Water loss control practices in developing countries: a case study of a Brazilian region

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ABSTRACT

The control of water loss in distribution systems has been highlighted in multiple discussions in the field of water and sanitation. However, there are few scientific studies on this topic that have focussed on loss control performance in developing countries. With the intention to expand the limited scientific framework investigating the management of water losses in economic scarcity scenarios, this paper provides an overview of which practices directed to water loss control are being conducted in a Brazilian region. Data were collected from 42 water utilities and show there is a direct relationship between the utilities' performances and the number of water loss practices adopted. The divergences in the number of practices applied by the water utilities may be influenced by technical–operational, planning and management factors. The paper brings greater robustness to the loss management debates in regions with economic scarcity, being able to support the action of utilities operating in similar scenarios.

Key words | management of water loss, non-revenue water, urban water services

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HIGHLIGHTS

- The mix of practices in water loss control is substantial for superior utilities performance.
- A relationship between water utilities' performances and number of water loss control practices applied is observed.
- Factors that influence water loss control are discussed.
- A greater robustness to debates of loss management in developing countries is provided.

INTRODUCTION

Within the urban cycle of water, the current discussions in the sanitation sector highlight a universal phenomenon: the urgency to reduce water loss levels in the distribution systems due to water scarcity, which has affected several cities in recent decades (Delgado-Galván *et al.* 2010; Lin *et al.* 2015; Molinos-Senante *et al.* 2016). According to Liemberger & Wyatt (2019), the global volume of Non-Revenue Water (NRW) has been calculated to be 346 million m^3/day and in the context of Latin America and the Caribbean region, Brazil has the highest NRW level. In part, this problem is associated with the lack of focus on the use of financial resources in maintenance and modernization of the sanitation sector in these regions. This issue has generated a series of inefficiency, aggravating economic and financial problems, high pressure on natural, public health and social resources that, in general, compromise the financial health and quality of service provision of utilities (Mutikanga *et al.* 2013).

In this sense, controlling water losses is seen as key to sustainable water management and one of the main challenges facing the diversity of control actions (Frauendorfer & Liemberger 2010; Van den Berg 2015; Zyoud *et al.* 2016).

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For Alegre & Coelho (2012), water utilities should adopt a set of processes that ensure that their performance meets service goals over time, that risks are adequately managed and that costs are as low as possible. The tools and methods for control, aimed at real or apparent losses, are diverse and they range from simpler actions to more complex and sophisticated practices that require large investments by the supply system utilities (Mutikanga *et al.* 2013).

Thus, given the scarcity of resources in developing regions and the diversity of control actions, studies mapping control practices commonly applied by utilities in these regions are important to understand how the fight against losses has been conducted in developing country scenarios, supporting other similar countries to define which practices can be applied generating efficient results in controlling water losses. However, there are still few scientific studies on this topic that focus on an integrated way on identifying practices and loss control performance in developing countries, such as those conducted by Mutikanga (2012) and Makaya (2015).

With the intention of expanding the research framework on this topic, this article presents the case study of the Piracicaba, Capivari and Jundiaí River Basins (PCJ Basins), which, in the panorama of the Southeastern region of Brazil, stands out for their focus on controlling the water loss. The mapping of the practices adopted by utilities in the study area shows what has been conducted to control water loss in scenarios of financial scarcity, creating the possibility to subsidize and guide the actions of others that fit into a Brazilian socioeconomic and technological context.

METHODOLOGY

The study was structured in three stages. The first stage included the bibliographic review of 255 documents, including scientific articles, books, guides, and reports aimed at identifying the main practices used at water loss control. Table 1 presents the practices identified in the literature (54 in total), which were organized into eight control macro processes, based on the macro actions presented by Thornton *et al.* (2008). These, in turn, composed the data collection questionnaire (step 2), prepared for the purpose of the case study, step 3.

Survey questionnaire and data collection

The data collection questionnaire was structured based on the 54 practices presented in Table 1. For each practice, a question was formulated to identify if the utility adopted, partially (This option of response was only applicable to P7, P9 and P17. For the data analysis the cases of 'partially adopted' has been considered as 'not', considering that the practices is not completely adopted.) adopted or not the practice. For the questionnaire application, the key functions of the utilities were previously identified, in a way that the respondent could master the organization's management process of water loss. Based on the structured questionnaire and the key functions identified, a survey was conducted, on site and for some cases online, with the water utilities of the municipalities that composed the case study, presented below.

