Geographic information systems - tool for evaluation of the hydro-energy performance of water supply systems

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ABSTRACT. The most relevant challenges in the water supply system (WSS) are high water losses and the waste of electric energy. This paper aimed to assess the capacity of the Geographic Information System (GIS) in the analysis of the hydro-energy performance of WSSs. The Stage 1 comprises the selection of data and the respective hydro-energy indexes are defined; cartographic data are defined in Stage 2 and a geo-referenced database is constructed in Stage 3. In the stage 4, the data of the Central Water Supply Zone administered by the Water Works Company of the state of Pará in Belém, Brazil were employed to assess its applicability, in which the sectors with the worst hydro-energy performance were identified, such as Sector 9, with the highest water loss rates (59.11%) and electric energy consumption per m^3 of water produced (1.57 kwh m^{-3}). The results shows that geo-referential assessment of the hydro-energy performance of WSSs provided accurate information for decision-taking related to the rational use of water and electricity in the systems.

Keywords: water loss, energy efficiency, GIS, spatialization.

Sistema de informações geográficas - ferramenta de avaliação do desempenho hidroenergético de sistemas de abastecimento de água

RESUMO. As elevadas perdas de água e o desperdício de energia elétrica são grandes desafios na gestão dos sistemas de abastecimento de água (SAA). Nesse sentido, o trabalho objetiva avaliar a potencialidade do uso de Sistema de Informações Geográficas (SIG) na análise de desempenho hidroenergético de SAAs, sendo, inicialmente, selecionados os dados e definidos os indicadores hidroenergéticos de interesse do trabalho; na etapa 2 foram definidos os dados cartográficos e na etapa 3 foi construído o banco de dados georreferenciado. Na etapa 4 foram utilizados dados da zona central de abastecimento de água, gerenciado pela Companhia de Saneamento do Pará, no município de Belém, Pará, Brasil, para verificar a aplicabilidade da ferramenta, nos quais foram identificados os setores com os piores índices de desempenho hidroenergético, como o setor 9, com os maiores índices de perda total (59,11%) e de consumo de energia elétrica por m^3 de água produzido (1,57 kwh m^{-3}). Os resultados demonstram que a avaliação georreferenciada do desempenho hidroenergético dos SAAs tornou as informações mais precisas para tomada de decisão relacionada com o uso racional de água e de energia elétrica nesses sistemas.

Palavras-chave: perdas de água, eficiência energética, SIG, espacialização.

Introduction

The electricity, one of the most relevant products in the Water Supply System (WSS), is targeted for several types of control and costs saving. Barry (2007) reports that pumping systems causes the highest consumption and expenditure rates of WSS electric energy, which, according to the Brazilian Information System on Water Works (SNIS), totaled BRL 3,070.6 million, or 10.9% of total water expenditure. In fact, it ranks second, below expenditure with personnel, with BRL 11,644.6 million, or 41.2% of total expenditure within all SNIS services in 2013 (Brasil, 2014).

Giustolisi, Laucelli and Berardi (2013) calculated approximately 0.6 kWh at a cost of BRL 0.16 for each cubic meter of water produced. The data above reveals that hydraulic and energetic efficiency are crucial for the performance of the water supply systems.

Since water loss increases the system´s electric energy, a reduction in water loss greatly affects savings in the sector´s electricity costs. To achieve water loss reduction, Hirner and Lambert (2000)

recommend the hydric balance method to determine true and apparent losses based on macro- and micro-measurements. The lack of operational data systematization, inadequate indexes and tool deficiency for the spatial representation of hydro-electrical data are issues that impair WSS administration.

In the case of water displacement, the energy in the supply system units (called 'aggregated energy' by the authors) should be taken into account. Since water loss impacts the consumption of electric energy within the entire system, the consumption of electric energy in all upstream units should be quantified and the loss of water in each WSS unit should be identified (Pereira & Condurú, 2014).

Although adequate tools are required to store a huge amount of hydro-energetic data produced in WSS units, several water supply companies still use simple handwritten data cards. Since the tools provide numerical and graph results, without any spatial representation, rapid visualization of the hydro-energetic situation in WSS units is rather limited.

