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Article in *Journal of Urban and Environmental Engineering* · December 2019

DOI: 10.4090/juee.2019.v13n2.209218

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## DEVELOPMENT OF MODELS FOR ASSESSING HYDRO-ENERGETIC LOSSES IN WATER SUPPLY SYSTEMS

Augusto G. Rego<sup>1\*</sup>, José A. R. Pereira<sup>2</sup> and Aline C. P. A. Santos<sup>2</sup>

<sup>1</sup>Sanitary and Environmental Engineering, Federal Institute of Education, Science and Technology of Pará, Brazil

<sup>2</sup>Sanitary and Environmental Engineering School, Federal University of Pará, Brazil

Received 7 November 2018; received in revised form 16 May 2019; accepted 18 June 2019

### Abstract:

Current tools and methods for assessing water supply systems no longer meet the new sustainability challenges, mainly the balance of the close relationship between water and energy in the perspective of unsustainable use of water resources and energy crisis. In this context, this study aimed to develop a model for hydro-energetic assessment of water supply systems, based on the systemic approach and diagnostic and simulation actions of the operation of water flows and electricity consumption. The analysis was developed in two steps, namely the development of the model and its formulations and subsequent application to the water supply system using synthetic data. The results showed that the developed model was effective in assessing the proposal, demonstrated easy practical applicability in any unit arrangement, promoted systemic understanding of water and electricity losses in the units in the stages of production, processing and distribution and in the system as a whole, and provided decision making for corrective actions with greater systemic impact. Finally, the proposed model represents an important technology in the search for improved social, economic and environmental sustainability of water supply systems.

### Keywords:

Process model. Water losses. Energy Losses. Hydro-energetic performance. Sustainable water supply.

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\* Correspondence to: Augusto G. Rego, Tel.: +55 91 98023 0043.  
E-mail: [augusto.rego@ifpa.edu.br](mailto:augusto.rego@ifpa.edu.br)

## INTRODUCTION

Drinking water supply is the Brazilian sanitation sector in which the development of methodologies and procedures for rational use of water and electricity is more advanced; however, there are still high levels of water losses that result also into electricity waste in the same magnitude (Pereira & Condurú 2014). Therefore, it is essential to question the level of preparedness of the companies on universalization of this service, given the challenge of balancing the increased supply of drinking water and the consequent increased demand for electricity in an unsustainable scenario of water use and energy crisis (Galvão & Bermann 2015; Rego *et al.*, 2013; Tomalsquim *et al.*, 2007). Consequently, it is possible to consider that the loss of water and the consequent waste of electricity in water supply systems (WSS) can become compelling barriers to the achievement of the millennium goals for sustainability, due to the important role of the sector in domestic demand for electricity, for example, in Brazil (2 to 3%, about 10 million GW/year) primarily intended for pumping water (90% estimates) (Gomes 2009).

In this way, there are undeniable losses related to this context, but widespread and consolidated methods for assessing the water supply system (WSS) do not meet the required sustainability. The Standard Water Balance, for example, despite being the most extensively used method for assessing water loss, does not intend to quantify the electricity consumption in systems and units. In an attempt to overcome this deficiency, indicators that relate electric energy consumption, its costs and pumped volumes are used for hydro-energetic assessment of WSS, such as, for example, the specific consumption indicator (SCI), which relates electric energy consumption per volume produced, measured in kWh/m<sup>3</sup>. In addition, there are models that are based on the energy dissipated in pipelines to identify electricity losses; it was even developed an interesting audit method to assess energy losses in WSS, which takes into account the natural energy existing in every system added to energy from machines, which are lost along the pipes, resulting in energy delivered to the consumer (Cabrera *et al.*, 2010). However, the current indicators do not provide an overall view of the system and do not determine the volumes of water and energy correctly, because they ignore that the same volume of water consumes electricity at different stages of the WSS. Besides that, the applicability of the audit method requires knowledge of the distribution networks, which developing countries are still far from achieving it, and also disregard the analysis of electricity consumption aggregate by the same volume of water as well as the existence of imports and exports.

Moreover, there is no consensus in determining the performance standard for WSS, bearing in mind the small timing between the conception, design and execution of works, which results in different control

routines of infrastructure for drinking water supply and, in this sense, it becomes very difficult to draw comparisons between different systems. Thus, the challenge was to develop a model that systemically considers the volumes of water and consumption of electricity and meets the most different systems, since the abstraction of water until the delivery to the final consumer. The model proposed herein for assessing water and electricity losses in WSS aimed to align theory and practice of engineering in providing the service for improvements and mainly sustainability.

## MATERIALS AND METHODS

The development of a systemic approach to assess water and electricity losses in WSS used the theoretical framework of the General Systems Theory (GST), which aims to formulate theories of generalized systems, that is, formulation of principles that are valid for "systems" in general, whatever the nature of their component elements and the relations or "forces" between them (Bertalanffy 2008). GST is designed as a program to join research branches in several disciplines simultaneously into a science of wholeness to overcome or complement mechanistic and reductionist approaches (Drack & Swartz 2010; Mele *et al.* 2010.). The central idea is that the understanding of the whole is determined by the understanding of its parts and the interrelationship between them (Hanne 2001).

