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Bárbara Brzezinski Azevedo

CONTROLE DE PERDAS EM SISTEMAS DE DISTRIBUIÇÃO DE ÁGUA: A PERSPECTIVA DA COMPLEXIDADE

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Tese submetida ao Programa de Pós-Graduação em Engenharia de Produção da Universidade Federal do Rio Grande do Sul como requisito parcial à obtenção do título de Doutor em Engenharia de Produção, modalidade Acadêmica, na área de concentração em Sistemas de Produção.

Orientador: Prof. Dr. Tarcísio Abreu Saurin

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Prof. Tarcísio Abreu Saurin, Dr.
Orientador PPGEP/UFRGS

Prof. Alejandro Germán Frank, Dr.
Coordenador PPGEP/UFRGS

Banca Examinadora:

Professor Ricardo Augusto Cassel, Dr. (PPGEP/UFRGS)

Professora Daniela Dietz, Dra. (PPGEC/UFRGS)

Professor Marcelo Fabiano Costella, Dr. (PPGTGI/UNOCHAPECO)

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RESUMO

Sistemas de Distribuição de Água (SDAs) são normalmente modelados apenas como sistemas técnicos. Contudo, tais sistemas também interagem com diversos sub-sistemas sociais (por exemplo, usuários e operadores dos SDAs) e organizacionais (por exemplo, sistemas gerenciais das empresas que operam os SDAs), sujeitos a influência do ambiente externo (por exemplo, político, econômico, regulatório). Além disso, os sub-sistemas citados interagem dinamicamente entre si, estando expostos à incerteza e variabilidade não antecipada. Dessa forma, esta tese aborda os SDAs como Sistemas Sócio-Técnicos complexos (SSTC), uma perspectiva nova na literatura sobre SDAs . Em particular, este estudo tem como principal objetivo identificar como a teoria da complexidade pode contribuir para a compreensão e controle de perdas em SDAs, as quais são um problema de grande relevância prática e persistente em diversos países. Os objetivos específicos são: a) identificar o estado da arte referente aos fatores que influenciam a complexidade de SDAs e impactam nas perdas de água; b) analisar, segundo a perspectiva de SSTCs , as relações entre os fatores contribuintes para as perdas em SDAs; c) investigar a relação entre o tamanho da população em sistemas urbanos, tamanho de SDAs e quantidade de perdas nesses sistemas, verificando se essa relação obedece a funções de escala não-lineares. A abordagem norteadora da tese é mista, incluindo pesquisa bibliográfica, estudo de caso e análise de banco de dados quantitativos. Para tanto, foram realizados três artigos. O primeiro foi realizado para atingir o objetivo específico a) através de uma revisão sistemática da literatura, a qual identificou 21 fatores inter-relacionados que influenciam a complexidade dos SDAs e as suas perdas. Esses fatores são responsáveis pela natureza sócio-técnica complexa desses sistemas, que geralmente não é enfatizada pelos métodos de controle de perdas. Seus resultados também indicaram que nenhum dos métodos para controle de perdas abrange todos os atributos de complexidade considerados na tese. Por exemplo, o atributo de complexidade interações não lineares, foi considerado por 45,2% dos métodos. O segundo artigo foi realizado para atingir o objetivo específico b). Para tanto, um estudo de caso foi conduzido em um SDA de uma grande cidade brasileira no qual foi desenvolvida e testada uma *framework* composta por cinco etapas para a análise de perdas, quais sejam: (i) definição dos limites e caracterização do sistema; (ii) quantificação de perdas, identificação e classificação de fatores contribuintes; (iii) modelagem das relações de causa-efeito entre os fatores; (iv) identificação de contramedidas para controlar as perdas; e (v) comparação dos atrasos esperados das contramedidas. A aplicação desta *framework* visou complementar os métodos existentes de controle de perdas na empresa, contribuindo para a avaliação dos impactos sistêmicos das ações propostas pelos mesmos. Ela permitiu a obtenção de um diagrama de causa e efeito para perdas de água, que apresentou os relacionamentos entre 17 fatores que geram as perdas de água, para o SDA estudado. Por fim, foi realizado o terceiro artigo para atingir o objetivo c), através de um estudo com dados quantitativos de 968 SDAs brasileiros.Seus resultados indicaram que, para esse conjunto de SDAslocalizados na região sul do Brasil, existe uma faixa de tamanho populacional (a partir de 15.870 habitantes) que obedece às leis de escala e, portanto, pode ter seu comportamento aparentemente “caótico” previsto. Existe uma ordem subjacente que indica hierarquia e regularidades quantitativas que podem ser apropriadas para estabelecer o planejamento de SDAs, considerando assim, o tamanho da cidade, o tamanho de SDAs, suas perdas de água e sua não linearidade.

Palavras-chave: sistemas de distribuição de água, perdas, sistemas sócio técnicos complexos, leis da escala.

ABSTRACT

Water Distribution Systems (WDSs) are usually modeled only as technical systems. However, such systems also interact with several social (for example, users and operators of WDSs) and organizational (for example, management systems of the companies that operate the WDSs), subject to the influence of the external environment (for example, political, economic, regulatory). In addition, the sub-systems mentioned interact dynamically with each other, being exposed to uncertainty and unanticipated variability. Thus, this thesis addresses WDSs as complex socio-technical systems (CSTS), a new perspective in the literature on WDSs. In particular, this study aims to identify how the theory of complexity can contribute to the understanding and control of losses in WDSs, which are a problem of great practical and persistent relevance in several countries. The specific objectives are: a) to identify the state of the art regarding the factors that influence the complexity of WDSs and impact on water losses; b) analyze, from the perspective of CSTSs, the relationships between the contributing factors to losses in WDSs; c) investigate the relationship between the size of the population in urban systems, the size of WDSs and the amount of losses in these systems, verifying whether this relationship obeys non-linear scale functions. The guiding approach of the thesis is mixed, including bibliographic research, case study and analysis of quantitative databases. For that, three articles were made. The first was carried out to achieve the specific objective a) through a systematic literature review, which identified 21 interrelated factors that influence the complexity of WDSs and their losses. These factors are responsible for the complex socio-technical nature of these systems, which is generally not emphasized by loss control methods. Their results also indicated that none of the methods for loss control encompasses all the attributes of complexity considered in the thesis. For example, the complexity attribute of non-linear interactions was considered by 45.2% of the methods. The second article was carried out to achieve the specific objective b). To this end, a case study was conducted at an WDS in a large Brazilian city in which a framework composed of five stages for the analysis of losses was developed and tested, namely: (i) definition of the limits and characterization of the system; (ii) quantification of losses, identification and classification of contributing factors; (iii) modeling of cause-effect relationships between factors; (iv) identification of countermeasures to control losses; and (v) comparison of expected delays for countermeasures. The application of this framework aimed to complement the existing loss control methods in the company, contributing to the assessment of the systemic impacts of the actions proposed by them. It allowed obtaining a cause and effect diagram for water losses, which presented the relationships between 17 factors that generate water losses, for the studied WDS. Finally, the third article was carried out to achieve objective c), through a study with quantitative data from 968 Brazilian WDSs. Its results indicated that, for this set of WDSs located in the southern region of Brazil, there is a population size range (from 15,870 inhabitants) that obeys the laws of scale and, therefore, can have its apparently "chaotic" behavior predicted. There is an underlying order that indicates hierarchy and quantitative regularities that may be appropriate to establish

WDS planning, thus considering the size of the city, the size of WDSs, its water losses and its non-linearity.

Key words: water distribution systems, losses, complex socio-technical systems, scaling laws.

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1. INTRODUÇÃO

1.1. Contexto

Em relação ao total de recursos hídricos disponíveis no mundo, 97,5% são de água salina e 2,5% da água doce, sendo que apenas 1% dessa última parcela é adequada para tratamento e abastecimento humano (ROZIN *et al.*, 2015). No entanto, um grande percentual de água é perdido nos Sistemas de Distribuição de Água (SDAs) no trânsito entre as estações de tratamento e o usuário final. Em nível mundial, os índices de perda de água geralmente estão entre 30% e 40% da produção de água tratada, sendo que os vazamentos compõem a maior parcela deste índice (FONTANA; GIUGNI; PORTOLANO, 2012). Em alguns sistemas de abastecimento, esta perda pode ser maior que 50% (KADU; DIGHADE, 2015).

A perda de água também tem impactos ambientais e econômicos devido ao uso de energia elétrica, produtos químicos para tratamento e outros custos associados. Embora as redes de água possam ser planejadas e construídas para satisfazer os requisitos de condições rigorosas, é difícil eliminar vazamentos durante a vida útil do sistema, em função de diversos fatores de natureza técnica e social (ABDULSHAHEED; MUSTAPHA; GHAVAMIAN, 2017).

Em SDAs, as perdas são classificadas em duas categorias, de acordo com a forma como a água deixa a rede de distribuição: perdas reais ou perdas aparentes. O volume de água que se perde através de vazamentos e transborda de reservatórios é conhecido como perda real ou física. As perdas aparentes ocorrem como consequência de medição inadequada (erros na leitura de hidrômetros ou hidrômetros descalibrados) e do uso não autorizado da água distribuída (fraudes e furto de água) (RÍOS *et al.*, 2014) que podem intensificar ainda mais os vazamentos físicos devido ao desperdício de água.

A literatura aplicada a perdas aparentes é mais escassa quando comparada à de perdas reais, pois, segundo TROJAN e MORAIS (2015), os programas de redução de perdas em empresas de saneamento apresentam um viés técnico. Os gestores assumem que a perda física é a principal parte do problema, quando na verdade as perdas aparentes podem estar na origem das perdas reais, pois o consumo indevido de água, pode ampliar o volume de vazamentos. No entanto, geralmente, as perdas aparentes em grande parte não são medidas pelas empresas de saneamento, devido à dificuldade em medi-las (TROJAN; MORAIS, 2015). Assim, é possível que os gestores não conheçam o total de água perdida no sistema.

Em parte, as grandes perdas e as dificuldades de controlar e medir as mesmas decorrem da natureza complexa dos SDAs, que estão em estado permanente de mudança devido a demandas flutuantes, exposição a desastres naturais, envelhecimento, deterioração, substituição, redesenho, expansão e crescimento populacional, dentre outros fatores. Além disso, os SDAs são essenciais para atender às demandas de consumo inclusive sob condições severas, como fogo ou interrupção de fornecimento. Construção, manutenção e expansão de SDAs são operações geralmente caras e sua otimização tem sido alvo de inúmeras pesquisas nas últimas décadas (MATOS *et al.*, 2014).