Thus, the Geographic Information System (GIS) is an important tool for information management, which provides the registry, storage, systematization and specialization of hydro-energy data of WSSs. Consequently, it is a help in the control of the system´s performance, decrease in water loss, energy efficiency and preventive, predictive and corrective maintenance of WSS units. In other words, it prevents or reduces costs in the maintenance and purchase of equipments.

It should be underscored that GIS is used for specific ends, or rather, in the management of WSS units, mainly in water distribution units. However, GIS should also be employed as a tool for the hydroelectric management in all WSS units.

Singh, Samaddar and Srivastava (2010) developed a methodology for the sustainable management of drinking water by assessing current WSS of Allahabad, India, to identify the problems and gaps within the system and produce solutions by GIS for water supply issues. SIG ArcInfo 9.1 was employed to store all relevant data for the analysis and decision-taking. Thematic maps were prepared to evaluate WSS issues and solutions for their sustainability.

Different types of data and specific information for good management are extant in a WSS unit. All the company´s departments should have their information stored and interlinked to GIS: the commercial sector (with the information system on clients), the project and planning sector, the operational sector (with a registry of operations,

maintenance and the condition of the distribution and equipment network), management of infrastructure, runoffs and administration.

Sargaonkar and Islam (2009) developed a GIS model for water distribution network employing as a case study the distribution pipes of the Moinbagh district in Hyderabad, India. GIS was locked to a mathematical model, called Pipe Condition Assessment (PCA) model, which spatializes information within the water distribution network, sewage, sink and soil system, data on the physical qualities of the network and other operational parameters. Foregrounded on stored operational data, the model proved to be satisfactory to monitor problems in the distribution network and to pinpoint faults.

Elgy, Charnock and Hedges (1996) analyzed the use of geoprocessing and remote sensing techniques to evaluate water demand, detect leaks and evaluate water quality in the pipes of a distribution network in Birmingham, UK. Leaks and water loss rates in the distribution network were identified and data on the quality of water distributed to the population were stored. Thus, a co-relationship between leaks and water quality was provided.

Tabesh, Yekta and Burrows (2009) applied GIS to evaluate losses in a water distribution network in the UK by 'yearly water balance' and 'minimum night leak' using EPANET and the commercial GIS ArcGis to assess the features of water losses and map the distribution network and leak sites. Favorable factors in the emergence of leaks in the distribution network were thus identified.

Although GIS is a relevant tool for managers of the water works system, its introduction and establishment require careful planning so that liabilities and deficiencies would be avoided. Qualified technical personnel, financial resources for the acquisition of plants, maps and pictures, specialized experts for the maintenance of the system, training of employees and others are requirements for the beneficial implantation of GIS.

The current assay evaluates the capacity of Geographic Information System (GIS) in the analysis of the hydro-energy performance of water supply systems by means of a geographic database.

Material and methods

A model for the organization and spatialization of hydro-energy information of WSSs was developed. Storage and organization structure in categories of primary hydro-energy data in electronic sheets were elaborated, followed by calculation and spatialization of primary data and

hydro-energy indexes in ArcGis Desktop 9.3 of the Environmental Systems Research Institute (ESRI).

Four stages were elaborated: Stage 1: selection of data and definition of indexes of hydro-energy performance; Stage 2: definition of cartographic data for the spatialization of WSS information; Stage 3: construction of a geo-referenced database; Stage 4: application of GIS to evaluate the performance of supply systems of the area under analysis.

Stage 1 – Selection of data and definition of indexes of hydro-energy performance

Databases of the Brazilian Information System on Water Works and of the National Program for Water Waste Avoidance of the Ministry for Cities and Towns were consulted for the selection of hydro-energy data required to assess the hydro-energy performance of WSSs (Phase 1) and define the indexes of hydro-energy performance (Phase 2).

Phase 1: Selection of hydro-energy data

Thirteen hydro-energy data were selected for current assay. They were subdivided into three categories, or rather, six operational data, four commercial data and three expenditure data (DEX) of WSSs.

Operational data referred to volumes in the supply water system units, whereas commercial data were related to the population target and payment of services. On the other hand, DEX data were expenditures paid for services rendered.

Phase 2: Defining hydro-energy performance indexes

Operational, commercial and DEX data were organized on electronic spread sheets, in the format .xls, to determine the evaluation indexes of the hydro-energy performance of WSSs. The following indexes per category were proposed.