In this sense, the consolidated classic definition of real losses states that they are the difference between the volume of water entering and leaving a unit (Hirner and Lambert, 2000). Nevertheless, for the evaluation of hydro-energetic losses in WSS, losses should be seen from a systemic perspective, and in this case, their values go beyond the mass balance, and should also consider the efficient use of water throughout WSS, including the volumes used in the processes. Thus, it was possible to define water losses as losses of water through leaks and overflow, as well as excessive volumes of water used in the steps of raw water abstraction, processing and distribution of treated water.

In the case of determining losses of electricity, the first idea is to consider only the portion of the electricity consumption referring to water losses through leaks and overflows, however the energy audit method considers that the energy balance is defined as the equality between energy entering the system and the sum of the energy delivered to consumers, the dissipated and the compensated (CABRERA *et al.*, 2010). But seeking greater practical applicability of the proposed model, it is not based on energy incorporated into volumes of water, but on the amounts of electricity consumed by them. Thus, through a systemic approach, the proposed model considers that in addition to electricity losses regarding leaks and overflows, there are also those related to the consumption by excessive volumes of water used in the WSS steps, and also to the

consumption of electricity inherent to water volumes that have not been lost, these also have excessive consumption values. Accordingly, the losses of electricity to the hydro-energetic model proposed are defined as all electricity consumed by the lost volumes of water as well as excessive consumption of electricity relating to the volumes not lost in the steps of abstraction, processing and distribution of treated water.

The systemic approach for the functioning of WSS units was imperative to design the proposed model, where the system was defined as open and therefore essential for the operation for water volume inputs (abstraction from the sources), consumption of electricity (for electromechanical equipment) and water volume outputs (actual losses, effective use in the process and effective consumption of the population). However, in WSS operation, there are actual greater water losses than predicted by the planning and this fact makes possible to draw a condition at which the volume of water to be abstracted from the source is equal to the sum of the effective volume of water consumed by the population, the optimal volume of water used in the processes and the volume of water lost predicted by the design, i.e., a reference condition. Then, it becomes evident the two different scenarios with their respective electricity consumption: the first with WSS working under actual conditions and the second with WSS operating under reference conditions.

Finally, the design of hydro-energetic performance that grounded the model is driven by the distance between the conditions of water volume and electricity consumption of the actual WSS and the conditions of water volume and electricity consumption of the reference WSS. Following this reasoning, this research was developed in two steps: the first focused on modeling the process for hydro-energetic assessment of WSS, based on formulations for losses of water and electricity, and the second step aimed at applying the model developed for validation in WSS arrangements commonly found in practice.

### **Step 1. Development of the proposed model**

It consisted of the systematization and description of the entire sequence of actions to identify portions of volumes of water and consumption of electricity for the actual WSS and reference WSS. Next, formulations were set for determination of all portions of volumes of water and consumption of electricity for the actual WSS and reference WSS. Then, it was considered that the model should present values that classify the performance of each WSS unit, each WSS step (abstraction of raw water, processing and distribution) and also the overall performance, that is, for WSS as a whole. In this sense, the best way to show how the actual WSS takes distance from the reference WSS is through percentages, with each unit, each step and the same as a whole can be classified as “very poor”,

“poor”, “fair”, “good” and “excellent”, according to the service planning.

### **Step 2. Application of model for assessing water and energy losses**

The application of the model developed for validation was performed on WSS with synthetic data, because at this time there is no concern about the behavior of time series of water flows and electric power demand in WSS, only requiring consolidated data of volumes of water and consumption of electricity of the actual WSS and reference WSS, being the real WSS the target of the model developed for the hydro-energetic losses assessment in water supply systems.

## **RESULTS AND DISCUSSION**

### **Development of the proposed model for assessing water and energy losses of WSS**

As the design of hydro-energetic performance that grounded the model proposed is driven by the distance between the values of water volume and electricity consumption of the actual WSS and the values of the simulated WSS, it is necessary to collect data of water volume and electricity consumption of the two scenarios. The experience in hydro-energetic diagnosis of WSS in Brazil shows that these data can be acquired through monitoring hydraulic and electrical variables in WSS and operational simulation of WSS in Epanet 2.0. Thus, it was possible to list all the activities required to develop the proposed model, however, such activities still need to be ordinated and interconnected to identify the best sequencing, namely: a) Identification of the WSS: identification of units; b) Diagnosis of the WSS: setting the water volume necessary for the WSS, electrical, electromechanical and hydraulic registration, identification of the variables of interest, selection of monitoring points, selection of monitoring equipment, data acquisition and collection, data systematization ; identification of the operating routine and definition of opportunities for hydro-energetic improvements; c) Simulation of the reference WSS: modeling WSS in Epanet 2.0, simulation of hydro-energetic improvements to define the reference WSS, data collection relative to simulation and systematization of data; d) Hydro-energetic assessment: calculation of hydro-energetic losses, determination of WSS performance and prioritization of hydro-energetic interventions.