Ademais, os SDAs estão muito integrados com vários aspectos da vida humana, influenciando o conforto do usuário, atividades de lazer e outros objetivos pessoais. Assim, pode-se considerar que SDAs também são Sistemas Sócio-Técnicos (SSTs), nos quais os aspectos sociais, técnicos e econômicos estão entrelaçados entre si (DEY; LEE, 2017), sujeitos ao ambiente externo.

Além disso, a visão clássica da evolução espaço-temporal de cidades, que são sistemas maiores onde os SDAs estão inseridos, é a de que os espaços urbanos são passíveis de controle e previsibilidade por meio de um planejamento centralizado (KÜHNERT; HELBING; WEST, 2006). Porém, a teoria de sistemas complexos indica que as cidades, assim, como os SDAs, podem ser entendidos como resultado de processos descentralizados de auto-organização.

Alguns autores (BETTENCOURT; WEST, 2010; HELBING *et al.*, 2007; KÜHNERT; HELBING; WEST, 2006), identificaram leis de dimensionamento que regem estruturas urbanas auto similares (estruturas semelhantes, exata ou aproximadamente, a uma parte de si mesmo[1]). Tais leis foram denominadas como leis de escala, tendo sido observadas empiricamente para variáveis como taxas metabólicas, crescimento populacional e expectativa de vida. Assim, parece promissor identificar leis de escala para a compreensão do relacionamento entre SDAs e suas perdas com o tamanho de estruturas urbanas (medido principalmente através da variável tamanho populacional).

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[1] Um exemplo de objeto auto similar são os fractais que são objetos geométricos que podem ser divididos em partes, cada uma semelhante à original, mas nunca totalmente idêntica.

No entanto, as linhas de pesquisa atuais sobre perdas em SDAs geralmente enfatizam aspectos técnicos. BERARDI *et al.* (2016) apresentam um módulo de software para controle de vazamentos de água, priorizando possíveis redes defeituosas. (FONTANA *et al.*, 2017) propõem um modelo para redução de vazamentos em redes de distribuição utilizando válvulas redutoras de pressão. D’ERCOLE *et al.* (2016) propõem uma ferramenta para a otimização do desempenho de SDAs, em termos de economia de água e redução do consumo de energia, através da análise hidráulica. MOLINOS-SENANTE; MAZIOTIS; SALA-GARRIDO (2016) propõem uma função de distância direcional para estimar custos de vazamentos como uma proxy de custos ambientais. KILINÇ *et al.* (2018) propõem o uso do método AHP para avaliar o desempenho técnico de tubulações de rede de água. Assim, os estudos e análises da operação destes sistemas não tem adotado uma visão holística, considerando as relações interdependentes de cada parte do sistema e seu comportamento dinâmico em diferentes condições sócio-técnicas (SHENG *et al.*, 2013).

Cabe destacar que há uma variação no número de características dos sistemas complexos apresentados na literatura, bem como nos termos adotados para designar cada um deles. De fato, a complexidade não é fácil de definir, e o termo é frequentemente usado sem definição (ERIK HOLLNAGEL, DAVID D. WOODS, 2006). Nessa tese foi adotada a perspectiva filosófica do realismo crítico (ARCHER, M., BHASKAR, R., COLLIER, A., LAWSON, T., NORRIE, 1998) para definir complexidade. Essa perspectiva considera que: (i) a complexidade é algo objetivo e passível de medição independente do observador, o que está alinhado com a perspectiva realista (HORNBY, 2007); (ii) as medições nunca serão perfeitas, o que pode ser minimizado pela triangulação de métodos e dados para obter uma melhor explicação da complexidade – o que está alinhado com a perspectiva construtivista, que por sua vez pode ser interpretada como uma crítica ao realismo.

Como definição de complexidade, foi adotado o conceito de complexidade em termos de atributos, identificados por SAURIN e GONZALEZ, (2013) a partir de uma revisão da literatura, na qual quatorze estudos de diferentes perspectivas filosóficas foram revisados. Os atributos e seus principais aspectos são os seguintes:

(i) Sistemas complexos possuem muitos elementos que interagem dinamicamente, tais como grande número de consumidores e redes de distribuição extensa;

(ii) Sistemas complexos possuem interações não lineares, implicando em que pequenas mudanças nas condições iniciais podem causar efeitos dramáticos no comportamento do sistema. Como exemplo, o abastecimento de água é altamente sensível às mudanças nas condições climáticas e às chuvas; vazamentos de água não reportados são bastante difíceis de serem localizados, variações no consumo de água, uso anormal da água ou furto de água;

(iii) Diversidade dos elementos. Os elementos são diferenciados de acordo com uma série de categorias, tais como diferentes categorias de consumidores; diferentes de fontes de abastecimento; diversos tomadores de decisão;

(iv) Variabilidade imprevista, decorrente da incerteza, o que é um resultado da riqueza das interações entre os elementos, bem como do fato de que os elementos recebem informação a partir de fontes de informação indiretas, especialmente em sistemas altamente automatizados. Essa variabilidade imprevista pode se manifestar, por exemplo, em termos de erros nas medições de água, medidores sujeitos ao desgaste e perda de precisão com o tempo; e

(v) Resiliência, que é a capacidade do sistema superar situações de estresse ou falha, para garantir a de distribuição de água aos usuários. A resiliência dos SDAs também pode se manifestar, por exemplo, quando o suprimento de água é projetado para ser maior que a demanda, suprir continuamente o serviço e reduzir a ocorrência de interrupções na oferta.

1.2. Problema de Pesquisa

Similarmente a outros estudos (por exemplo, BRAINARD e HUNTER (2016)), o termo “teoria da complexidade” é aqui adotado como um guarda-chuva que abrange os princípios centrais do pensamento sistêmico, teoria dos sistemas sócio-técnicos e sistemas complexos adaptativos. Assim, este termo é usado principalmente como uma perspectiva para a modelagem e compreensão de sistemas, ao invés de uma teoria unificada (MOREL; RAMANUJAM, 1999).

A teoria de sistemas complexos tem sido amplamente usada para modelagem de uma ampla variedade de sistemas (químicos, físicos, biológicos, tecnológicos, sociais e organizacionais) devido a sua capacidade de entender sistemas que operam com dinâmicas não lineares, caracterizadas por fenômenos emergentes, auto-organização e evolução (BOHÓRQUEZ; ESPINOSA, 2015).

Por exemplo, SERRANO-SANTOYO (2013) propõe uma *framework* para conceituar a inovação, baseando-se na teoria de sistemas complexos. Seus resultados apontam que para criar ambientes que estimulem a inovação, é necessário considerar aspectos como resiliência e qualidade das interações, bem como adotar uma atitude de aprendizagem em todas as etapas do processo. Em sistemas de manufatura, BOZARTH *et al.* (2009) apresentam e testam empiricamente uma *framework* para medir a complexidade, em sete países. Os resultados mostram que o não gerenciamento de atributos de complexidade no fluxo de produção tem um impacto negativo no desempenho da fábrica. COOK *et al.* (2015) aplicam os conceitos da teoria de sistemas complexos ao gerenciamento de sistemas de tráfego aéreo. Os autores verificaram que a teoria da complexidade contribui para o gerenciamento desses sistemas e para otimizar o seu projeto, por considerar princípios como incerteza, resiliência e comportamento emergente.

Conforme exposto anteriormente, SDAs são SSTCs, que possuem um nível considerável de perdas, nos quais existe uma interação dinâmica entre pessoas e tecnologia, inseridos em sistemas urbanos resultantes de processos descentralizados de auto-organização, regidos por leis de escala não-lineares. Assim, a teoria de sistemas complexos pode contribuir para a interpretação do comportamento de SDAs, identificando como se relacionam dinamicamente os fatores geradores de perdas de água e como estas ocorrem em sistemas urbanos com diferentes tamanhos populacionais. Para tanto, é necessário o estudo mais aprofundado de alguns atributos de complexidade citados na seção 1.1., como: elementos que interagem dinamicamente e interações não-lineares.

Em termos acadêmicos, a presente abordagem justifica-se por ser este o primeiro trabalho que interpreta as perdas de água em SDA através da teoria de sistemas complexos, em termos práticos, esta abordagem possibilita a aplicação de ferramentas para a compreensão das interações dinâmicas entre os elementos causadores de perdas de água.

Além disso, essa perspectiva é importante, pois a teoria da complexidade enfatiza, sobretudo, a não-linearidade de interações entre fatores causais. Essa não-linearidade pode resultar de processos descentralizados de auto-organização (KÜHNERT; HELBING; WEST, 2006) que ampliam a variabilidade, às vezes indesejada, através da retroalimentação entre os níveis micro e macro de um sistema (DERBYSHIRE, 2016). Assim, é importante identificar se existe uma relação não linear entre o tamanho de estruturas urbanas, tamanho de SDAs e as perdas de água. No caso de SDAs, essa variabilidade indesejada corresponde às perdas de água. Desta forma, a teoria da complexidade pode contribuir para a compreensão e controle das perdas nesses sistemas, enfatizando o atributo de complexidade não-linearidade.

1.2.1. Questões de Pesquisa

Com base no contexto apresentado, a principal questão de pesquisa a ser investigada nesta tese é enunciada da seguinte forma: como a teoria da complexidade pode contribuir para a compreensão e controle das perdas em SDAs?

1.2.2. Questões secundárias de pesquisa

As questões secundarias que surgem da questão principal apresentada nessa tese são as seguintes;

a) Qual é o estado da arte referente aos fatores que influenciam a complexidade de SDAs e impactam nas perdas de água?
b) Como analisar, segundo a perspectiva de sistemas sócio-técnicos complexos, as perdas em SDAs e as interações entre os fatores causais?
c) Existe uma relação não-linear entre o tamanho da população de sistemas urbanos, tamanho de SDAs e quantidade de perdas nesses sistemas, que obedece a funções de escala?

1.2.3. Objetivo Geral

O objetivo principal da tese é identificar como a teoria da complexidade pode contribuir para a compreensão e controle das perdas em SDAs.

1.2.4. Objetivos Específicos

A partir do desdobramento do objetivo geral desta Tese, três objetivos específicos foram postulados:

a) Identificar o estado da arte referente aos fatores que influenciam a complexidade de SDAs e impactam nas perdas de água;
b) Analisar, segundo a perspectiva de sistemas sócio-técnicos complexos, as perdas em SDAs, identificando as interações entre os fatores causais;

c) Identificar a relação existente entre o tamanho da população de sistemas urbanos, tamanho de SDAs e quantidade de perdas nesses sistemas, verificando se essa relação obedece a funções de escala não-lineares.