Case study – control practices in the PCJ basins

With an area of 15.377 km², the PCJ Basins are formed by three hydrographic basins: Piracicaba, Capivari and Jundiaí, which encompass 76 municipalities, totally and partially inserted, with approximately 5.8 million inhabitants (Figure 1). The region is highlighted as an object of study because of the strong commitment of the Basin Committees to direct resources to reduce water losses, whose average among the analyzed utilities is equivalent to 237 liters/connection/day. The management of losses is one of the strategies to reduce water demand in the region, whose water availability is critical. It is estimated that until 2035 US$ 8.02 million will be invested to address the major problems of water losses in the basins. The Agency Foundation of Basins PCJ, an entity that supports the execution of projects in the scope of the river basins under analysis, has invested, from 1994 to 2019, approximately US$ 36.7 million.

Among the 76 cities that are part of the PCJ Basins, there was a response from utilities located in 42 of them. Considering the management model of the utilities responsible for municipal sanitation, there is a predominance of mixed economy institutions (65%), followed

Table 1 | Analyzed loss control practices

Practices of water loss control	
Pressure Management	P1. Use of pressure gauges and monitoring network pressures. P2. Telecontrol center to monitor pressures in the network. P3. Using pressure reducing valves. P4. Reduction of water pressure at night. P5. Average network pressure according to NBR 12218/1994 (100 kPa (10 mH_2O) dynamic pressure and 500 kPa (50 mH_2O) static pressure). P6. Automated tanks.
Infrastructural management	P7. Replacement of old building extensions. P8. Macro measurement. P9. Geo-referenced register of pipelines. P10. Annual network maintenance plan (Cleaning/Rehabilitation). P11. Quality control of materials and equipment used in network maintenance. P12. Establishment of standard operational procedures. P13. Periodical calibration of network equipment (gauges, valves). P14. Training for the maintenance and operation team (Certification).
Pipe corrosion control	P15. Internal pipe coating. P16. External pipe coating. P17. Prioritizing the use of non-metallic piping.
Leak control	P18. Use of ground listening devices to detect non-visible leaks. P19. Defining the best frequency for finding leaks. P20. Full-time team to repair the leaks. P21. Use of computer/mathematical simulation models for leakage detection. P22. Use of zero consumption method to detect non-visible leaks. P23. Use of the minimum overnight consumption method to detect non-visible leaks. P24. Organizing the system in measurement zones (sectorization, MCD). P25. Exclusive team for 'leak hunting'. P26. Watertightness test using hydrometers. P27. Communication channel for the user to alert about leaks in the streets (visible).
Measurement error control	P28. Corrective exchange of hydrometers. P29. Optimized preventive exchange of hydrometers. P30. Supervision of hydrometers to verify measurement errors. P31. Use of more accurate hydrometers. P32. Use of hydrometers with radio frequency telemetry. P33. Proper training of hydrometers reading team.
Control of fraud and clandestine connections	P34. Public awareness of the problem concerning fraud and clandestine connections. P35. Regular inspection of suspicious and inactive connections. P36. Repair of sloping hydrometers. P37. Use of technology to detect clandestine connections. P38. Monitoring users' monthly consumption to detect fraud. P39. Acting in areas of poverty to control fraud. P40. Reports of fraud by the community. P41. Annual update of user registration.
Strategic Planning	P42. Establishing a plan/program to fight water losses. P43. Definition of a loss reduction target. P44. Specific department/section of the organization focused on loss control. P45. Diagnosis of the loss situation in the city. P46. Use of indicators to evaluate loss control performance. P47. Development of studies to prioritize the most critical areas for loss control. P48. Cost benefit analysis for loss control actions. P49. Periodic meeting to analyze the results of the control actions and to plan the consecutive ones.
Investment and Innovation	P50. Investing in loss control technologies. P51. Implementation of continuous improvement methodologies. P52. Investing in training courses for staff aimed at loss control. P53. Use of GIS in loss control assistance. P54. Investing in the development of loss management manuals.