The category of operational indicators comprised:
- True loss in the adduction of raw water (%)

$$I_{LossAd} = \frac{Vop1 - Vop2}{Vop1} = 100 \qquad (1)$$

where:

I_{LossAd} = Index of true loss of raw water in the pipelines;

Vop1 = Volume of water from the source (macro-measured at the Raw Water Station);

Vop2 = Volume of adducted water (Macro-measured at the end of the raw water pipeline or at the entrance of the Water Treatment Station)

True loss during water treatment (%)

$$I_{LossTreat} = \frac{Vop2 - Vop3 - Vop4}{Vop2} \times 100 \qquad (2)$$

where:

$I_{LossTreat}$ = True loss index during the treatment of water;

Vop3 = Volume of treated water (Volume of water macro-measured at the exit of the Water Treatment Station);

Vop4 = Volume of operational water (Volume of water used in the washing of equipments in the Water Treatment Station).

- Losses during Distribution or Non-calculated Water

$$I_{LossDist} = \frac{Vop5 - Vop6}{Vop5} \times 100 \qquad (3)$$

where:

$I_{LossDist}$ = water loss index during water distribution;

Vop5 = Water available to consumers (Volume of water macro-measured at the exit of the reservoir of the Water Treatment Station).

Vop6 = Water consumed (Micro-measured on consumers´ premises).

- Total True Loss (%)

$$I_{LossTot} = \frac{Vop1 - Vop6}{Vop1} \times 100 \qquad (4)$$

where: $I_{LossTot}$ = Index of total water loss in the supply system;

The category of commercial indexes comprises:
- Non-billed water (%)

$$I_{NBW} = \frac{Vop5 - VC1}{Vop5} = 100 \qquad (5)$$

where:

I_{NBW} = Index of non-billed water by the Water Works Company;

VC1 = Water billed by the Water Works Company.

- Billing per active economy (BRL homes⁻¹)

$$I_{BAE} = \frac{VC2}{VC3} \qquad (6)$$

where:

I_{BAE} = Billing Index per active economy

VC2 = Bill rates by the Water Works Company;

VC3 = Number of active economies (homes in which water is effectively consumed).

- Water collected per active economy (m³ econ.⁻¹)

$$I_{WCAE} = \frac{VC4}{VC3} \qquad (7)$$

where:

I_{WCAE} = Water Index collected per active economy;

VC4 = Water Volume collected by the Water Works Company (Water effectively paid by consumers).

The category of Expenditure comprises:

- Consumption of electric energy by the WSS (Kwh m^{-3})

$$I_{CEEWSS} = \frac{DEX1}{Vop5} \qquad (8)$$

where:

I_{CEEWSS} = Index of electric energy consumption by WSS;

DEX1 = Total Consumption of Electricity by WSS;

- Expenditure of electricity by WSS (%)

$$I_{DEXEE} = \frac{DEX2}{DEX3} \, x \, 100 \qquad (9)$$

where:

I_{DEXEE} = Expenditure Index of electricity by WSS
DEX2 = Expenditure of electricity by WSS.

DEX3 = Total expenditure of electricity by WSS;

- Expenditure of electricity per water volume produced (BRL m^{-3})

$$I_{DEXVo1} = \frac{DEX2}{Vop3} \qquad (10)$$

where: I_{DEXEE} = Expenditure Index of electricity per water volume produced.

Stage 2 – Definition of cartographic data for the spatialization of information of WSSs

The cartographic data required for the application of GIS were defined at this stage, according to district limits, sectors´ attendance area and WSSs. In current analysis, WSS was formed by groups of intake units (pumping of raw water, adduction of raw water), processing (Water Treatment Station – WTS, reservoir, Pumping Station of Treated Water - PSTW) and the water distribution sector (Reservoir, PSTW, distribution network).

Topological cartography was also elaborated for current model, identifying hydrography, road maps and the installation sites of WSS units. A data model for GIS representation that would organize cartographic information in shape-file layers normally used in most GIS was prepared. The procedure provided spatialization and geo-referencing of cartographic data based on the reference datum SIRGAS 2000 and employing the geographic coordinate system.

A layer was prepared for each type of information, provided with polygons, lines or points for space representations and a list of attributes to represent numerically each cartographic item of the model.

Three main layers were prepared for each WSS: Supply Sectors, Adductors and System Units. Auxiliary layers such as district limits, roads and hydrography were also foreseen.