As relações entre o objetivo geral e os específicos estão ilustradas na Figura 1.1. Observa-se na figura que o objetivo específico (a) serve como suporte a todos os demais, dado sua natureza exploratória, enquanto que os objetivos (b) e (c) são os meios necessários para o cumprimento do objetivo geral.

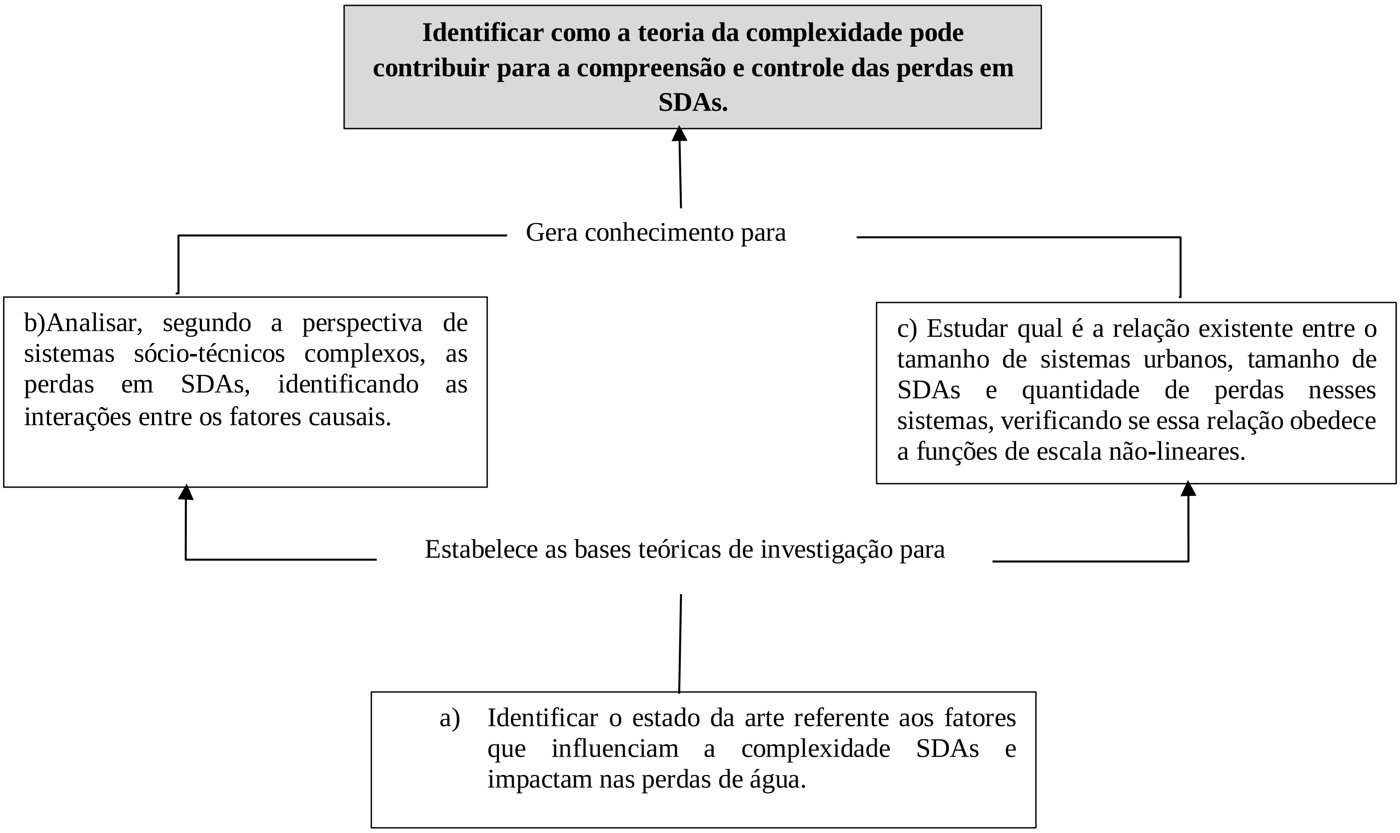

Figura 1-1 Relações entre os objetivos geral e os específicos

1.3. Estrutura da Pesquisa

A pesquisa está dividida em três fases, conforme estrutura de tese definida pelo Programa de Pós-Graduação em Engenharia de Produção da UFRGS. Assim, um artigo é apresentado como produto final de cada fase. O item 1.4.2 apresenta os artigos, bem como a relação dos mesmos com os objetivos da tese.

1.3.1. Abordagem epistemológica

A tese adota uma abordagem epistemológica mista, incluindo pesquisa bibliográfica, estudo de caso e métodos quantitativos. Pesquisas que utilizam métodos mistos combinam métodos qualitativos e quantitativos (MOLINA-AZORIN, 2016), proporcionando uma compreensão holística de fenômenos complexos (CLARK, 2009). GREENE; CARACELLI; GRAHAM (1989) apontam também outras vantagens como possibilidades mais ricas de triangulação de dados, bem como o desenvolvimento de inovações metodológicas a partir da combinação entre métodos que são usualmente aplicados de forma isolada.

Nesta pesquisa, inicia-se com uma revisão sistemática da literatura para descobrir quais são os atributos de complexidade que influenciam nas perdas de água e como os métodos aplicados na literatura para controlar perdas de água consideram tais atributos. A partir disso, pode-se explorar em maior profundidade como cada atributo de complexidade atua nas perdas em SDAs, modelando as interações entre os atributos através de um estudo de caso, aplicado na segunda fase da pesquisa, onde se propõe uma *framework* para auxiliar a análise de perdas de um SDA. Na terceira fase da pesquisa é estudado em maior profundidade o atributo de complexidade de não linearidade. A ênfase é no uso de dados quantitativos aplicados a uma grande amostra de SDAs, a fim de explorar suas relações com sistemas urbanos, onde se verifica que possuem relação de escala não –lineares com as cidades em que estão localizados e verifica-se que perdas de água crescem de forma mais rápida que o crescimento populacional.

1.3.2. Delineamento da pesquisa

Esta pesquisa está delineada em três etapas, cada uma associada a um artigo. A Figura 1-2 apresenta a contribuição de cada artigo no alcance dos objetivos da tese. Para tanto, apresenta a principal questão de pesquisa respondida em cada artigo, o método escolhido para responder à questão e a relação com os objetivos da tese.

Artigo	**Questão de Pesquisa**	**Método**	**Relação com os objetivos da Tese**			
			Geral	a)	b)	c)
1	Quais são os atributos de complexidade que influem os fatores geradores de perdas de água e como os métodos aplicados na literatura para controlar perdas de água consideram os atributos de complexidade de SDAs?	Revisão sistemática da literatura	X	X	X	X
2	Como analisar as interações entre os fatores que geram as perdas em um SDA?	Estudo de caso	X		X	
3	Qual é a relação existente entre sistemas urbanos, SDAs e quantidade de perdas na distribuição de água?	Métodos quantitativos	X			X

Figura 1-2: Contribuição dos artigos no alcance dos objetivos da pesquisa

O segundo capítulo apresenta o primeiro artigo, intitulado "*Analysis of losses in urban water distribution systems from the perspective of complexity theory: a systematic literature review*", publicado no periódico Water Resources Management, Qualis A1, Fator de impacto 2.848. Esse artigo visa responder quais são os atributos de complexidade que influem nos fatores geradores de perdas de água e como os métodos aplicados na literatura para controlar perdas de água consideram tais atributos. Ele apresenta uma revisão sistemática da literatura que identifica os atributos de complexidade que influenciam nos fatores causadores das perdas nos SDAs e verifica se os métodos empregados na literatura para controlar perdas consideram a natureza complexa desses sistemas. Para ser compatível com a complexidade, o método de controle deveria contemplar cinco atributos da complexidade: grande número de elementos, interações não lineares, diversidade dos elementos, variabilidade imprevista e resiliência. A partir dos resultados obtidos foi proposto um modelo que representa as relações dinâmicas entre os 21 atributos de complexidade encontrados.

O terceiro capítulo traz o segundo artigo, intitulado "*A framework for the analysis of losses in water distribution systems: a system dynamics perspective*" visa responder como analisar as interações entre os fatores que geram as perdas em um SDA. Para tanto, propõe uma framework para análise das relações entre perdas de água. A framework possui 6 etapas, quais sejam: (i) definição de limites e descrição do sistema; (ii) identificação das perdas de água e fatores geradores; (iii) classificação dos fatores geradores de perdas; (iv) modelagem das relações causais entre os fatores contribuintes para as perdas de água; (v) identificação de possíveis contramedidas de controle das perdas; e (vi) avaliação do impacto das contramedidas. O artigo apresenta a aplicação da framework em um SDA de uma grande cidade no Brasil. Essa aplicação, através de um estudo de caso, proporcionou uma base empírica para caracterizar a natureza sócio-técnica das perdas em SDAs, bem como para caracterizar as mesmas como fenômenos emergentes.

O quarto capítulo está reservado para apresentar o terceiro artigo, intitulado "*População Urbana e Perdas em Sistemas de Distribuição de Água: Análise sob a Perspectiva de Leis de Escala em Cidades Brasileiras*" o qual objetiva estudar qual é a relação existente entre a população das cidades, tamanho dos SDAs e quantidade de perdas na distribuição de água, verificando se essa relação obedece a funções de escala não-lineares como leis de potência. Para tanto, um estudo quantitativo com um banco de dados de 968 municípios da região sul do Brasil é realizado, para os quais se verifica que, a partir de uma população de 15.870 habitantes e perdas anuais de 82.000 m^3 de água as distribuições de frequência seguem leis de escala. Esse resultado sugere que, a partir daqueles valores, as características de complexidade dos SDAs e de seu contexto social, são amplificadas. O que demonstrou um comportamento superlinear da variável perdas de água em relação a população dos sistemas urbanos onde os SDAs estão inseridos, semelhante a outras variáveis socioeconômicas apontadas em MEIRELLES *et al.* (2018), como: Produto Interno Bruto (b=1,15); número de Organizações não governamentais (b=1,19); número de habitantes atendidos por coleta de lixo (b= 1.12) e número de habitantes com medição de eletricidade (b= 1.08). Assim, as perdas escalam, ou seja, crescem, com a população do mesmo modo que indicadores de atividade socioeconômica e crescem em proporção um pouco maior do que era de se esperar em uma relação linear com os volumes produzido e consumido. Por fim, o quinto capítulo está reservado para apresentar as conclusões da tese, retomando os principais resultados obtidos.