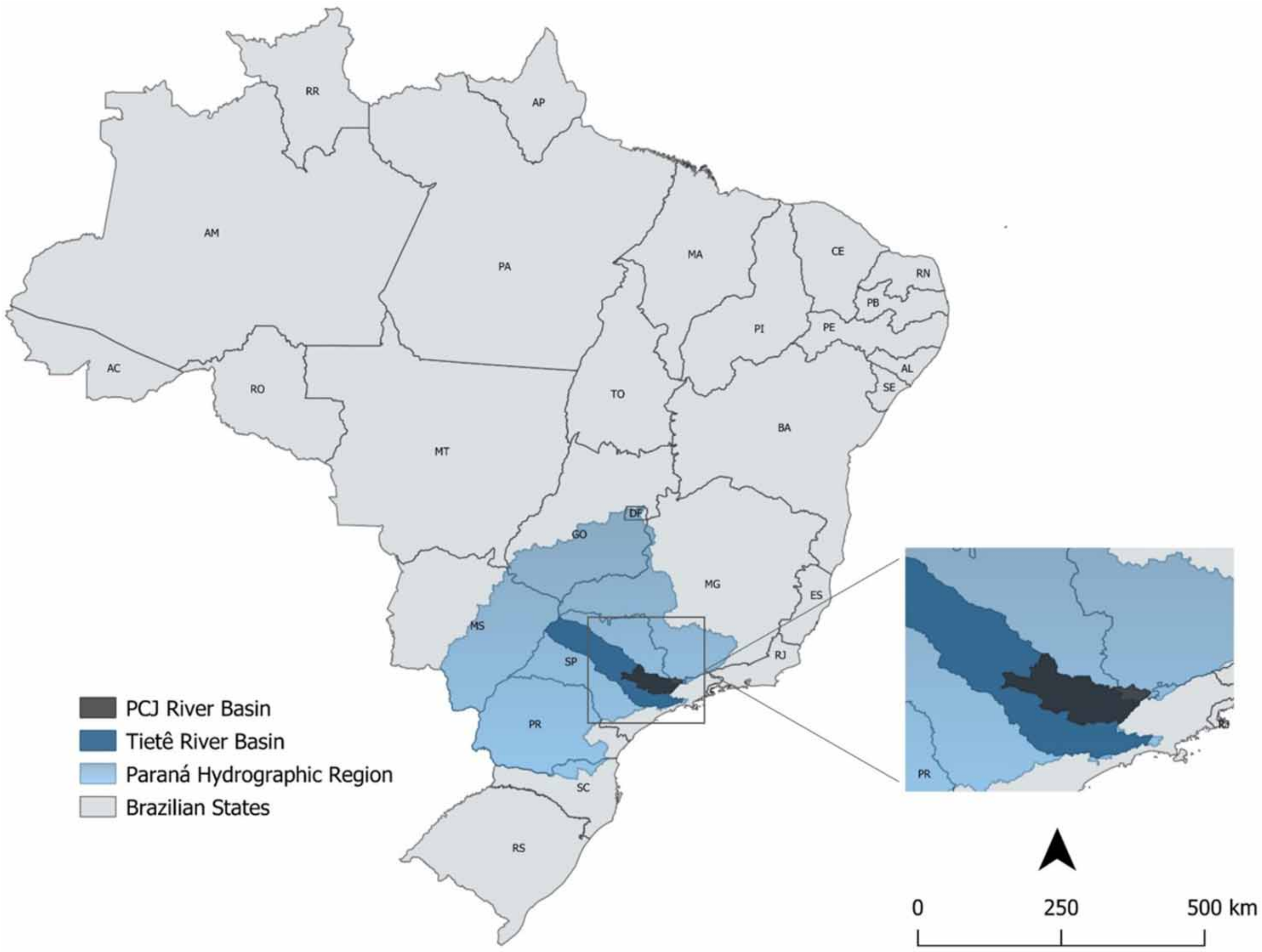

Figure 1 | Location of the PCJ Basins.

by local government (21%), private concessionaires (7%) and direct public administration (4%), where the municipal government is responsible for sanitation management. The average water loss data show that private concessionaires perform better, with less water losses, while local government shows the highest levels of water losses.

In order to analyze the application level of control practices considering utilities' performance, they were categorized into five performance groups (A1, A2, B, C and D) (Figure 2), following the classes for low and medium development countries of the International NRW Assessment Matrix (Table 2) (Liemberger 2010). Figure 2 also illustrates the prevalent management model in each performance group.

RESULTS AND DISCUSSION

The condensed percentage of utilities applying the practices under study, in each performance category and for each practice, are displayed on the graph in Figure 3. It is analyzed that the more points near the axis (0), for each group, the lower is the level of employment of practices by the group. The distribution of data for groups A1 and A2 is practically similar and indicates that there is a greater level of control practices, ranging from 80 to 100% of the utilities that apply the practices. Conversely, it can be seen that as performance categories get closer to the level considered inferior (B, C and D) there is a bigger proportion of points close to the center (0), what suggests less applicability of practices by utilities of these groups.

