocity was observed in Xingó reservoir and the lowest in Funil reservoir.

3.1. Time Series Examples

With this continuously collected data procedure it is possible to obtain a time series of meteorological and limnological data of each monitored reservoir. As example, the Figure 4 shows the time series of the Itumbiara reservoir (see Figure 2 for location). In this example, the passage of a cold front was identified.

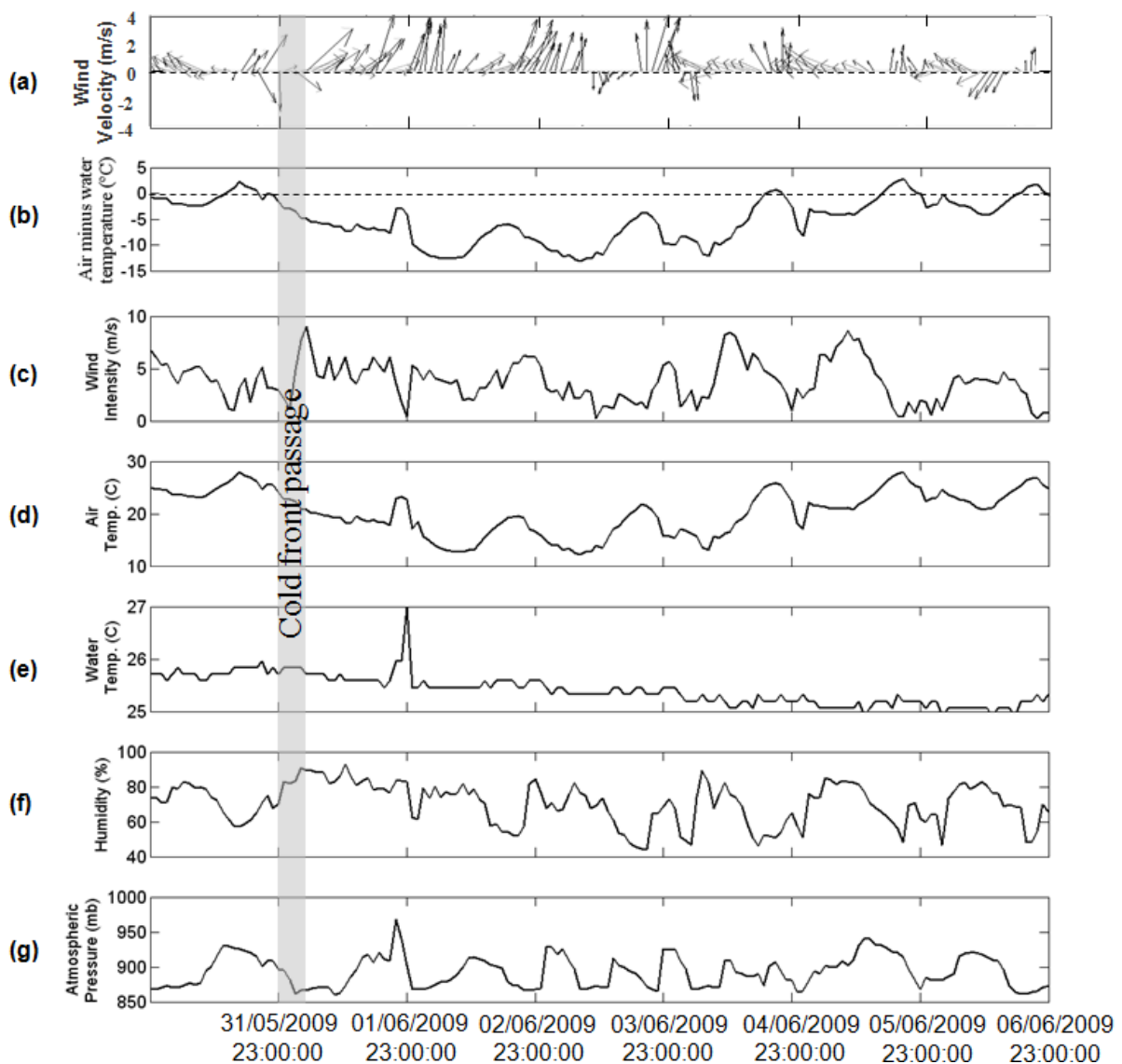


Figure 4: Meteorological and limnological time series data of Itumbiara reservoir: (a) stick plot of wind velocity (ms^{-1}), (b) air minus water temperature ($^{\circ}\text{C}$); (c) wind intensity (ms^{-1}), (d) air temperature ($^{\circ}\text{C}$), (e) water temperature; (f) relative humidity (%), (g) atmospheric pressure (mb) collected by the SIMA buoy from May 31st to June 06th 2009. Source: Alcântara et al. (2010b).

It is clear that during the passage of the cold front the atmospheric pressure and the air temperature decrease; the wind and relative humidity show a slight increase. The surface temperature of the water decreases after the passage of the cold front.

As per Alcântara et al. (2010b), the passage of cold front over a region decreases atmospheric pressure and air temperature, enhancing relative humidity. With the formation of cloud cover, long-wave radiation increases and transfers heat by turbulent convection to the water surface. The sensible flux presents small variability but an increase occurs due to convective turbulence caused by the front's passage; concurrently, the latent flux decreases, though not enough to cause condensation, only evaporation decreases. These occurrences are responsible for the continuing loss of heat after the cold front's passage.

This type of continuous data offers many opportunities for potential analyses, and some common methods of analysis are: Fourier Power Spectrum (Press et al. 1992), Wavelet Analysis (Torrence and Compo, 1998) and Cross Wavelet and Coherence and Phase (Grinsted et al. 2004).

4. CONCLUSIONS

A long-term, system for the continuous collection and satellite transmission of both meteorological and limnological data was discussed. A database with web access that has the capacity to display and download any of the time series data was also discussed.

This system allows any researcher to access the database from any location by use of the Internet. All stored data is backed-up on the local server. This initiative will enhance limnological studies in the involved reservoirs as the time series data will enhance understanding of environmental dynamics. It is best if the data is analyzed seasonally to allow researchers a preview diagnostic of the study area before prospective field trips.

Ecological models which use hydrodynamic approaches also require these long time series data as inputs for the models, in order to analyze the influence of meteorological parameters in the water column as well as in water quality.

The SIMA technology is a promising approach to assist researchers in monitoring water quality as well as to identify and explain how meteorological parameters can affect water column stability.

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