1.4. Delimitações da Tese

Há algumas delimitações deste estudo que devem ser destacadas. A primeira delimitação se refere ao tipo de sistema de distribuição de água estudado: é interesse desta tese apenas SDAs urbanos (sistemas que abrangem apenas o abastecimento de água potável aos consumidores nos centros urbanos) e não SDAs agrícolas (que utilizam redes de irrigação agrícola).

Outra delimitação se refere à abrangência do estudo de caso do artigo 2, o qual estudou apenas uma empresa de abastecimento, selecionada intencionalmente, para que fosse um caso relevante em que todos os construtos de interesse fossem prováveis de existir, permitindo, portanto, sua investigação empírica.

O artigo 3 também apresenta uma delimitação quanto à abrangência das empresas inclusas no estudo: foram estudados somente os SDAs das empresas que responderem todas as questões requisitadas. As que tiverem alguma variável estudada sem preenchimento foram excluídas, assim como aquelas que apresentaram informações inválidas, como um índice de perdas negativo. Tal estudo também só abrange SDAs pertencentes a região Sul do Brasil, com questões respondidas referentes a dados do ano de 2016, dados de 2017 e 2018 ainda não estão disponíveis no banco de dados consultado. Além disso, não é objeto desta tese criar um novo método para controle de perdas de água, mas sim integrar ferramentas para análise de fatores de complexidade que considerem o comportamento dinâmico de SDAs a métodos já existentes.

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2. PRIMEIRO ARTIGO: LOSSES IN WATER DISTRIBUTION SYSTEMS: A COMPLEXITY THEORY PERSPECTIVE[2]

Bárbara Brzezinski Azevedo Tarcísio Abreu Saurin

Abstract

Water Distribution Systems (WDSs) have losses, which are difficult to be eliminated due to the complex socio-technical nature of these systems. This paper presents a systematic review of the literature on losses in WDSs, which addresses two questions: which are the factors that influence the complexity of WDSs, having an impact on the losses of water? How do the methods used to control losses in WDSs account for complexity? We assumed that to be compatible with the nature of WDSs, the loss control methods should account for five attributes of complexity. Twenty-one factors that influence these attributes were identified from 49 selected papers, based on a content analysis. Non-linear interactions were the attribute most frequently accounted by the methods (36.5%), and none of the methods simultaneously accounted for all the five attributes. The review also supported the development of a model of the relationships between the factors that influence the complexity attributes. This model is a basis for the analysis of the impacts of actions for tackling losses.

Keywords: water distribution systems, losses, complex socio-technical systems.

2.1. Introduction

Regardless of the scarcity of fresh water usable for human consumption, many Water Distribution Systems (WDSs) have significant losses (Hunaidi et al. 2000). Worldwide, the levels of water loss are usually between 20% and 30% of the production of treated water, being the water leaks the major part of this figure (Cheong 2003).

In WDSs, losses are usually classified in two types: real and apparent losses. The water volume that is lost through leakings and the overflow of reservoirs is known as real loss, while the apparent loss is due to inadequate measurements (e.g. hydrometers reading errors) and from the non-authorized use of potable water (Ríos et al. 2014).

In both the literature and in practice, the control of losses in WDSs is approached mostly as a technical problem (Starczewska et al. 2015). However, WDSs have an impact on several aspects of human

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life, affecting users´comfort, activities and personal objectives. Hence, it is possible to frame WDSs as complex socio-technical systems (CSSs), which are characterized by strongly interrelated social, technical and organizational sub-systems, which are all interacting with the external environment (political, legal, cultural, and economic) (Dey and Lee 2017). As such, complexity science can offer insights into how losses occur and can be prevented in WDSs. The lens of complexity has been used to make sense of a number of problems of modern societies, such as urban planning (Heracleous et al. 2017). In this context, to the authors´ knowledge, this paper presents the first systematic review of losses in WDSs and the selected studies are interpreted through the perspective of complexity science. Two research questions guide this study, as follows: (i) which are the factors that influence the complexity of WDSs, having an impact on the losses of water? (ii) How do the methods used to control losses in WDSs account for complexity?

2.2. Definition of Water Distribution System

WDSs deliver potable water to consumers in urban centers, through a multitude of interconnected components such as pipes and reservoirs (Liu and Yu 2014). In this article, we extend and reframe this concept as follows: a WDS is a complex socio-technical system that is physically, geographically, ciber and logically interconnected with other critical infrastructure systems, aiming at the delivery of potable water to consumers in urban centers. Thus, the adopted concept is not limited to the structural and technical aspects of WDSs, but it also recognizes the interactions with the broader social context and the external environment. This socio-technical perspective opens the possibility of exploring the root causes of losses, in addition to emphasizing a functional analysis of WDSs. It is worth noting that the proposed concept of WDSs does not cover agricultural water distribution systems (Abadia et al., 2012), which are focused on farming and irrigation of agricultural activities.

2.3. Complex socio-technical systems: an approach to understand WDSs

Complex systems are never fully known nor knowable (Cilliers 2002), and as such they are mathematically intractable (Page, 2008). Due to the rich web of interactions that give rise to complexity, the action of any agent controls very little, but influences in almost all of the system (Dekker et al. 2012). In this sense, WDSs are complex because of their interactions with the environment and the people, thus being also a complex socio-technical system (CSS).

WDSs, and CSSs in general, can be described in terms of their attributes of complexity, which may be sources of problems (e.g. contributing to the loss of water) or assets, depending on the context. The attributes mentioned by Saurin et al. (2013) are adopted as a basis (Table 2-1), since they are a compilation of classical works, like Cilliers (2002) and Dekker (2003).

Table 2-1 - Attributes of complex socio-technical systems

Attribute	Aspects of the atributes	Examples in WDSs
Large number of elements	The system has many elements, such as technical parts, people, procedures, and regulations.	Consumers, technical parts such as pipes and valves, maintenance and operating teams, designers
Non-linear interactions	The interactions are non-linear, which means that small changes in the initial conditions can cause dramatic effects in the system's behavior.	Small changes can cause major impacts, such as unauthorized water consumption and amplified leaks; water supply is highly sensitive to changes in rainfall
Diversity of elements	The elements differ according to several categories, such as hierarchical levels, division of tasks, inputs and outputs	The elements that form WDSs differ according to several categories, such as: profile of consumers, sources of supply, and regulations
Unexpected variability	Complex systems are open, which means that they interact with their environment, which is in itself a major source of variability	Unexpected variability in WDSs can be due to their strong interactions with the external environment – e.g. excavation during construction works can accidentaly damage existing pipes
Resilience	Resilience is the ability of a system to maintain and adapt its operational performance in the face of failures and other adverse conditions	As for WDSs, resilience is the ability of continuously supplying the service and reducing the occurrence of supply disruptions, under both expected and unexpected situations

Source: Adapted from (Saurin et al. 2013)

2.4. Research Method

The stages proposed by the protocol *Preferred Reporting Items for Systematic Reviews and Meta-Analysis* (PRISMA) (Moher et al. 2009) were followed (Figure 2-1) These are:

(i) Identification of the papers: six databases available in the instituiton of the authors were consulted, namely ScienceDirect, Web of Science, Emerald, IEEE Xplore; Scopus; and EBSCO Business Source Complete. These databases were acessed between the 18th and the 23rd of January 2017. The algorithm used in the search was as follows: "water

distribution network" OR "water distribution system" AND "loss" OR "waste" in the abstract, title and keywords. The period of the publications was not specified. The search indicated a total of 2.032 results. After excluding 1.372 entrances without complete access to its contents, 660 entrances remained. From these, 191 were duplicates and hence 469 papers were selected in the end of this stage.

(ii) Screening: six exclusion criteria were applied: magazine papers and technical reports (15); papers not written in English (4); conference papers (79); and book chapters (2). Based on this, 100 entrances were excluded and 369 remained to the next stage.

(iii) Elegibility: one last filter was applied to exclude papers that did not have any explicit connection to water losses, considering our adopted definition of WDSs. This filter was applied by reading the papers´ abstracts and, based on this, 320 papers were excluded and 49 remained for the next stage.

(iv) Inclusion: all 49 papers were ordered alphabetically from the title, their identification data were recorded and the paper contents were included in the data analysis.

Data analysis was an iterative process, based on the criteria described in Table 2-2. A first round of analysis was conducted by the first author. Next, the second author randomly selected some results obtained by the first author and carried out his own analysis. In cases of discrepancies, the authors discussed to reach a consensus.

The complexity attributes were identified from the articles using the content analysis technique (Bengtsson 2016). We defined that a complexity attribute is influenced by a set of inter-related complexity factors. Thus, through the content analysis, we firstly identified excerpts of text that mentioned factors that influenced the complexity of WDSs. Then, these factors were grouped according to their similarity – e.g. residential, industrial, and commercial consumers were all regarded as part of the same factor, referred to as "different categories of consumers". Next, factors were associated with the five categories of complexity attributes mentioned in Table 1. This association was to some extent a compromise solution, since the attributes are inter-related.

As for the data analysis category related to the country where the study was carried out, the countries were classified as low and middle income countries (LMI) versus upper middle and high income (UHI) based on the World Bank list of economies available at www.databank.worldbank.org/data/download/site-content/CLASS.xls. From the 49 articles analyzed, 44 were empirical and 39 of these informed the country in which the study was performed. From these 39 studies, 69% were performed in UHI countries and 31% were in LMI countries.

It is also worth noting that this review is focused on losses in continuous supply WDSs. Only two selected papers mentioned intermmitent supply (Burrows et al. 2000; Grimmeisen et al. 2016) and they were included because they *also* discussed losses and continuous supply. Furthermore, continuous supply systems may, in certain occasions and temporarily, resort to intermittent supply in order to keep serving customers.

Table 2-2 - Categories of data analysis

Categories	Information sought in the papers	Relevance for this research
Factors that have an influence on complexity	Factors that have an influence on the complexity attributes mentioned in Table 1, considering all selected studies	To identify the factors that influence the complexity of WDSs, having an impact on the losses of water (research question *i*)
Association between the factors and the type of loss	To identify whether studies referred to each factor as relevant only for apparent losses, only for real losses, or for both	To shed light on the extent to which the same factor plays a role in both types of losses, which can occur given the complex nature of WDSs (research question *i*)
Association between the factors and the country where the empirical study was carried out	To identify whether each factor was mentioned by authors in the context of studies focused on either LMI or UHI countries	To shed light on the extent to which the same factor plays a role in both LMI and UHI countries (research question *i*)
Methods to control water losses	It includes studies that focused on developing new methods and / or improvement of existing methods to control losses	To identify which are the most applied methods to control losses and their main characteristics (research question *ii*)
Attributes of complexity accounted by the methods for loss control	Evidence that the methods to control water losses accounted for the complexity attributes mentioned in Table 1	The extent to which the methods account for the complexity attributes is adopted as a proxy measure of their theoretical and practical compatibility with the complex nature of WDSs, using content analysis (research question *ii*).