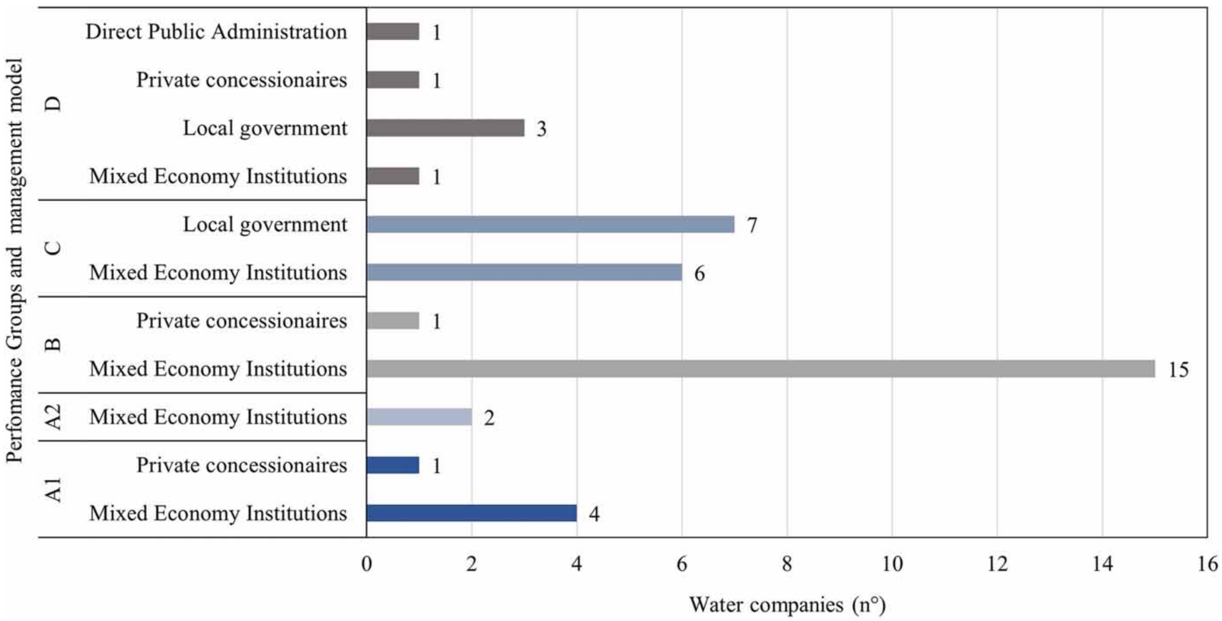

Figure 2 | Number of utilities in the study area by performance group, according to Table 2, and management model.

Table 2 | International Non-revenue Water Assessment Matrix

NRW management performance category		**Non-revenue water in liters/connection/day When the system is pressurized at an average pressure of:** 10 m	20 m	30 m	40 m	50 m
High income countries	A1		<50	<65	<75	<85
	A2		50–100	65–125	75–150	85–175
	B		100–200	125–250	150–300	175–350
	C		200–350	250–450	300–500	350–650
	D		>350	>450	>550	>650
Low and middle income countries	A1	<55	<80	<105	<130	<155
	A2	55–110	80–160	105–210	130–260	155–310
	B	110–220	160–320	210–420	260–520	310–620
	C	220–400	320–600	420–800	520–1,000	620–1,200
	D	>400	>600	>800	>1,000	>1,200

The data presented in Figure 3 demonstrate that, although all utilities analyzed fit into a similar national economic context of development, there are considerable differences in the levels of practices application among the groups, especially between groups A1 and D. In front of this evidence, this study proposed to examine in detail which are the practices that present great discrepancies of applicability between the groups mentioned, allowing the analysis of possible factors related to the occurrence of differences in the levels of application of the practices. From this perspective, Figures 4 and 5 show the distribution of practices for groups A1 and D, respectively. The red lines outlined in Figures 4 and 5 delimit the practices that compose each macro-process of water loss control, previously described in Table 1.

The data gathered in the graphs show there is a high level of control-oriented applicability by utilities categorized as superior performance (A1) in all control processes (Figure 4). Conversely, for the group of utilities with inferior-performance (D), a variation in the practices applicability is visualized, for each process (Figure 5), presenting practices with high level of applicability and others with low employment, as also visualized in Figure 3, where there are several points near the 0 axis.