Stage 3 – Construction of a geo-referenced database

The construction of a geo-referenced database was organized with hydro-energy data in electronic spread sheets, format .xls. Database was linked to the layer Supply Sectors which was already geo-referenced in SIRGAS 2000 reference Datum and in the geographic coordinate system.

GIS field calculator was employed to calculate the indexes of hydro-energy performance defined in Stage 1. Mathematical operations are used to determine hydro-energy performance indexes in WSSs units. Results were automatically fed to the geo-referenced database.

Hydro-energy data defined in the categories of Stage 1 and stored in the geo-referenced database were related. Consequently, the generation and spatialization of new information within a GIS environment, such as hydro-energy performance indexes, occurred. The visualization and information analysis of WSSs performance were available against water and electric energy losses.

Stage 4 –Application of GIS to evaluate the performance of supply systems of the area under analysis

The practical application of the model was undertaken on the hydro-energy and cartographic data of WSS Bolonha administered by the Waterworks and Sewage Company of Pará (COSANPA) in downtown Belem, Para State, Brazil, 1º 45' S and 48º 47' W (Figure1).

Approximately 475,200 m^3 day^{-1} of stored water of the Lake Bolonha are pumped by the Bolonha and Utinga Pumping Stations to the three Water Treatment Stations (WTSs) and then to the supply water sectors of Belem, Brazil.

The supply systems of the downtown area are:

a) Utinga System (São Braz) receives raw water adducted from the lake Bolonha and pumped to the Utinga unit. After treatment at the WTS São Braz,

the water is distributed to the 1st, 2nd and 3rd Supply Sectors (SSs) in downtown Belém;

b) Utinga System (5th Sector) receives and treats raw water adducted from the lakes Bolonha/Utinga. After treated at the Marco WTS, it is distributed to the 5th Sector (Marco District) of water supply in downtown Belém;

c) Bolonha System – Downtown receives and treats raw water adducted from lake Bolonha; after treatment (within the same area, at the WTS–Bolonha), the water is distributed to five supply sectors (4, 6, 7, 8 and 9th sectors) in downtown Belém and to nine sectors in the municipality of Belém and Ananindeua.
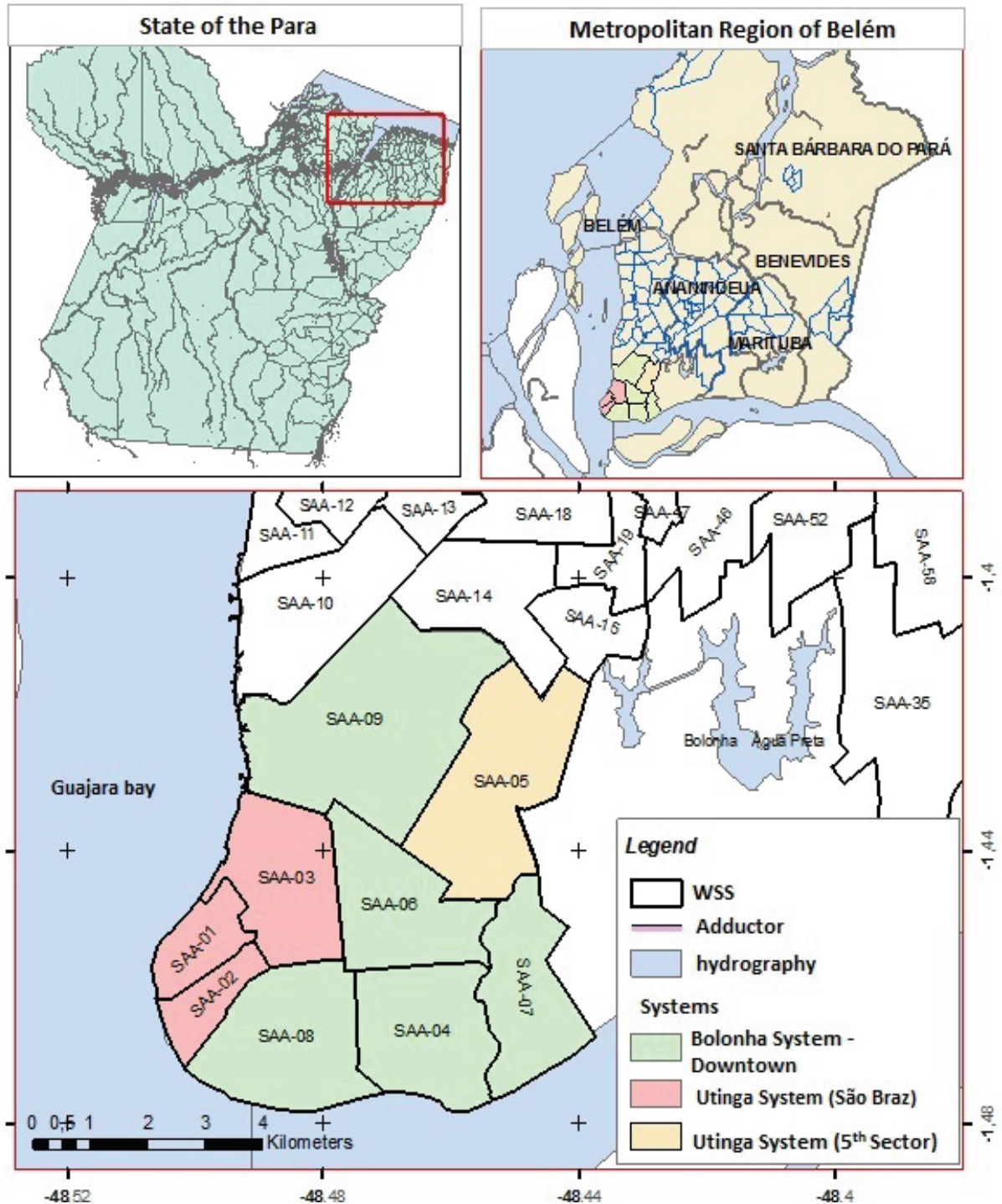
Figure 1. The studied area