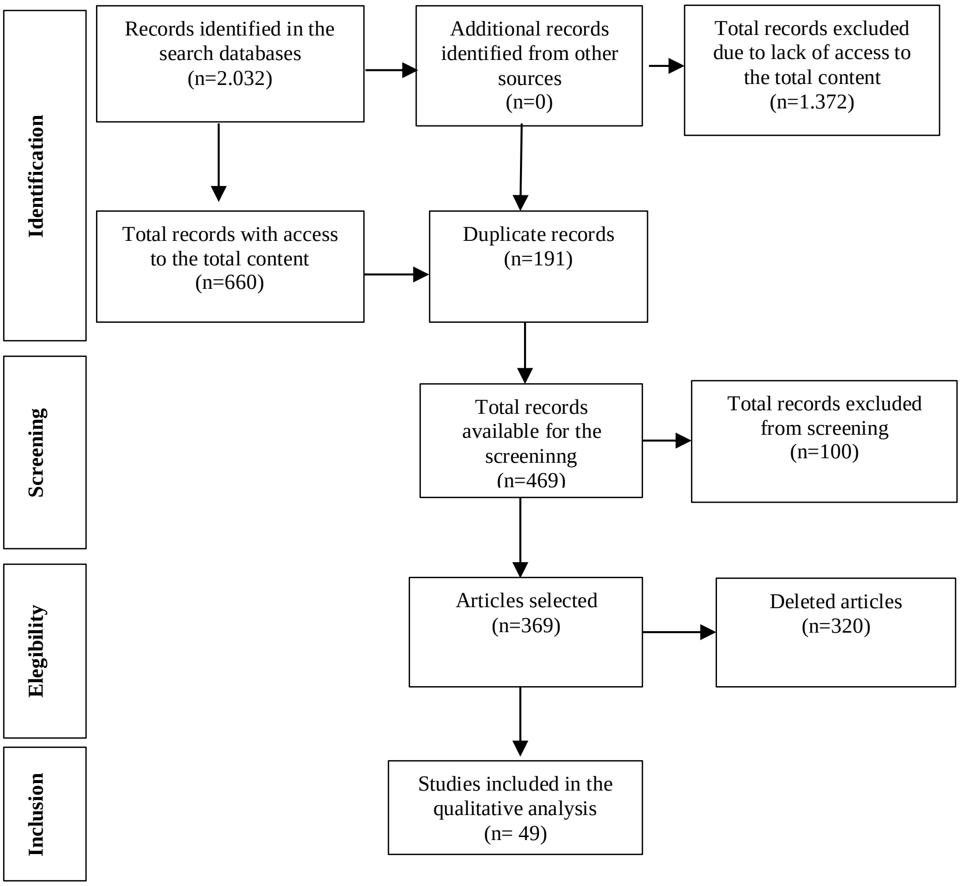

Figure 2-1 - Steps to carry out the systematic review

2.5. Results

2.5.1. Factors that influence the complexity attributes and impact on losses

Twenty-one factors that influence the complexity attributes were identified in the analyzed articles (Tables 2-3 to 2-7). Some clarifications regarding the contents of these Tables need to be presented, as follows:

(i) As for the loss types, the numbers in ( ) indicate the *number of excerpts of text* in which the factor was associated with real losses, apparent losses, or both types;

(ii) As for the national income, the numbers in ( ) correspond to the *number of studies* that referred to the factor. For instance, Table 3 conveys that the factor “enginering attributes” was cited as playing a role in losses by three studies focused on low and middle income countries, while being cited by eleven studies focused on upper and higher income countries; and

(iii) “N.” refers to the number of excerpts of text in which each factor was cited. The value of "N" can be equal to or greater than the sum of the numbers in ( ). This can occur because "N" represents the overall frequency at which the factor was cited and not all studies explicitly associated the factor with a certain type of loss or particular country.

Overall, the complexity attributes were mentioned in 191 excerpts of text from the selected papers. The distribution of the excerpts according to the attributes was as follows: nonlinear interactions (36.5%), large number of elements (28.1%), unexpected variability (14.6%), resilience (12.5%), and diversity of elements (8.3%).

Regarding the “**large number of elements**”, three factors were found (Table 2-3). One of these is related to the concentration of urban populations in small areas (Smith et al. 2015), which stresses the demand from the sources of water. This concentration is a source of complexity, because the physical proximity between the elements of a system increases the likelihood of unwanted interactions (Perrow 1984). This is consistent with the findings by Smith et al. (2015) who concluded that there is a correlation between the rate of leakage and the population of the urban area served by the WDSs. In this sense, the rapid urban population growth poses more difficulties for water supply in developing countries, such as Turkey and Jordan (Kanakoudis et al. 2014; Karadirek et al. 2012; Bulu et al. 2015; Jaber et al. 1997; Grimmeisen et al. 2016).

Due to this high and concentrated demand, water supply infrastructures are increasingly large and difficult to manage (Gomes et al. 2013), which is referred to in Table 2-3 as the factor “extensive distribution network“. Out of the 49 articles, 19 reported the size of the networks, which had an average size of 1829 km in length.

However, a large network is not necessarily a severe drawback in modern water distribution networks, if they are designed with District Metered Areas (DMAs). This design approach consists of dividing the water distribution system into smaller areas of flow measurement in order to facilitate pressure management (Gomes et al. 2013). Thus, DMAs allow for the partiotining of large WDSs in smaller and mostly independent systems, which are easier to manage. However, in complex systems any "solutions" are elusive, due to the possibility of non-linear interactions that may give rise to unanticipated effects. For example, the technologies to control water consumption required by DMAs are subject to failure modes and fallible maintenance procedures. In addition, the implementation of DMAs in old networks demands an infrastructure investment that the service provider may not be able to afford. Due to the need for the said investment, water distribution networks are more likely to be designed with a suitable number of DMAs in developed countries (Al-omari 2013).

Engineering attributes also contribute to the large number of elements. For instance, incorrect assembly of the connections between pipes can cause a considerable loss of water (Covelli et al. 2016). The role played by engineering attributes in water losses was also recognized by Alkasseh et al. (2013). These authors concluded that 97.5% of the reported leaks occurred in tubes with diameters less than or equal to 50 mm. Pipes within this range are normally used as piping and service connections. In fact, the large number and diversity of engineering attributes makes it difficult to control and monitor water losses, which seems to be a concern especially in developed countries, such as Italy and England (Tanyimboh and Seyoum 2016; Covelli et al. 2016).

Table 2-3 – Factors influencing complexity: large number of elements

Factor	N.	Apparent losses (A); Real losses (R); Both types (B)	LMI countries; UHI countries	What the factor looks like and/or its implications
Engineering attributes	22	A (1); R (12); B (5)	LMI (3);UHI (11)	High water pressure, large flow of water, leaks; materials of tubing, variations in soil conditions, location within a network, pumping dynamics
Large number of consumers	18	A (1); R (6); B (8)	LMI (4);UHI (11)	Rapid urbanization, large urban population concentrated in a small area
Extensive distribution network	14	A (2); R (7); B (3)	LMI (2);UHI (8)	Extensive distribution networks are harder to manage
	54			

Table 2-4 describes the factors related to **non-linear interactions**. The emphasis placed on these factors, which were the most frequently mentioned by the selected studies (36.5%) is positive since it gives visibility to less obvious problems in WDSs.

The two most frequent factors related to nonlinear interactions are undetected leaks and high network pressure. Malm et al. (2015) also found that these two factors, when combined, may cause dramatic effects on the behavior of the system. Estimates indicate that leaks not detected represent up to 10% of total water consumption, especially in the residential sector (Britton et al. 2013). The increase in leakages can also indicate that the pressure in the network is high, also resulting in more energy consumption by the water pumps, which in turn leads to an increase in CO_2 emissions.

Variations in water consumption (cited in 4.70% of the articles) can also greatly amplify or dampen the effects of leaks, thus being related to the attribute non-linear interactions. Since the demand for water varies over time (Nicolini et al. 2011), leakages in times of greater consumption tend to be amplified.

Table 2-4 - Factors influencing complexity attributes: non-linear interactions

Factor	N.	Apparent losses (A); Real losses (R); Both types (B)	LMI countries; UHI countries	What the factor looks like and/or its implications
Water supply pressure	19	A (1); R (10); B (7)	LMI (3); UHI (13)	High pressure leads to increased leakage
Leaks not detected	18	A (1); R (10); B (5)	LMI (6); UHI (6)	Unreported leaks that are not so easily detected
Climate changes	9	A (0); R (4); B (5)	LMI (0); UHI (5)	The city's water supply is highly sensitive to changes in weather conditions and rainfall
Variations in water consumption	9	A (1); R (2); B (6)	LMI (3);UHI (4)	The demand for water changes over time
Consumption of water not authorized	6	A (0); R (1); B (4)	LMI (1);UHI (3)	Abnormal use of water or water theft
Price of water	4	A (1); R (0); B (2)	LMI (1);UHI (3)	Rising water prices can lead to a decrease in daily water consumption. Consumers charged on a flat rate tend to waste water
Interconnection with other systems	3	A (0); R (3); B (0)	LMI (1);UHI (1)	Sewer and water distribution networks are often very close
Domestic use usually accounts for the majority of the demand	1	A (0); R (1); B (0)	LMI (0);UHI (0)	Small changes in residential water consumption can have a major impact on WDSs
Others	1	A (0); R (1); B (0)	LMI (0);UHI (0)	Damage to property, consequences of service interruption, increases in driving time, traffic jams and CO_2 emissions from energy consumption
	70			

Table 2-5 presents the complexity factors related to the **diversity of elements**. The different types of consumers, which was the most frequent factor, implies a wider diversity of consumption meters of various sizes, according to the consumption profile (Yuksel et al. 2004). Meters with capacities not suitable for this profile can generate measurement errors, incurring apparent water losses.

As for the factor diversity of income of the population, this implies in different patterns of consumption, according to the varying living standards within a same geographical region. For instance, longer and more frequent baths, as well as the increasing use of washing machines and dishwashers (Prieto et al. 2015), may be associated with improvements in living standards.