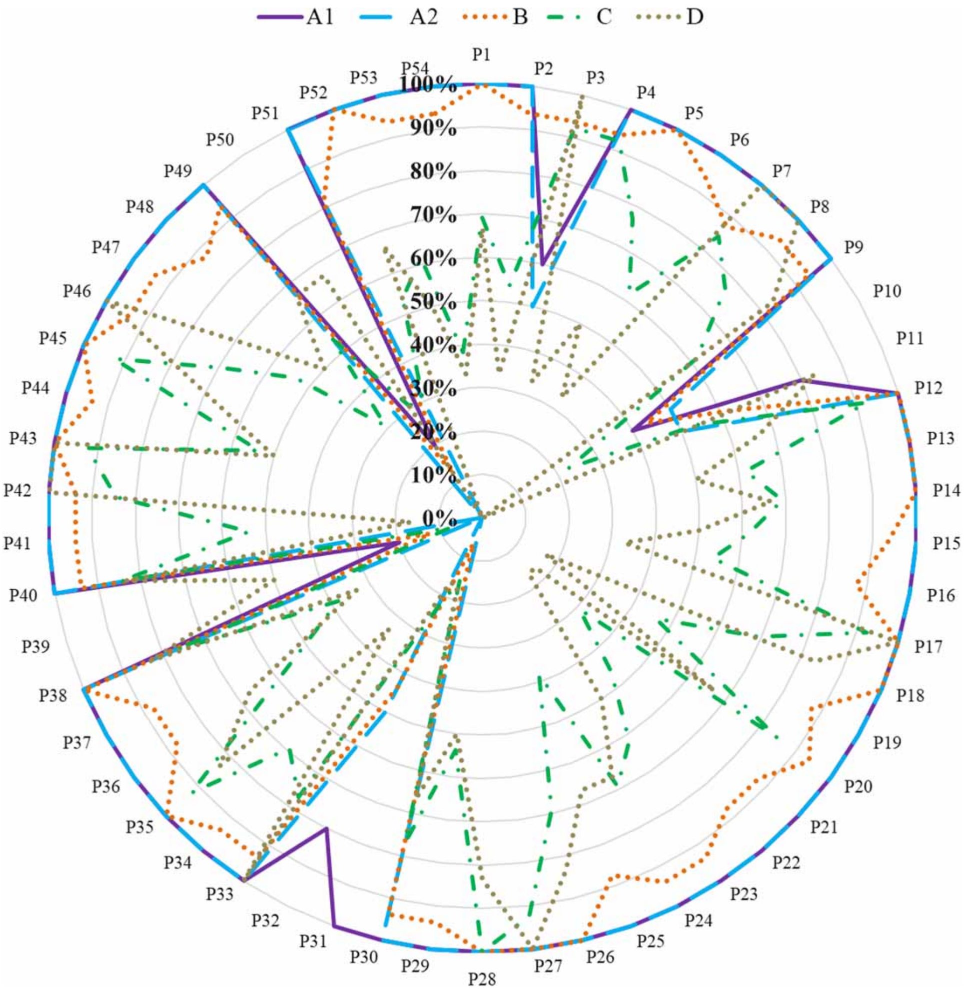

Figure 3 | Application of control practices by performance groups.

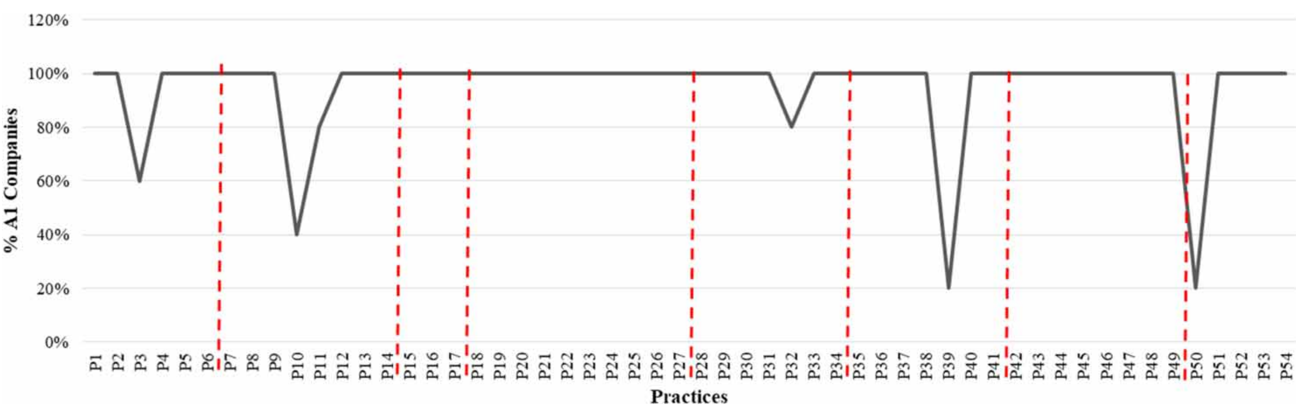

Figure 4 | Control practices proportion of the A1 utility group.