The developed model shows the entire process of calculation for determination of the hydro-energetic performance of WSS in the form of a block diagram based on the diagnosis of the WSS in the real scale (through the hydro-energetic monitoring) and computer simulation of the reference WSS operation (with the use of Epanet 2.0), and the initial step is related to the identification of WSS and units, as illustrated in **Fig. 1**.

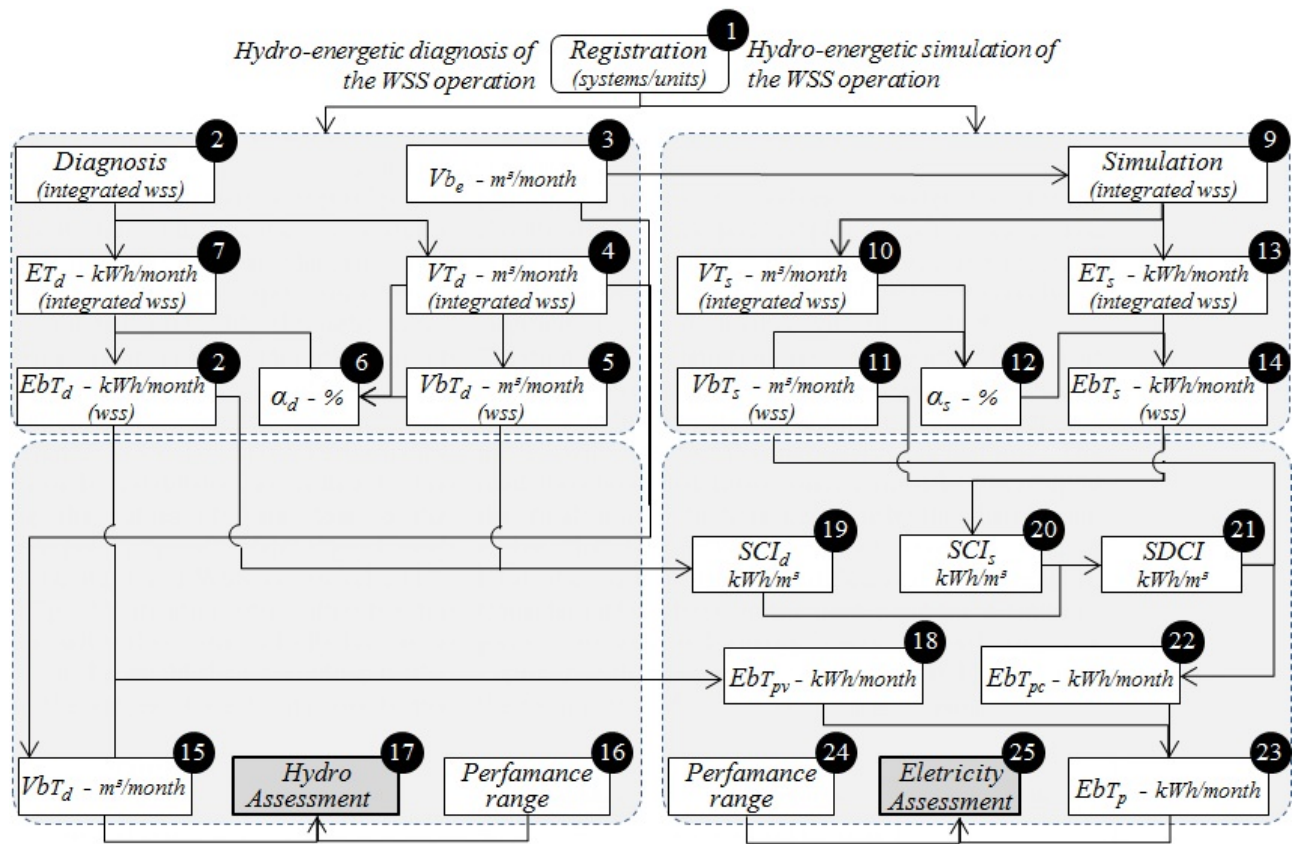


Fig. 1 Model for assessing water and energy losses, based on diagnosis and simulation of WSS.

Here are some activities (the rest is identified on notations): (1) Registration: identification of systems and units to be evaluated; (2) Diagnosis: data survey of water volumes and electricity consumption in systems and units to be evaluated, preferably through hydro-energetic monitoring as it enables identification of operational improvements for simulation; (9) Simulation: simulation of the reference WSS operation for obtaining reference WSS data; (16) Performance range for  $VbT_p$ : can be established according to the planning, aligning the values of water loss to the classifications “very poor”, “poor”, “fair”, “good” and “excellent” for units, steps and WSS as a whole; (17) Assessment of  $VbT_p$ : classification of results of water loss in accordance with the goals; 24. Performance range for  $EbT_p$ : can be established according to the planning, aligning the values of electricity loss to the

planning, aligning the values of water loss to the classifications “very poor”, “poor”, “fair”, “good” and “excellent” for units, steps and WSS as a whole; and (25) Assessment of  $EbT_p$ : classification of results of electricity loss in accordance with the goals.