The diversity of institutional arrangements of water supply companies (e.g. public, private, mixed, organizational policies and management practices) may also influence the losses. For instance, this factor is possibly associated with the lack of qualified and trained personnel, a low level of public awareness and corruption as some of the reasons why services are poorly managed (Trojan and Morais 2015). In this review, we did not find any study that compared the performance of private supply companies with public companies, which is thus a gap in the literature. In addition, the diversity of criteria to analyze water demand and water losses is another complexity factor, which can explain the variations in the data provided to governments (Prieto et al. 2015).

Table 2-5- Factors influencing complexity attributes: diversity of elements

Factor	N.	Apparent losses (A); Real losses (R); Both types (B)	LMI countries; UHI countries	What the factor looks like and/or its implications
Different categories of consumers	4	A (0); R (3); B (1)	LMI (0);UHI (3)	Residential, commercial, industrial, consumption meters of various sizes
Population's income	4	A (1); R (0); B (2)	LMI (2);UHI (2)	Changes in patterns of consumption and production
Institutional arrangements	4	A (1); R (1); B (1)	LMI (1);UHI (3)	Lack of qualified personnel, low level of public awareness, method adopted for controlling losses
Diversity of criteria for the assessment of losses and demand	2	A (0); R (0); B (2)	LMI (1);UHI (1)	Uncertainty in the judgment of decision makers, conflicting decision criteria, lack of established criteria to analyze water demand and losses
Different supply sources	2	A (0); R (0); B (1)	LMI (0);UHI (2)	Dams, groundwater, neighboring cities
	16			

Table 2-6 shows the frequency of factors related to **unexpected variability**. Errors in water measurement, which account for the unbilled fraction of treated water produced, may vary widely (Dube and Zaag 2003). Consumption meters, like any other mechanical devices, are subject to wear and tear and therefore loss of accuracy over time. Furthermore, the manual reading of customer consumption meters, in which the readers visit individual meters to collect readings, is susceptible to human errors (Mutikanga et al. 2011).

Thus, errors in water measurements can cause managers not to even know the true loss in the production of treated water. This can generate what Ramasesh and Browning (2014) refer to as “known unknowns”, since it is known that there is imprecision, but it is not known its extent. In this case, the “unexpected variability” refers to the extent of the water measurement errors, instead of the errors themselves.

Regarding the infrastructure conditions of WDSs, a study by Kim et al. (2016) concluded that the older the network, the greater the leaks. The pipe materials also strongly influence the amount of water lost. According to Malm et al. (2015) there is a clear correlation between the volume of water lost and the proportion of gray cast iron tubes. In these examples, the "unexpected variability" refers to the timing and extent of infrastructure failures.

Table 2-6 - Factors influencing complexity attributes: unexpected variability

Factor	N.	Apparent losses (A); Real losses (R); Both types (B)	LMI countries; UHI countries	What the factor looks like and/or its implications
WDS infrastructure conditions	16	A (1); R (11); B (3)	LMI (4);UHI (8)	The older the network , the greater the leaks, the pipe materials deteriorate over time and influence the amount of water lost
Errors in water measurements	12	A (1); R (3); B (6)	LMI (5);UHI (6)	Meters subject to wear and loss of accuracy over time, meter reading is susceptible to human error
	28			

Table 2-7 presents the factors related to the **Resilience** attribute, which in WDSs is essential for maintaining service quality under fault conditions (Herrera et al. 2016). Resilience also implies anticipating rare events, which may lead to a lack of water supply, and enhancing WDS's ability to deal with disturbances (Thissen et al. 2017). Thus, the design of WDSs should include redundancies and alternative routes to meet demand. The literature presents tools to quantify the resilience of WDSs as a measure of a network's ability to maintain supply under fault conditions (Herrera et al. 2016).

The water supply should also be designed to be greater than the demand, which contributes to the resilience and reliability of supply in WDSs (Zyoud et al. 2016). Of course, since overcapacity contributes to continuous supply this is also a drawback, in the sense that real losses may increase while the leak is not interrupted. Thus, one of the key issues in the planning of WDSs refers to the definition of the adequate level and type of system resilience, so that supply is continuous, without increasing water losses.

Another factor strongly related to resilience is the intermittent water supply. Especially in arid and semi-arid regions, dealing with water scarcity is a practical necessity. In this case, consumers are forced to collect and store water for the hours and days without supply (Grimmeisen et al. 2016). In this case, resilience relies not only on the WDS itself, but also on the consumer's behaviour. Thus, social factors are likely to play a greater role in the control of water losses when there is intermittent supply, in comparison with continuous supply.

Table 2-7- Factors influencing complexity attributes: resilience

Factors	N.	Apparent losses (A); Real losses (R); Both types (B)	LMI countries; UHI countries	Examples
Continuous Supply	23	A (2); R (9); B (5)	LMI (7);UHI (11)	Water supply designed to be larger than demand, in order to reduce the occurrence of supply disruptions
Intermittent Supply	2	A (0); R (1); B (0)	LMI (1);UHI (0)	Intermittent water supply is a common practice for dealing with water scarcity
	25			

2.5.2. Methods for controlling water losses

Appendix 2-1 (on-line) presents the 36 loss control methods described in the analyzed articles, as well as their frequency in the studies and the influence factors on complexity that were considered by each method. Thirty-five (97.2%) methods were applied to control real losses and only 14 (38.9%) to apparent losses. Thirteen methods (36.11%) covered both types of losses. The lower number of methods applied to apparent losses can be due to the previously mentioned technical bias of loss reduction programs, which focus on physical leakages.

In this Section, the discussion is focused on the methods most frequently reported in the literature. The most frequent method, applied in 20.4% of the 49 analyzed articles, is the District Metered Areas (DMA).

As mentioned in Section 2.5.1, a DMA is a part of the network that is physically isolated from the rest of the distribution system, by closing some gate valves. By isolating portions of the water distribution network, it is possible to monitor the inflow and outflow within the isolated area, facilitating leak detection (Xin et al. 2014). Thus, DMAs can be interpreted as a means for reducing the complexity of the system, by tackling the complexity factor large size of the distribution network. The high frequency citation of DMA is consistent with the fact it is widely used internationally (Farley, 2001).

The second most frequent method (10.1%) is the Minimum Night Flow (MNF). The consumption of water in urban areas is minimal over the night. In this period, the leaks are easier to be identified, being at their maximum percentage in relation to the measured total flow (Nicolini et al. 2011), because a sudden spike in water consumption may reflect the actual leak (Xin et al. 2014). Therefore, this method accounts for the influencing factors referred to as undetected leaks.

The literature on water losses has also made use of Genetic Algorithms (8.70%), which are techniques used in computer science to find approximate solutions to optimization and search problems. In the analyzed articles, this technique was applied to calculate the measurement error of water consumption (Xin et al. 2014) and the optimization of WDSs considering engineering attributes (Tanyimboh and Seyoum 2016; Covelli et al. 2016) and infrastructure conditions (Xu et al. 2013).

The method using Pressure Reducing Valves (PRV) also corresponded to 8.7% of the total. According to this method, the daily volume of water lost in the network can be reduced by minimizing the pressure through an appropriate choice of valve positions and their configurations in the system (Covelli et al. 2016). Thus, by reducing unnecessary high pressure, leakages can be reduced.

It was also verified the use of time series (5.8%) as models in which the calculated parameters were used to predict the water demand in the short and long term, in order to improve decision-making on the management of the network. Furthermore, a method proposed by the International Water Association (IWA) was applied to standardize the international assessment of water losses (4.3%). This method includes a database of 170 performance indicators based on 232 variables that should be regularly measured and monitored (Kanakoudis and Muhammetoglu 2014). This method can encompass various factors that influence complexity, such as unauthorized water consumption, water network pressure, and variations in water consumption, accounting for both actual and apparent losses.

2.5.3. Complexity attributes considered by the methods for controlling water losses

The identification of the complexity attributes accounted by the loss control methods (Table 2-8) was made through a content analysis, as mentioned in Section 2.4. For example, the following excerpt of text related to the DMA method was selected from the study by Gomes et al. (2013): "*Water Network Partitioning is a recent research line and consists in dividing the water distribution network into smaller* *zones called District Metered Areas (DMAs) with one (or more, in exceptional cases) supply point, to reduce the network complexity and/or allow pressure management*." Based on this, it was possible to infer that the DMA method could be associated with the influencing factor "extensive distribution network", which in turn is related to the complexity attribute "large number of elements".

The method that accounts for most factors was the Time Series (TS), being related to three out of the five categories. In turn, 45.2% of the methods considered non-linear interactions, the most frequent attribute, while the attributes of resilience were the least included in the analyzed methods (7.1%). In addition, DMA, the most applied method (20.4%), considers only two out of the five attributes of complexity. Thus, there seems to be a need for developing methods for water loss control that consider all attributes of complexity analyzed.

Table 2-8 - Methods for the control of water losses versus complexity attributes

Methods	**Non-linear interactions**	**Diversity of elements**	**Large number of elements**	**Unexpected variability**	**Resilience**	**Total**	**Real Losses**	**Apparent Losses**
District Metered Areas	x		x			2	x	x
Minimum Night Flow	x			x		2	x	x
Genetic Algorithm			x	x		2	x	x
Pressure Reducing Valves	x			x		2	x	x
Time Series	x					1	x	x
Water Balance	x					1	x	x
Hierarchical Analysis Process		x				1	x	
Sensor Placement for Leak Localization	x					1	x	
Replacement of water networks	x					1	x	
Cumulative integral, floor function,curva-ture function				x		1	x	
Multi-stage rehabilitation analysis of water distribution systems				x		1	x	
Field Audit		x				1		x
Bursts and background estimate	x					1	x	
Passive leak control	x					1	x	x
Decision support system		x				1	x	x
Elimination Et Choix Traduisant la Réalité					x	1	x	x
Stochastic hydrologic					x	1	x	x
Demand Management			x			1	x	x
Survey				x		1	x	x
Kalman Filtering		x				1	x	
Management Optimization	x					1	x	
Infuence-matrix to nodal pressure Synthesis				x		1	x	
Single-period inventory model with stochasticc,		x				1	x	

ontinuous,and uniform demand								
Multi-Criteria Decision Analysis	x					1	x	
Noise monitoring leakage	x					1	x	
Optimum pressure management	x					1	x	
Network treatment plants				x		1	x	
Rehabilitation analysis procedure of water distribution systems	x					1	x	
Wireless Sensor Networks	x					1	x	
Sound recorders			x			1	x	
Multiple Linear Regression			x			1	x	
SCADA data system	x					1	x	
Sustainable economic level of leakage	x					1	x	
Manual listening sticks and acoustic Correlators			x			1	x	
Variable Operating Strategy	x					1	x	
WEAP system	x					1	x	x
TOTAL	**19**	**6**	**6**	**8**	**3**	42	**35**	**14**

2.6. Discussion

Based on the collected data, it can be infered that there are dynamic relationships between the attributes of complexity. A model of these relationships is proposed (Figure 2-2), by developing a causal loop diagram, which is a commonly used system dynamics tool to schematically represent the interactions of variables in complex systems in general.