Results and discussion

GIS was applied to WSSs in downtown Belem, Brazil, according to methodology described above. Cartography basis and COSANPA reports for operational, commercial and expenditure data determined the performance indexes of the supply systems of the area studied. Consequently, the spatialization of the cartographic base in GIS for the construction of geo-referential database was performed.

Geo-referencing of data provided a general visualization of data from the WSS under analysis, their integration and relationship, with new and relevant information for the performance report. Figure 2 shows the representation of the main layers of WSS Bolonha-Downtown.

Every layer comprises cartographic items and a geographic database in which each cartographic item, represented by lines, points and polygons, is related to a line in the database. The layer 'Adductors' is composed of cartographic items in the shape of a line, representing the WSS pipelines; the layer 'Units' is composed of items in the shape of points / which represent WSS units; the layer 'Sectors' is composed of cartographic items in the shape of polygons which represent the limits of the WSS sectors (Figure 3).

The operational, commercial and DEX data, referring to the systems´ supply sectors and used as an example for GIS application, were stored in the layer which corresponded to the area covered by the supply sector.

Hydro-energy performance in GIS were determined and spatialized by Field Calculator where database variables were selected and the formulations defined in Stage 1 were inserted. The result of the mathematical operation was automatically stored in the geographic database. Based on the rates employed, color-graded maps were prepared to easily visualize information of the hydro-energetic performance of WSSs.

The rates of the following indexes of hydro-energy performance could be related and visualized: index of water loss in adduction, treatment, distribution; index of total loss of water; index of non-billed water; index of billing per home; index of collection per home; index of electric energy consumption; index of expenses with electric energy per supply sector and index of expenses with electric energy per volume produced. Graded color tones were applied, with highest indexes marked by bolder tones.

Indexes of physical losses in adduction, treatment and distribution units (Figure 4) and the indexes of electric energy consumption per volume of water produced (Figure 5) for the nine sectors of downtown supply are exemplified in the maps.

In the case of loss indexes in the adduction, treatment and distribution units of the WSSs under analysis, it has been verified that the highest water loss rates in the supply systems occurred in the distribution. Sector 9 actually features the greatest loss rate in distribution (57%); Sector 3 with the greatest loss rate in treatment (3.4%); Sectors 6 and 8 with the greatest loss rate in adduction (3.5%).