The first step, registration, is very important because it is the representation of the entire sequencing of water volumes and electricity consumption that the proposed model will use for the necessary calculations. The model assumes that this sequence must be linear up to the final unit, which is necessarily the distribution sector, that is, the WSS does not have any kind of bifurcation, except those identified as import or export. Considering the above on the model and the definitions given for water and energy losses, it has been made **Table 1** with references to guide the establishment of the formulations.

Table 1. Subdivision of water and energy losses in WSS into water losses and energy losses.

Portion	Water		Electricity		Portion
	Category	Reasons	Reasons	Category	
Losses	Leak and overflow	Visible and non-visible leaks Improper operation of reservoir levels Use of excess water in the processes	Improper operation of CMB	Consumed by water loss	Losses
	Processes			Excessive consumption	
Effective		-	-	Properly consumed	Effective
	Consumption		Improper operation of CMB	Consumida em Excess	Losses

Thus, the definition of formulations for evaluation of water and energy losses should consider the portions of water flow: “*Effective for consumption*”, “*Effective for process*” and “*lost*” as well as “*Exported*” and “*Imported*”, and the sum of these values must equal the volume of water “*Total Input*” (1), for the scenario of actual WSS (2) and for reference WSS (3).

From hereafter, it will be used only the notations for the formulations of the actual WSS, but they also apply to reference WSS. In the case of units, they should be identified with indices  $i$  in the direction of water flow, where  $i = 1$  on the first unit,  $i = i_{max}$  in the distribution network (4).

For obtaining “*base volumes of water*”, those relating only to the WSS to be evaluated, it is necessary to subtract the “*Exported*” volume of water from “*Total input*” and multiply the result by the *proportionality coefficient*  $a$ . This coefficient is equal to the ratio between the volume of water entering a WSS unit and the volume of water entering the same unit for the integrated WSS, subtracting the exported volume (5), and must be also applied to the values of volumes “*Effective for process*” (6) and “*Imported*”(7).

Substituting (5), (6) and (7) into (4) results in (8), which represents portions of water volumes for the WSS to be evaluated, and finally, the approach adopted for volumes of water should be the *top-down*, so it is initiated from the distribution network unit where  $i=i_{max}$  (9) and should continue until reaching  $i = 1$ , and with  $V_{ec,d,i} = V_{T,d,(i+1)}$  for this sequence (10).

In the case of formulations for determining electricity losses, they initially obey the same idea for water losses. The “*Total consumed*” electricity in WSS (11) or its units (12) is equal to the sum of the electricity “*Effectively consumed*”, “*lost*”, “*Imported*” and “*Exported*” in the same, valid for the actual (13) and reference (14) WSS.

The model must necessarily consider that even the volume of water not lost also has a portion of energy loss, which is related to excessive consumption in operation and therefore the electricity losses are divided into energy “*Lost by volumes*” and “*Lost by*

*consumption*”. Furthermore, the proportionality coefficient is used to define only the electricity consumption relating to the WSS of the diagnosis (15) and simulation (16) scenarios.

For each WSS scenario, there is an *specific consumption indicator* of electricity and the difference between the value for the diagnosis WSS (17) and the reference WSS (18) results in the *specific consumption deficiency indicator* of electricity (19), which multiplied by “*base volume of water*”, which was not lost, results in energy “*Lost by consumption*” in diagnosis WSS (20); for the reference WSS this value is null (21).

The performance is calculated in water context by relating the water volume lost to the water volume entering the units, in the steps and in the system as a whole; in the energy scope, it is calculated by relating the lost electricity consumption to electricity consumption accumulated in the units, in the steps and in the system as a whole, and the results are shown in percentages.

Finally, the analysis of electricity loss is characterized as *bottom-up*, i.e., from  $i = 1$  towards  $i = i_{max}$ , this because the water volumes, for each unit traveled of WSS, consume successive amounts of electricity, and when lost, also result in loss of the whole sum of all electricity consumed so far. Thus, for each WSS unit, it is necessary to analyze the accumulated consumption of electricity until it and by multiplying that value by the percentage of water loss, we have the electricity “*Lost by volume*” (22). Therefore, substituting (20) and (22) in (15) and (21) and (23) in (16), we have, respectively, the equations for electricity consumption for the diagnosis WSS (24) and reference WSS (25).

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$$V_T = V_{ec} + V_p + V_{ep} + V_{imp} + V_{exp} \quad V_{Td} = V_{ecd} + V_{pd} + V_{epd} + V_{impd} + V_{expd} \tag{1}$$

$$V_{Ts} = V_{ecs} + V_{ps} + V_{eps} + V_{imps} + V_{exps} \tag{2}$$

$$V_{T,s,i} = V_{ec,s,i} + V_{p,s,i} + V_{ep,s,i} + V_{imp,s,i} + V_{exp,s,i} \tag{3}$$

$$\alpha_{d,i} = \frac{V_{Td,i} - V_{epd,i} - V_{expd,i}}{V_{Td,i} - V_{epd,i}} \tag{4}$$