The diagram consists of a set of nodes and arrows. Nodes represent the variables and the arrows are the links between the variables. A positive causal relationship means that the two nodes change in the same direction - e.g. if the variable in which the connection starts decreases (or increases), the other variable also decreases (or increases). By contrast, the negative causal relationship means that the two nodes change in opposite directions (Lee et al. 2014). The model shows the relationships among the five complexity attributes adopted as a basis in this paper, and the nodes correspond to the 21 identified factors that influence the complexity of WDSs, having an impact on water losses.

According to Saurin et al. (2013), the attributes a large number of dynamically interacting elements and diversity of elements play a paradoxical role: although they create conditions for unexpected variability, which can be a problem, they also support resilience, which compensates for variability. The said paradoxical role can be illustrated in the context of WDSs. For example, as can be seen in Figure 2, the variable “large number of consumers” tends to increase the variable “diversity of consumers”. In turn, the existence of more and more diverse profiles of consumers increases the likelihood of unauthorized consumption of water (i.e. unexpected variability, at least in terms of its extent), because each category of consumer has a different consumption profile that must be measured by appropriate meters, which often does not occur.

However, the large number of dynamically interacting elements is a resource for resilience as it can provide slack (e.g. some elements can be functionally redundant). For example, an extensive water distribution network can increase the likelihood of different sources of water supply and ensure overcapacity to maintain continuous supply to the population by providing alternatives and thus resilience to WDSs.

It is also worth noting that the continuous supply, which is factor associated with resilience, is a positive characteristic of the WDS in the sense of keeping the population served. Paradoxically this factor may also be a hindrance in the sense that the greater this type of resilience, the greater the losses of water in case of ruptures of pipes or even theft of water. Therefore, resilience can be both an asset and a source of problems for WDSs.

The model also sheds light on the interdependences between real and apparent losses. Apparent losses can be caused by errors in consumption measurements and water thefts, causing the consumer to pay a lower bill than actually consumed. Therefore, this can stimulate excessive water consumption, which in turn may require greater pressures in the network and the effects of leaks can be amplified. Thus, reducing apparent losses could contribute to reducing real losses. For clarity, the causal links described in this example are presented in Figure 2-2 with dotted arrows.

The interdependence between both types of losses is also suggested by the data presented in Tables 2-3 to 2-7. According to these Tables, 18 out of the 21 complexity factors were cited by authors as being relevant for the control of both real and apparent losses. Of course, this does not necessarily mean that the factors are equally relevant for both types. A similar reasoning applies for the association between the factors and the national income level. Indeed, 18 out of the 21 factors were cited in studies conducted in both UHI and LMI countries, although the relative importance of each factor for each country type had not been analyzed.

Overall, the model suggests that the control of losses in WDSs requires the use of methods that can support the real-time management of the trade-offs between the variables, which are inevitable given their dynamic relations. As each variable interferes in the behaviour of the other, and in large part this relation is nonlinear, small changes in one can generate large effects on the others. In this respect, it is necessary to use modelling and simulation approaches that recognize the socio-technical nature of WDSs when evaluating the impact of loss control measures. This nature is reflected by several of the identified influencing factors – e.g. wide diversity of consumers, variations in consumption due to different living standards and lifestyles, consumption of water not authorized, price of water, population's income, and institutional arrangements.

The potential value of the complex socio-technical perspective can be illustrated by a hypothetical example of outsourcing water distribution. In this case, attention must be paid to the relationship that the supply company already has with the user, which can be lost when passing on the activity to a third party. The knowledge derived from this relationship is an asset for the control of losses, because it can indicate different consumption profiles and regions of the city more prone to water losses, among others. The knowledge that the company has about the different categories of consumers takes a certain length of time to be acquired, since the employee who directly provides the customer service knows the consuming habits, indications of fraud or excessive consume that contribute to losses.

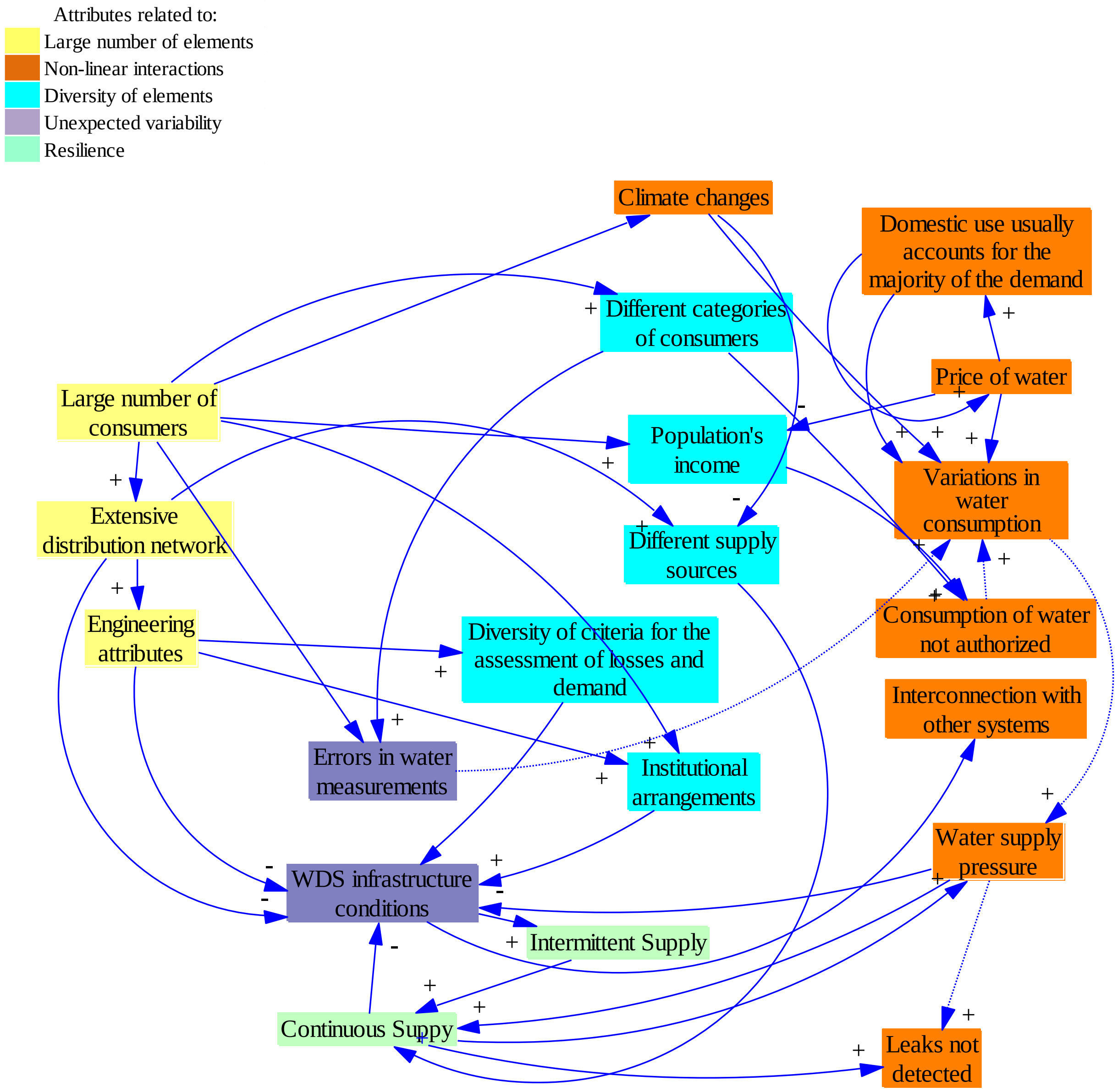

Figure 2-2 - Relationship between the complexity attributes of a WDS

2.7. Conclusions

2.7.1. Contributions of this study

The two research questions that guided this study were stated as follows: (i) which are the factors that influence the complexity of WDSs, having an impact on the losses of water? (ii) How do the methods used to control losses in WDSs account for complexity?

Both questions were answered through a systematic literature review of losses in WDSs, interpreting the findings in light of complexity science. This perspective, while operationalized in other domains, has not received the same attention in the literature of losses in WDSs. As for research question (i), we identified 21 interrelated factors that influenced the complexity of WDSs and the corresponding losses. These factors account for the complex socio-technical nature of WDSs, which is not usually emphasized by the methods of loss control.

As for research question (ii), our findings indicated that none of the methods for loss control covers all five complexity attributes. For instance, non-linear interactions (a defining feature of complexity), are considered by only 45.2% of the methods. In principle, methods with a full coverage would be expected to produce better results, in line with findings obtained in other domains. In fact, there is a vast and established literature on socio-technical systems (e.g. Clegg, 2000; Trist and Bamforth, 1951), which indicates that better performance in general, not only in financial terms, arises from the joint optimization of the technical and social systems, rather than the optimization of either in isolation.

It is also important to note that in the literature reviewed losses are defined from the point of view of the water distribution company, instead of the customer. From the point of view of the end users, the fundamental loss is caused by lack of water and disruption of supply. Another loss from this viewpoint may be the customer´s dissatisfaction with the quality of the water. In fact, this insight indicates that a broader conceptualization and taxonomy of losses in WDSs is necessary, considering the requirements of all stakeholders involved in this system.

Overall, our results indicate the value of framing WDSs as complex socio-technical systems, in order to better understand the nuances of the water losses and to better design interventions that lead to the greatest improvement in outcomes for reduction of losses, bringing economic and social benefits to the system.

2.7.2. Limitations

Some limitations of this research should be emphasized. First, the inclusion and exclusion criteria, as well as the databases used, may have neglected relevant studies. Second, there is a philosophical limitation in the sense that a complete description of complex socio-technical systems such as WDSs is impossible - otherwise the system would not be complex. Third, our model of the relationships between the influencing factors on complexity was not empirically tested. Finally, there was a limitation in carrying out an in-depth analysis of each method to control losses. Indeed, there are other possible criteria for analysing the methods, in addition to the adopted attributes of complexity.