Before discussing in detail each practices of losses controlling process, it should be noted that the level of practices application can be influenced by technical–operational factors, as well as by environmental, economic, social and corporate governance issues, as evidenced by Lai *et al.* (2020). In the context of corporate governance, it is

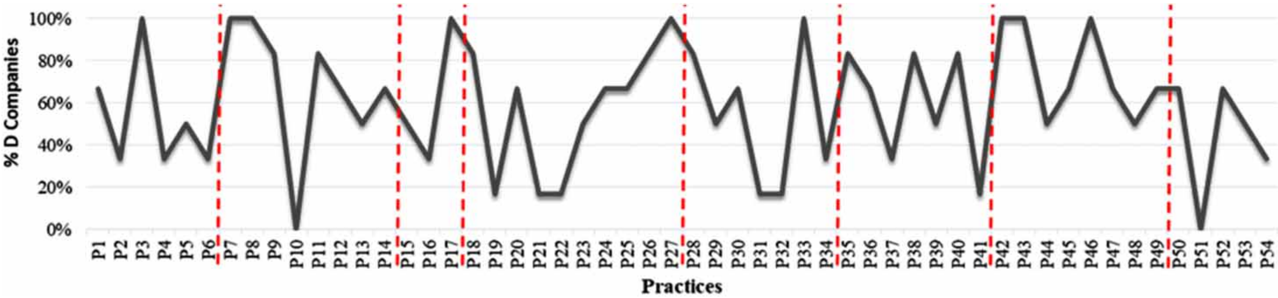

Figure 5 | Control practices proportion of the D utility group.

fundamental to consider the management model of sanitation companies and the factors inherent to these models, which influence, in different proportions, the processes of performance improvement of the entities.

Faced with these assertions, it is analyzed that the utilities of group A1 are managed in a mostly mixed economy model, while the utilities of category D are, in a larger proportion, local government. The legal nature and the different management models of the utilities are directly linked to its investment capacity, whether for the acquisition of maintenance equipment or strategic planning actions. From this perspective, the combination of public and private capital encourages investments in the mixed economy management model. On the other side, the local government, despite having administrative autonomy, present budgetary restrictions that make it harder for the entity to invest in improvement actions.

Therefore, it can be seen from the overview in Figure 4 that 88% of water loss control practices are practiced by all cases in group A1. This aspect shows that the mix of practices in loss control is substantial in the search for good performance and reduction of water loss levels, as also evidenced by Naik & Glickfeld (2017).

Following the same approach of the presented processes of water loss control in Table 1, it is verified, by the frequency of 'Pressure Management' practices (P1-P6), that one of the least used practices by group A1, P3, (Figure 4) is one of the most applied practices by group D (Figure 5). This practice focuses on the use of pressure reducing valves (PRVs), which, even though it is pointed out as essential for the correct operation of the system and reduction of operating costs (García-Todolí Iglesias-Rey & Martínez-Solano 2017), has its use conditioned to the system's need to reduce water pressure in the networks. From this perspective, the discrepancies in the applicability of this practice are attributed to operational aspects of the supply systems. In some cases PRVs are not necessary, because the water pressure in the network remains constant all the time, either due to the influence of the local topography or other factors (cases in group A1) while in other situations they are fundamental to control water pressure oscillations in the distribution network (higher proportion of cases in group D).

Regarding the controlling practices of Process 2 'Infrastructure Management' (P7–P14), Figures 4 and 5 show that P10 is the least used practice by the two groups of utilities analyzed. The low use of this practice, which foresees the existence of a network maintenance plan (cleaning and rehabilitation), may compromise control of water losses since, as commented by Thornton *et al.* (2008), all the components of a water system reach their useful life, being unquestionably the establishment of a plan that programs the maintenance or replacement of assets so that they can continue to provide quality services.

Moreover, still in the scope of infrastructure management practices, the most practiced actions by group D (P7 and P8) have a frequency of 100% in the group of A1 utilities. These practices, highly used by the two groups, provide the replacement of old building extensions (P7) and the use of macrometers for mapping water flows in the network (P8). Moreover, they are, respectively, essential to control leaks and to monitor the volume made available and consumed, what makes it possible to calculate the volume of water actually lost in the systems, thus directing the strategic planning of control actions.

Among the practices that support corrosion control in water pipelines (P15–P17), it is noted, as illustrated in Figures 4 and 5, that 100% of the utilities in category A1 employ the practices analyzed, while in group D, P17, which addresses the preventive use of external structures to protect the pipes, is the most applied. According to Li *et al.* (2016), corrosion in pipelines generates disadvantages both in technical and economic terms. An example of a disadvantage is the generation of public health problems, what increases network maintenance costs, thus reinforcing the importance of adopting practices of this kind

Therefore, in view of the low use of corrosion control practices by group D utilities, the Agency Foundation of Basins PCJ has established contracts, with a financial institution, to support the exchange of water networks in critical points of some municipalities that fall into group D, seeking to raise their standards.