$$Vb_{epd,i} = \alpha_{d,i} \times V_{epd,i} \tag{5}$$

$$Vb_{impd,i} = \alpha_{d,i} \times V_{impd,i} \tag{6}$$

$$Vb_{expd,i} = \alpha_{d,i} \times V_{expd,i} \tag{7}$$

$$Vb_{T d,i} = Vb_{ec d,i} + Vb_{p d,i} + (\alpha_{d,i} \times V_{ep d,i}) + (\alpha_{d,i} \times V_{imp d,i}) \quad (8)$$

$$Vb_{p d,i} = Vb_{T d,i} - \{Vb_{ec d,i} - [(\alpha_{d,i} \times V_{ep d,i}) - (\alpha_{d,i} \times V_{imp d,i})]\} \quad (9)$$

$$Vb_{p d,i} = Vb_{T d,i} - \{Vb_{T d,(i+1)} - [(\alpha_{d,i} \times V_{ep d,i}) - (\alpha_{d,i} \times V_{imp d,i})]\} \quad (10)$$

$$E_T = E_{ec} + E_p + E_{ep} + E_{imp} + E_{exp} \quad (11)$$

$$E_{T i} = E_{ec i} + E_{p i} + E_{ep i} + E_{imp i} + E_{exp i} \quad (12)$$

$$E_{T d,i} = E_{ec d,i} + E_{p d,i} + E_{ep d,i} + E_{imp d,i} + E_{exp d,i} \quad (13)$$

$$E_{T s,i} = E_{ec s,i} + E_{p s,i} + E_{ep s,i} + E_{imp s,i} + E_{exp s,i} \quad (14)$$

$$Eb_{T d,i} = (\alpha_{d,i} \times E_{ec d,i}) + E_{pc d,i} + Eb_{pv d,i} + Eb_{ep d,i} + Eb_{imp d,i} \quad (15)$$

$$Eb_{T s,i} = (\alpha_{s,i} \times E_{ec s,i}) + E_{pc s,i} + Eb_{pv s,i} + Eb_{ep s,i} + Eb_{imp s,i} \quad (16)$$

$$ICE_{d,i} = \frac{E_{T d,i} - E_{imp d,i}}{V_{T d,i}} \quad (17)$$

$$ICE_{s,i} = \frac{E_{T s,i} - E_{imp s,i}}{V_{T s,i}} \quad (18)$$

$$IDCE_i = ICE_{d,i} - ICE_{s,i} \quad (19)$$

$$Eb_{pc d,i} = [IDCE_{d,i} \times (Vb_{ec d,i} + Vb_{ep d,i})] \quad (20)$$

$$Eb_{pc d,i} = 0 \quad (21)$$

$$Eb_{pv d,i} = \left[ \left( \frac{Vb_{p d,i}}{Vb_{T d,i}} \right) \times \sum_{i=1}^{i=i_{max}} Eb_{T d,i} \right] \quad (22)$$

$$Eb_{pv s,i} = \left[ \left( \frac{Vb_{p s,i}}{Vb_{T s,i}} \right) \times \sum_{i=1}^{i=i_{max}} Eb_{T s,i} \right] \quad (23)$$

$$\sum_{i=1}^{i=i_{max}} Eb_{T d,i} = \{ \alpha_{s,i} \times E_{ec s,i} \} + \left\{ [IDCE_{d,i} \times (Vb_{ec d,i} + Vb_{ep d,i})] + \left[ \left( \frac{Vb_{p d,i}}{Vb_{T d,i}} \right) \times \sum_{i=1}^{i=i_{max}} Eb_{T d,i} \right] \right\} + \sum_{i=1}^{i=i_{max}} Eb_{ep d,i} + \sum_{i=1}^{i=i_{max}} Eb_{imp d,i} \quad (24)$$

$$\sum_{i=1}^{i=i_{max}} Eb_{T s,i} = \{ \alpha_{s,i} \times E_{ec s,i} \} + \left\{ \left[ \left( \frac{Vb_{p s,i}}{Vb_{T s,i}} \right) \times \sum_{i=1}^{i=i_{max}} Eb_{T s,i} \right] \right\} + \sum_{i=1}^{i=i_{max}} Eb_{ep s,i} + \sum_{i=1}^{i=i_{max}} Eb_{imp s,i} \quad (25)$$

### Application of the proposed model for assessing water and energy losses of WSS

For application of the proposed model, it will be used the integrated WSS with synthetic data on volumes of water and consumption of electricity shown in **Fig. 2**, with a focus on WSS1. The results of steps 1 and 2 are presented, respectively, in **Tables 2** and **3**, in which it can be registered the distance between the values of diagnosis WSS and reference WSS. Along the sequence of units, there was a decrease in the volumes of water, which, represent increasingly higher amounts of energy

consumed due to the accumulation proposed. In addition, the measures of simulated improvements for WSS operation efficiency demonstrated a high potential for reducing losses of water and consumption of electricity, thus decreasing the proportionality coefficient from 64.30% to 50.00%.