The highest consumption rates in electric energy per water volume produced occurred in Sectors 9 and 4, respectively with 1.57 and 1.45 kwh m^{-3} of water produced. When compared to the 2013 Brazilian average, 0.68 kwh m^{-3}, published by SNIS (Brasil, 2014), the above rates demand an intervention in the hydro-energy management of the systems.
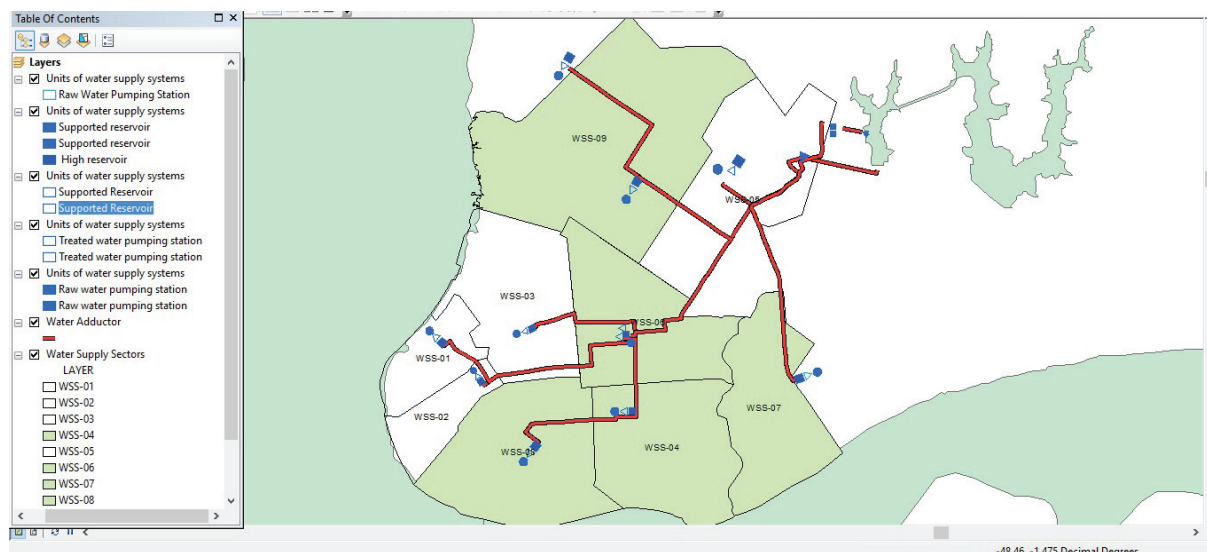
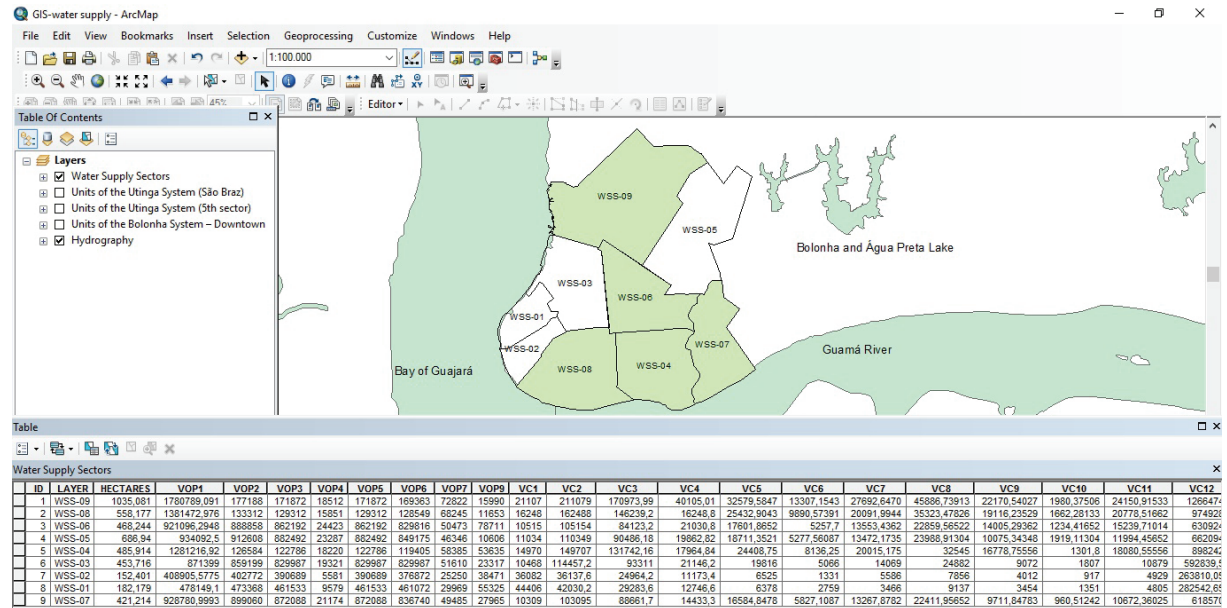**Figure 2.** Composition of the main lasses of features of the WSSs under analysis