Regarding the leakage control and detection practices (Process 4), it can be seen from Figures 4 and 5 that the use of these practices in group A1 is unanimous, while in group D, there is an oscillation in the applicability of the practices, being P27 (existence of a communication channel for leakage alert) the only practice applied by all utilities in the second group. The practices P19, P21 and P22 are applied in a lower proportion by utilities D, less than 50%. Except for the advantages, already evidenced in studies (i.e. Rogers 2014; Soldevila *et al.* 2016; Parra *et al.* 2018), on the use of hydraulic models in the simulation and prevention of network leakage (P21), the low applicability of this tool may be associated with technical–operational factors, such as the limited technical capacity of utilities to execute this tool, as well as management and planning aspects such as financial limitations, present in some management models. These aspects may also underlie the low number of studies investigating the best frequency for researching leaks (P19), as well as the low use of the zero consumption method (P22) which, by isolating the supply in a sector, makes it possible to verify the occurrence of non-visible leaks.

In terms of the practices that assist in controlling measurement errors, the data collected suggest that P32 is the least applied by both groups in analysis. Such practice refers to the use of radio frequency measurement, one of the most common forms of remote consumption measurement, and stands out for its practicality, agility in reading, safety and reliability of generated data, eliminating consumption estimation (AWWA 2009).

The low diffusion of this technology in Brazil as well as the costs involved in the acquisition of radiofrequency equipment are factors that may be related to low application between the groups, especially in group D.

Among several aspects that lead to measurement errors of hydrometers, the technological characteristics of the equipment being used emerge. Although the greater accuracy and sensitivity of volumetric hydrometers, the velocimetric meters are the most attractive in the market for their low cost and simple maintenance. This approach is in line with the study that found that P31, which deals with the use of more accurate hydrometers, is one of the least used practices for group D.

Except for the practices less applied in this process, the training of the reading team (P33), is applied by all the utilities analyzed in both groups, A1 and D. This practice is pointed out by several authors (i.e. Kunkel *et al.* 2008; AWWA 2009; Carteado & Vermersch 2016) as essential for them to perform their functions with vigor and quality and anticipate the solution of problems related to fraud.

Regarding the actions that subsidize fraud control, which is the main factor responsible for the apparent levels of water losses, it is observed that in group A1 all practices are applied by all utilities, except P39, the least practiced. This practice addresses the issue of fraud control in areas of social vulnerability which, due to inefficiency or in many cases the lack of access to this resource, induces the populations of these areas to make clandestine connections, one of the main causes of the high levels of apparent water losses, as expressed by Bharti *et al.* (2020). The low applicability of this practice demonstrates that utilities should seek to act in this context, preventing the occurrence of fraud in these areas, in constant expansion. However, it should be noted that utilities should also have a careful look for frauds that occur in areas of high economic standard, having already identified cases in the study area.

In the group D panorama, the application level of the practices showed significant heterogeneity, being the annual update of the users' registry (P41) the least used practice, although presented as opportune to follow the actions related to the registry of new calls and deactivation of others, helping to identify unregistered, clandestine or reactivated calls without authorization from the utility (Mutikanga *et al.* 2011). In contrast, P35, P38 and P40, which address, respectively, regular inspections of suspicious and inactive calls, analysis of users' consumption history and reports of fraudulent calls, are the most applied practices, in the same proportion, by five of the six utilities that belong to group D.

Considering the strategic planning process, it is essential to note that its practices include actions related to the administrative and planning sector of water utilities. For group A1, it was verified that the eight practices of this process are applied by all utilities under analysis. For group D, the data consolidated in Figure 5 reflect the establishment of a plan or program to combat water losses (P42), the definition of a target for loss reduction (P43) and the use of performance indicators (P46) in the process of monitoring and planning new actions are the practices most frequently performed by water utilities. In relation to the lesser applied practices, the existence of a specific department internally in the utilities, for control of losses (P44) and cost–benefit analyses of the control actions (P48), can be justified, as well as other actions not feasible in this group, by the reduced technical staff of the utilities, as well as by the budget difficulties.

Concluding the loss control processes which were examined in this study, the investment and innovation practices

Table 3 | Summary table of the application level of the practices by groups A1 and D