The results of steps 1 and 2 of the model proposed support the idea that even a small increase in efficiency of the pumping operation can result in significant savings of electricity (Giustolisi *et al.*, 2012). Nevertheless, there is great difficulty in modeling WSS operational optimization problems, because it includes

discrete and continuous variables, incorporates closed loop networks and temporary coupling over the planning horizon (Burgschweiger *et al.*, 2009). Furthermore, optimization is often impractical due to lack of data and conditions for its implementation (Rodríguez, 2012), mainly because most systems do not have a fixed infrastructure of water and energy monitoring, which do not indicate the operational performance (Ahonen *et al.*, 2012). Thus, it must be emphasized the role of computer simulation for operational improvements, which becomes fundamental for the proposed model.

In step 3, water losses were calculated for WSS1, which were classified according to the goals set out in Table 4. The goals are divided into values for local

assessment, step assessment and global assessment, and it is important to distinguish the values that contain the WDNs, as they are units that have values much higher than the others. The results of the model for hydro-energetic assessment of WSS show that despite the excellent scenario for water losses in some units, when grouped into step and global, they present a very poor classification, as seen in Table 5.

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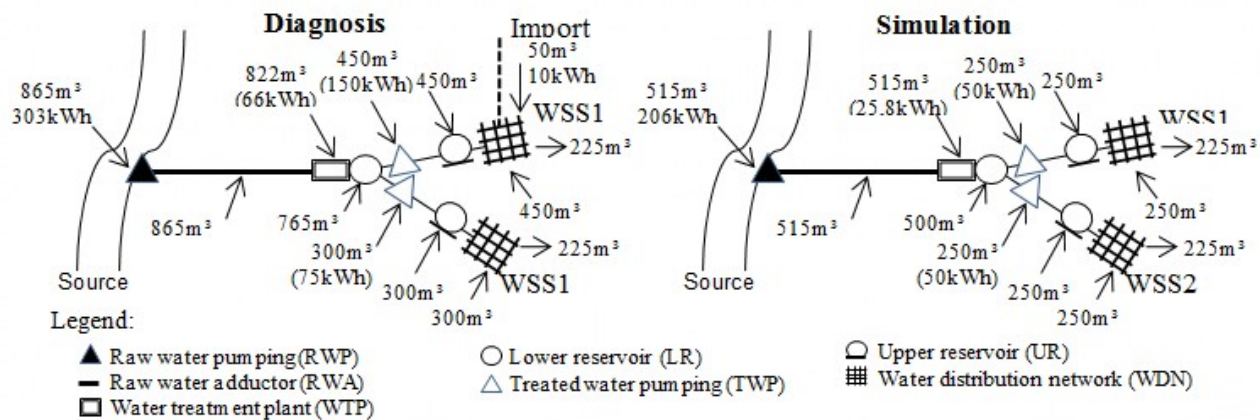


Fig. 2 Guide the establishment of the formulations.

Table 2. Base volume of water and base consumption of electricity for WSS 1 diagnosed.

Diagnosis	Id.	$V_{Td,i} - V_{impd,i}$	$V_{epd,i}$	$V_{impd,i}(+) - V_{expd,i}(-)$	$\alpha_{d,i}(\%)$	$V_{bTd,i}$	$ET_{d,i} - E_{impd,i}$	$E_{impd,i}(+) - E_{expd,i}(-)$	$E_{bTd,i}$	$\Sigma E_{bTd,i}$
RWP	1	865.00	0.00	0.00	64.30	555.71	303.00	0.00	195.00	195.00
RWA	2	865.00	0.00	0.00	64.30	555.71	0.00	0.00	0.00	195.00
WTP	3	822.00	24.70	0.00	62.37	512.71	66.00	0.00	41.00	236.00
LR	4	765.00	0.00	-300.00	60.78	465.00	0.00	0.00	0.00	236.00
TWP	5	450.00	0.00	0.00	100.00	450.00	150.00	0.00	150.00	386.00
UR	6	450.00	0.00	0.00	100.00	450.00	0.00	10	0.00	386.00
WDN	7	450.00	0.00	50.00	100.00	500.00	0.00	0.00	10.00	396.00
Consumed	-	225.00	-	-	-	-	-	-	-	-

Table 3: Base volume of water and base consumption of electricity for WSS 1 simulated.

Simulation	Id.	$V_{Ts,i} - V_{imps,i}$	$V_{eps,i}$	$V_{imps,i}(+) - V_{exps,i}(-)$	$\alpha_{s,i}(\%)$	$V_{bTs,i}$	$ET_{s,i} - E_{imps,i}$	$E_{imps,i}(+) - E_{exps,i}(-)$	$E_{bTs,i}$	$\Sigma E_{bTs,i}$
RWP	1	515.47	0.00	0.00	50.00	257.74	103.00	0.00	51.50	51.50
RWA	2	515.47	0.00	0.00	50.00	257.74	0.00	0.00	0.00	51.50
WTP	3	515.47	15.47	0.00	50.00	257.74	13.00	0.00	6.50	58.00
LR	4	500.00	0.00	-250.00	50.00	250.00	0.00	0.00	0.00	58.00
TWP	5	250.00	0.00	0.00	100.00	250.00	50.00	0.00	50.00	108.00
UR	6	250.00	0.00	0.00	100.00	250.00	0.00	0.00	0.00	108.00
WDN	7	250.00	0.00	0.00	100.00	250.00	0.00	0.00	0.00	108.00
Consumed	-	225.00	-	-	-	-	-	-	-	-