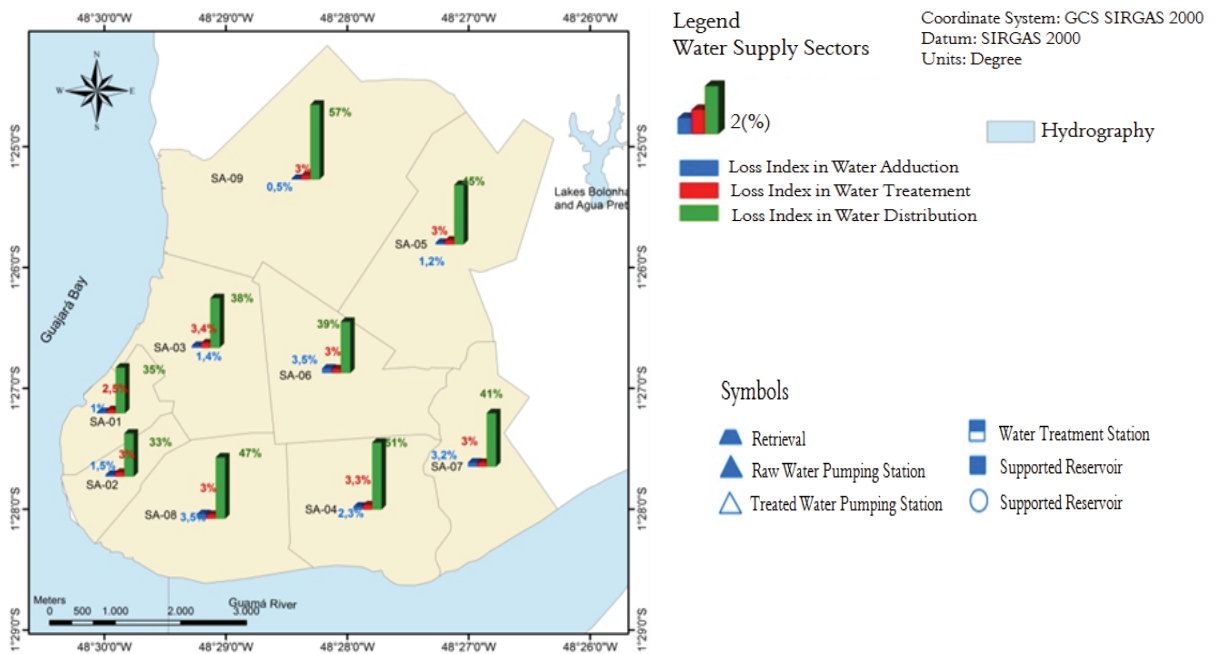**Figure 3.** Geo-referenced database in GIS 9.3

Figure 4. Index of physical loss in WSS units studied.

The greatest total loss index was verified in Sector 9, with 59.11%, followed by Sectors 4, 8 and 5. The above rate is higher than the average water losses in Brazilian WSS for 2013, with 37.1% (Brasil, 2014) whereas developed country averaged 11% (Associação Brasileira de Engenharia Sanitária e Ambiental, 2013). High water losses and waste of electric energy in WSSs increase energy expenditure. In fact, the highest rates occurred in Sectors 9 (0.40 BRL k Wh⁻¹) and 4 (0.38 BRL k Wh⁻¹) in the WSS under analysis.

The most significant non-billed water index occurred in sector 9 and 4, respectively with 48.43 and 44.85%, whereas Sector 1 had the highest asset rate (59.30%) per home.