Control process	Application level of the practices	Groups A1	Groups D	Possible factors influencing the application level
Pressure Management (P1 – P6)	Practices applied by more than 60% of the group's utilities	P1, P2, P4, P5, P6	P1, P3	Technical-Operational
	Practices applied by less than 60% of the group's utilities	P3	P2, P4, P5, P6	
Infrastructural Management (P7-P14)	Practices applied by more than 60% of the group's utilities	P7*, P8**, P9*, P11**, P12*, P13**, P14*	P7, P8, P9, P11, P12, P14	Technical-Operational(**) and Planning and Management (*)
	Practices applied by less than 60% of the group's utilities	P10*	P10, P13	
Pipe corrosion control (P15-P17)	Practices applied by more than 60% of the group's utilities	P15, P16, P17	P17	Planning and Management
	Practices applied by less than 60% of the group's utilities	----	P15, P16	
Leak Control (P18-P27)	Practices applied by more than 60% of the group's utilities	P18, P19, P20, P21, P22, P23, P24, P25, P26, P27	P18, P20, P24, P25, P26, P27	Planning and Management
	Practices applied by less than 60% of the group's utilities	----	P19, P21 P22, P23	
Measurement error control (P28-P33)	Practices applied by more than 60% of the group's utilities	P28, P29, P30, P31, P32, P33	P28, P30, P33	Technical-Operational
	Practices applied by less than 60% of the group's utilities	----	P29, P31, P32	
Control of fraud and clandestine connections (P34-P41)	Practices applied by more than 60% of the group's utilities	P34*, P35**, P36**, P37*, P38**, P40*, P41*	P35, P36, P38, P40	Technical-Operational(**) and Planning and Management(*)
	Practices applied by less than 60% of the group's utilities	P39*	P34, P37, P39, P41	
Strategic Planning (P42-P49)	Practices applied by more than 60% of the group's utilities	P42, P43, P44, P45, P46, P47, P48, P49	P42, P43, P45, P46, P47, P49	Planning and Management
	Practices applied by less than 60% of the group's utilities	----	P44, P48	
Investment and Innovation (P50-P54)	Practices applied by more than 60% of the group's utilities	P51, P52, P53, P54	P50, P52	Planning and Management
	Practices applied by less than 60% of the group's utilities	P50	P51, P53, P54,	

are the ones with less applicability by group D utilities. The practice P51, is not applied by the refereed group utilities, despite being highlighted as an important practice to reduce, through a process of planning, monitoring and action, the non-conformities of operational processes, what increases the quality of services (Pohlmann *et al.* 2015). The adoption of this practice assumes a high organizational level by the utilities, which in the cases of the companies that make up the group is unreal.

In the context of group A1, the only practice that is not applied by 100% of the utilities is P50, which refers to investment in technologies aimed at loss control. According to Cetrulo *et al.* (2020), the investment capacity of utilities linked to water losses would be affected by water scarcity and water treatment costs. This fact shows that the superior performance of the utilities is not necessarily driven by investments in high cost and advanced technologies for loss control, indicating that basic, routine actions of operational control produce good results in the control of loss levels.

An overview of the practices applied by the utility groups considered in this study is presented in Table 3. In front of the detailed analysis of each practice of water loss control presented in this article, in the last column of Table 3 the possible factors that influence the level of application of the practices by the groups are highlighted. As technical–operational factors it is considered, for example, the existence of a specialized technical team to implement the actions or even external factors such as topography, which directly influence the operational aspect of the system. The factors of planning and management refer mainly to the capacity of the utilities to invest in improvement and control actions, which is directly related to the management model of the sanitation utilities.

CONCLUSION

The study's findings show that, although utilities are within the same national economic context, there are significant differences in the proportion of the adoption of loss control practices. There was also a direct relationship between utilities' performances (A1, A2, B, C and D) and the level of application of water loss practices, identifying a trend in the reduction of utilities' performance, i.e., higher levels of losses with the decrease in the proportion of application of practices. The differences in application levels between the analyzed groups (A1 and D) may be influenced by technical–operational factors as well as by planning and management factors, with the utility's management model being one of the determining factors, considering that some models make investments in improvement actions more flexible, while others restrict actions.

The management of water losses is a key factor in the improvement of supply networks, where the guarantee of the economic balance of its operation is subject to the development of strategies that establish a balance in the execution of all control practices. Apart from the urgency of efficient loss management, especially in the face of climate change and water scarcity scenarios, this study does not exhaust the discussion about loss management in a development context, much less imposes actions that should be applied to control losses in these scenarios. The study acted in the sense of bringing contributions to the limited scientific framework that investigates the management of water losses in developing countries. The paper also provides an overview of which practices directed to the control of water loss are being conducted in this context and which factors influence the adoption of these practices, thus being able to support the action of utilities that act in similar scenarios or still be a model for them.

In consideration of the specificity of each region of the globe, both in economic, environmental, and social terms, it is recommended that other studies analogous to the one presented be conducted. The development of new studies would facilitate to analyze the difference and similarity between utilities from different geographical regions, thereby verifying if there is a trend in the occurrence of the scenario identified in this study in other developing countries. This kind of study also contributes to an expansion of the scientific framework in this issue, bringing greater robustness to debates of loss management in regions of economic scarcity.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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