**Table 4.** Classes of water volume loss.

Assessment		Excellent (up to)	Good (up to)	Fair (up to)	Poor (up to)	Very poor (higher than)
Location	WDN	15%	20%	25%	30%	50%
	Other units	2%	3%	4%	5%	6%
Step	Obtaining	2%	3%	4%	5%	6%
	Processing	2%	3%	4%	5%	6%
	Distribution	15%	20%	25%	30%	50%
Global	Entire system	15%	20%	25%	30%	50%

**Table 5.** Performance assessment of water volumes of WSS 1.

Assessment	Id.	Location	Step	Global	Location	Step	Global	Location	Step	Global
RWP	1	0.00	43.00		0.00%	7.74%		Excellent	Very poor	
RWA	2	43.00			7.74%			Very poor		
WTP	3	32.30	47.30		6.30%	9.23%		Very poor	Very poor	
LR	4	15.00		365.30	3.23%		65.74%	Fair		Very poor
TWP	5	0.00			0.00%			Excellent		
UR	6	0.00	275.00		0.00%	61.11%		Excellent	Very poor	
WDN	7	275.00			55.00%			Very poor		

discrete and continuous variables, incorporates closed loop networks and temporary coupling over the planning horizon (Burgschweiger *et al.*, 2009). Furthermore, optimization is often impractical due to lack of data and conditions for its implementation (Rodríguez, 2012), mainly because most systems do not have a fixed infrastructure of water and energy monitoring, which do not indicate the operational performance (Ahonen *et al.*, 2012). Thus, it must be emphasized the role of computer simulation for operational improvements, which becomes fundamental for the proposed model. In step 3, water losses were calculated for WSS1, which were classified according to the goals set out in **Table 4**. The goals are divided into values for local assessment, step assessment and global assessment, and it is important to distinguish the values that contain the WDNs, as they are units that have values much higher than the others. The results of the model for hydro-energetic assessment of WSS show that despite the excellent scenario for water losses in some units, when grouped into step and global, they present a very poor classification, as seen in **Table 5**.

With knowledge of water losses, starts to step 4 by calculating the electricity losses related to lost volumes of water and by calculating the excess electricity consumed in the units, and the sum of these values is equal to the total amount of energy lost and, at that time, it was verified the importance of the proposed model. It

could be identified electricity losses in units in which there is no consumption and even units considered as *excellent* from the water perspective can have high levels of electricity losses, mainly the initial units, as they have the greatest values of water input, as observed in **Table 6**. The goals of classification for electricity losses have met previous guidance for water losses in relation to the WDNs, but for the other units, there were no specific studies identifying standard values. The alternatives applicable to energy efficiency in conventional water supply systems are mastered technologies widely reported in the literature (Vilanova and Balestieri 2014). Energy savings can vary, for example, from 10% to 50% from control and optimized operation strategies, based on data from SCADA systems, and reach up to 70% with the use of frequency inverters instead of valve bottlenecks (New York State 2010; Jamieson *et al.*, 2007; Zhang *et al.*, 2012). In this way, it was initially opted for low levels of electricity losses for other units and groups that do not consider the WDNs, as listed in **Table 7** In addition, almost all units of WSS were classified as *very poor*, except the two reservoirs, as well as the units RWP and TWP, although they were classified as *excellent* from the water perspective, they were classified as *very poor*, demonstrating the systemic perception of the model proposed, as shown in **Table 8**.

**Table 6.** Calculation of lost electricity consumption loss in WSS 1.

Losses	Id.	$\sum EbT_{d,i}$	$a_{d,i}$ (%)	$Eb_{pv_{d,i}}$	$SCI_{d,i}$	$SCI_{s,i}$	$SCDI_i$	$Vb_{ec+ep}$	$Eb_{pc_{d,i}}$	$Eb_{d,i}$
RWP	1	195.00	0.00	0.00	0.35	0.20	-0.15	240.41	84.00	84.00
RWA	2	195.00	7.74	15.00	0.00	0.00	0.00	240.41	0.00	15.00
WTP	3	236.00	6.30	15.00	0.08	0.03	-0.06	240.41	26.00	41.00
LR	4	236.00	3.23	8.00	0.00	0.00	0.00	225.00	0.00	8.00
TWP	5	386.00	0.00	0.00	0.33	0.20	-0.13	225.00	60.00	60.00
UR	6	386.00	0.00	0.00	0.00	0.00	0.00	225.00	0.00	0.00
WDN	7	396.00	55.00	218.00	0.00	0.00	0.00	225.00	0.00	218.00

**Table 7.** Classes of electricity loss.

Assessment		Excellent (up to)	Good (up to)	Fair (up to)	Poor (up to)	Very poor (higher than)
Location	WDN	15%	20%	25%	30%	50%
	Other units	2%	3%	4%	5%	6%
Step	Obtaining	2%	3%	4%	5%	6%
	Processing	2%	3%	4%	5%	6%
	Distribution	15%	20%	25%	30%	50%
Global	Entire system	15%	20%	25%	30%	50%