Sectors 9 and 4 are the largest supply areas and the most populous, requiring greater amounts of electric energy and water for consumption, impairing operational control, identification of illegal connections and other illicit uses. In addition, the conditions of the pipelines should be taken into account and in-depth studies for the identification of
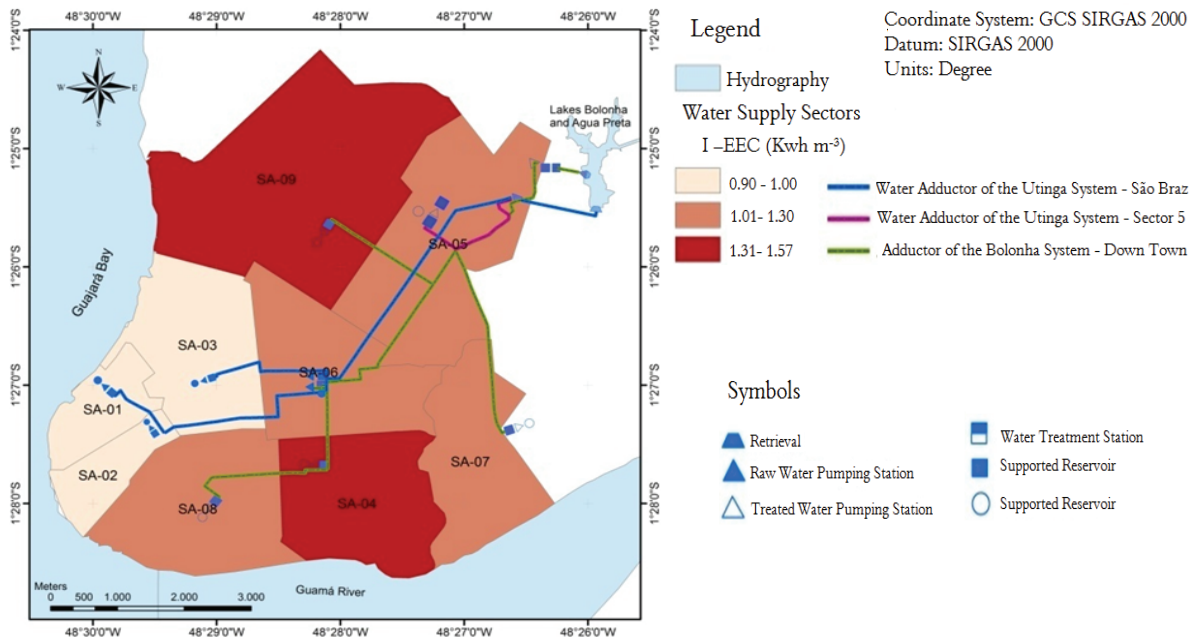
Figure 5. Index of electric energy consumption in the WSSs studied.

causes for higher hydro-energy performance indexes should be undertaken.

The employment of operational, commercial and DEX rates within the limits of sectors, units and supply system shows the importance of GIS in the simulation of hydro-energy performance, specifically with regard to the results of spatialization.

Storage of WSS data, based on symbols to represent the topology of data and the preparation of geo-referenced database, guaranteed the visualization and identification of cartographic data in GIS with regard to the units and sectors of the supply water systems under analysis. In fact, they are highly relevant for the management of technical and cartographic data in the assessment of the hydro-energy performance of WSSs.

The calculation of performance indexes provided conditions for information and analysis of hydro-energy performance of each supply sector. Furthermore, the determination of DEX and the evaluation of commercial performance with regard to billing and assets of the supply systems provided a general view of the financial situation, coupled to the identification of critical issues, underscoring the water supply units or sectors with the best or worst hydro-energy performance. Accordingly, planning and decision-taking became easier.

Results demonstrate that GIS Technologies are adequate tools for the spatialization of data and information of the hydro-energy performance of WSSs due to the rapid identification of the performance of the supply system units and their possible problems.

Conclusion

The relationship between hydro-energy data and index spatialization provided the visualization and the information analysis given by GIS and the evaluation of the performance of the WSS sectors studied, where Sectors 9 and 4 proved to have the system´s worst hydro-energy performance when compared to other indexes.

The spatialization of information on hydro-energy performance in GIS is recommended for planning and decision-taking. In fact, it is an important tool for managers, technicians and administrators of waterworks-sewage companies in their efforts against water losses and for the rational use of electric energy in WSSs, enhancing operation control and the prevention of problems.

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