**Table 8.** Performance assessment of electricity consumption of WSS 1.

Assessment	Id.	Location	Step	Global	Location	Step	Global	Location	Step	Global
RWP	1	36.17	51.25		18.57%	26.31%		V. poor	V. poor	
RWA	2	15.08			7.74%			V. poor		
WTP	3	28.11	35.72		11.91%	15.14%		V. poor	V. poor	
LR	4	7.61		334.76	3.23%		84.54%	Fair		V. poor
TWP	5	30.00			7.77%			V. poor		
UR	6	0.00	247.79		0.00%	62.58%		Excellent	V. poor	
WDN	7	217.79			55.00%			V. poor		

Finally, another important aspect to note is that all the values for the actual WSS should be displayed for comparison with the calculated values also for the reference WSS, enabling the visualization of the distance between them and the decision-making regarding corrective actions in the short, medium and long term to improve the hydro-energetic performance of WSS at the systemic level, making it more sustainable socially (improvement in the quality of service), environmentally (mitigation of direct or indirect negative impacts of the chain of production, processing and distribution of water on the environment) and economically (reduction of expenses and revenue enhancement).

**CONCLUSIONS**

The assessment of WSS required new perspectives beyond the classic emphasis on water resources, especially given the emergence of environmental challenges, in which energy issues are embedded. The systemic approach has provided new horizons for the WSS performance concept, by identifying and focusing on the close relationship between water and energy, which is characterized as the main source of reduction of expenses in WSS. Accordingly, the model proposed for hydro-energetic assessment of WSS was considered quite effective for its potential application to practical cases of WSS in any setting, because of the water volume and electricity consumption lines, the need of punctual measurements of hydraulic and electrical variables and mainly the presentation of a reference scenario, which becomes the target of WSS planning and management. The presentation of performance in percentage values facilitated understanding in all decision-making levels (operational, tactical and strategic), and the lower the value of losses, the closer the WSS to its reference scenario and the better its

performance. Lastly, it has to be mentioned that the application of the model to real cases is in the final stages and the results obtained are quite important and promising, including the possibility of including financial aspects to the model.

**ACKNOWLEDGEMENTS**

Current assay comprises results of the project “Development of technologies in management and costs control which optimize water and electric energy consumption in water supply urban system” funded by the Financiadora de Estudos e Projetos (FINEP, Brazil). The first author would like to thank the Coordination for the Improvement of Higher Education Personnel (Capes) for the doctoral scholarship.

**NOTATIONS**

$V_{be}$  = Effective volume of water consumed: effective volume in each unit of the WSS and integrated WSS.  
 $V_{Td}$  = Volume diagnosed of water: volume entering each unit of the integrated WSS;  
 $V_{bTd}$  = Base volume diagnosed of water: volume entering each unit referring to the WSS;  
 $\alpha_d$  = Proportionality coefficient of diagnosis: applied to certain values of the integrated WSS for obtaining values of WSS in the diagnosis.  
 $E_{Td}$  = Diagnosed consumption of electricity: consumption referring to  $V_{Td}$  (integrated WSS);  
 $E_{bTd}$  = Base consumption diagnosed of electricity: consumption referring to  $V_{bTd}$  (WSS);  
 $V_{Ts}$  = Simulated water volume: volume entering each unit of the integrated WSS;  
 $V_{bTs}$  = Base volume simulated of water: volume entering each unit of the WSS;  
 $\alpha_s$  = Proportionality simulated coefficient: applied to certain values of the integrated WSS for obtaining values of WSS in the simulation.

$E_{Ts}$  = Simulated consumption of electricity: consumption referring to  $V_s$  (integrated WSS);

$E_{bTs}$  = Base consumption simulated of electricity: consumption referring to  $Vb_s$  (WSS);

$V_p$  = Lost volume of water: volume lost in the integrated WSS;

$Vb_p$  = Lost base volume of water: volume lost in the WSS;

$E_{pv}$  = Base electricity lost by volume: amount of electricity consumed by  $V_p$ ;

$E_{b_{pv}}$  = Electricity lost by volume: amount of electricity consumed by  $Vb_p$ ;

$SCI_d$  = Specific consumption indicator diagnosed: represents the amount of electricity consumed per cubic meter of water entering units of WSS in the diagnosis;

$SCI_s$  = Specific consumption indicator simulated: represents the amount of electricity consumed per cubic meter of water entering units of WSS in the simulation;

$SCDI$  = Specific consumption deficiency indicator: difference between  $SCI_d$  and  $SCI_s$ , represents the deficiency in consumption of electricity per cubic meter entering each unit of the WSS;

$E_{pc}$  = Electricity lost by excessive consumption: amount of electricity excessively consumed referring to water volumes not lost in the integrated WSS;

$E_{b_{pc}}$  = Base electricity lost by excessive consumption: amount of electricity excessively consumed referring to water volumes not lost in the WSS;

$E_p$  = Lost electricity: total amount of electricity lost in the integrated WSS;

$E_{b_p}$  = Lost electricity: total amount of electricity lost in the WSS.

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