2.7.3. Future research

This literature review identified theoretical and practical gaps regarding the loss of water in WDSs. These gaps provide a basis for future research, as follows: (a) to develop loss control methods that consider the five complexity attributes analysed, recognizing the role played by socio-technical factors; (b) to investigate empirically what would be the ideal level and nature of resilience in a WDS in order to maintain supply continuously, while minimizing water losses; (c) to develop a broader concept and taxonomy of losses in WDS; (d) to empirically test the model proposed in Figure 2 as well as to develop similar models, based on empirical data from specific contexts and scenarios; and (e) to evaluate the relative importance of the identified complexity factors, according to the loss type and national income level.

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Appendix 2-1 - Methods for water loss control

Method	Definition	References	Freq.	%	Real Losses	Apparent Losses	Complexity factors
District Metered Areas	Division of the macro system into small areas of flow measurement, in order to reduce network complexity and facilitate pressure management.	Choi et al. 2016; Xin, Tao, Lu and Xiong 2014; Malm et al. 2015; Gomes et al. 2013; Karadirek et al. 2012; Trojan and Morais 2015; Nicolini et al. 2011; Britton et al. 2013; Fontana and Morais 2013; Burrows et al. 2000	10	14,49	x	x	Extensive distribution network, Leaks not detected
Minimum Night Flow	The Minimum Night Flow, usually between 2 am and 4 am, is the most significant time period for detecting water leakage levels. In this period, customer consumption is minimal and leakage is at its maximum ate in relation to the total measured flow	Asadiyani and Burrows 2009; Xin, Tao, Lu, Xiong, et al. 2014; Alkasseh et al. 2013; Al-omari 2013; Marunga 2006; Britton et al. 2013; Burrows et al. 2000	7	10,14	x	x	Errors in water measurements, Water pressure, Leaks not detected
Genetic Algorithm	Meta-heuristic, non-deterministic, search, optimization and learning techniques that manipulate a space of possible solutions, were invented to mimic some of the processes observed in natural evolution.	Xin, Tao, Lu and Xiong 2014; Nicolini et al. 2011; Tanyimboh and Seyoum 2016; Xu, Ma, et al. 2013; Covelli et al. 2016; Araujo et al. 2006	6	8,70	x	x	Errors in Water Measurements, Engineering Attributes, WDS Infrastructure Conditions
Pressure Reducing Valves	The volume of water lost in the network can be reduced by minimizing the pressure through an appropriate choice of valve positions as well as their settings.	Dube and Zaag 2003; Obradovi 2000; Covelli et al. 2016; Duc and Pu 2016; Araujo et al. 2006; Burrows et al. 2000	6	8,70	x	x	Leaks not detected, pressure in the water network
Time Series	Models in which the calculated parameters can be used to predict the demand for water in the short and long term	Agathokleous and Kourti 2016; Grimmeisen et al. 2016; Prieto et al. 2015; Yalçıntaş et al. 2015	4	5,80	x	x	Different categories of consumers, Variations in water consumption, Unauthorized water consumption, Intermittent supply
Water Balance	Method proposed by the International Water Association (IWA) to standardize the international assessment of water losses. The method includes a database of 170 performance indicators based on 232 variables that should be regularly measured and monitored.	Asadiyani and Burrows 2009; Kanakoudis et al. 2014; Kanakoudis, Tsitsifli, Samaras, et al. 2015	3	4,35	x	x	Consumption of unauthorized water, water pressure, Variations in water consumption.
Hierarchical Analysis Process	A multi-attribute decision making method that uses comparisons in pairs with numerical judgments	Zyoud et al. 2016; Benítez et al. 2012	2	2,90	x		Diversity of criteria for the assessment of losses and demand
Sensor Placement for Leak Localization	Method that uses cost-benefit functions to predict the positioning quality of sensors for locating leakage depending on the number of sensors as well as the strength of general uncertainties and demand.	Steffelbauer and Fuchs-hanusch 2016; Christodoulou et al. 2013	2	2,90	x		Leaks not detected

Replacement of water networks	This approach assumes that the construction of new and correctly installed networks have a leak near zero	Malm et al. 2015; Wang et al. 2014	2	2,90	x		Leaks Not Detected, WDS Infrastructure Conditions
Cumulative integral, floor function,curva-ture function	Algorithm that uses cumulative integral, function of floor and curvature for detection of small leaks and estimation of intervals for their identification	Kim, Je, et al. 2016	1	1,45	x		Leaks not detected
Multi-stage rehabilitation analysis of water distribution systems	Method that uses dynamic programming combined with partial enumeration schemes to select, for each pipe in an existing network, the rehabilitation alternative and the time of its implementation. The aim is to minimize the cost of the investment in rehabilitation and all maintenance costs over a horizon time and subject to certain restrictions.	Adams and Rogers 1998	1	1,45	x		WDS Infrastructure Conditions
Field Audit	Data capture audit to compare input data used for billing and readings on meter reading sheets sent by meter readers.	Mutikanga et al. 2011	1	1,45		x	Errors in water measurements
Bursts and background estimate	The equation that describes the annual losses and nocturnal flows of water, through mathematical deduction and concepts about losses	Lambert 1994	1	1,45	x		Engineering attributes
Passive leak control	Incentives for residential plumbing leak repairs to be proactive in offering free technical advice when needed	Dube and Zaag 2003	1	1,45	x	x	Leaks not detected
Decision support system	The decision support system that mimics the decision process inherent to a human being, but extrapolated to the organizational decision making.	Kanakoudis, Tsitsifli, Cerk, et al. 2015	1	1,45	x	x	Consumption of water not authorized
Elimination Et Choix Traduisant la Réalité	The method aims to obtain a subset of alternatives, in which the alternatives that form part of this subset over-class those that do not. It seeks to reduce the size of the set of alternatives by exploring the concept of dominance. For this, two indices are used: the concordance index, which measures the relative advantage of each alternative over the others, and the discordance index, which measures the relative disadvantage.	Trojan and Morais 2015	1	1,45	x	x	Diversity of criteria for the assessment of losses and demand
Stochastic hydrologic	Stochastic hydrology is a set of procedures for computingquantities of hydrological interest, through analysis of a hydrological record (of rainfall, discharge, lake levels, volumetric water content of soil), the values of which are regarded as observations of a random variable: that is, a variable subject to probabilistic laws.	Arena and Cannarozzo 2014	1	1,45	x	x	Continuous Supply

Demand Management	It is a management approach that uses regulatory, technological, economic and social measures. The economic aspect includes water tariffs noting that, although water is an economic good, accessibility and equity should not be compromised in the implementation of the tariff	Marunga 2006	1	1,45	x	x	Continuous Supply
Survey	Opinion polls for component installation, including type of leak, demographics and family awareness, which will influence any development of a leak correction policy	Britton et al. 2013	1	1,45	x	x	Large number of consumers
Kalman Filtering	The Kalman filter is essentially a set of mathematical equations that implement a predictor-corrector type of estimator that is optimal in the sense that it minimizes the estimated error covariance when the condition of a linear Gaussian system is met. It was employed in order to detect ruptures and leakage	Choi et al. 2016	1	1,45	x		WDS infrastructure conditions
Management Optimization	WDS optimization can provide the release of the same amount of dams' water at convenient times, with a more uniform balance and more effective use, to treat and to control of the waste water and water losses	Burrows et al. 2000	1	1,45	x		Different supply sources
Infuence-matrix to nodal pressure Synthesis	Matrix of influence based on complementary regression for estimation of internal pressure of the water network	Burrows et al. 2000	1	1,45	x		Water supply pressure
Single-period inventory model with stochasticc, ontinuous,and uniform demand	Mathematical model that minimizes the total cost of maintenance of water networks and penalizes water losses	Bach 2000	1	1,45	x		WDS infrastructure conditions
Multi-Criteria Decision Analysis	Evaluation method that classifies the performance of decision options against several criteria. Each decision option is classified according to each criterion with performance measures, which collectively forms an evaluation matrix	Fontana and Morais 2013	1	1,45	x		Diversity of criteria for the assessment of losses and demand
Noise monitoring leakage	Leakage can generate noise when water flows out through a bore or fracture of a pipe and when water flows past substances outside the pipe. Noise can propagate along the pipe and ground, thus capturing the noise will aid in the search for leakage	Xu et al. 2014	1	1,45	x		Leaks not detected
Optimum pressure management	Reduces variations in water pressure. Pressure management tools include pump controls, altitude controls and lift valves	Karadirek et al. 2012	1	1,45	x		Water supply pressure

Network treatment plants	Integrated pumping station to compensate for pressure losses during treatment. As a result, it is possible to correct the quality of the water flowing through the station and reduces water losses	Jako et al. 2015	1	1,45	x		Interconnection with other systems
Rehabilitation analysis procedure of water distribution systems	Method whereby the decision to implement an infrastructure rehabilitation action at a given moment is determined not only by the current state of the system but also by future rehabilitation actions where the cost associated with each pipe in the network is calculated as the present value	Kleiner et al. 1998	1	1,45	x		WDS infrastructure conditions
Wireless Sensor Networks	Communication model for the water distribution monitoring network and channel measurement for the determination of an appropriate path loss model	Min Lin 2008	1	1,45	x		Leaks not detected
Sound recorders	Instruments that detect leak noise and transfer data via text messages	Malm et al. 2015	1	1,45	x		Leaks not detected
Multiple Linear Regression	Statistical technique to determine the factors that contributed to the Minimum Night Flow	Alkasseh et al. 2013	1	1,45	x		Engineering attributes
SCADA data system	System that monitors water levels in reservoirs, flow rates and pressures online	Karadirek et al. 2012	1	1,45	x		Engineering attributes
Sustainable economic level of leakage	Developed to determine the optimal level of leakage. Requires quantification of environmental costs and associated water leakage	Molinos-senante et al. 2016	1	1,45	x		Leaks not detected
Manual listening sticks and acoustic correlators	Instruments used for leak detection	Malm et al. 2015	1	1,45	x		Leaks not detected
Variable Operating Strategy	Optimization procedure to select the best water pump to be used for both pressure control and energy recovery in water distribution networks	Carravetta et al. 2013	1	1,45	x		Engineering attributes
Water Evaluation And Planning system	The method is based on the fact that the apparent portion of unbilled water is delivered to the demand site and arrives at the sewage collection system. In turn, the real loss portion of unbilled water is lost from the system and consequently does not reach the sewage collection system.	Al-omari 2013	1	1,45	x	x	Interconnection with other systems
Total of 36 different methods			69	100	35	14	

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3. SEGUNDO ARTIGO: A SOCIAL-TECHNICAL ANALYSIS OF LOSSES IN WATER DISTRIBUTION SYSTEMS: A STUDY IN SOUTHERN BRAZIL

Bárbara Brzezinski Azevedo, Tarcísio Abreu Saurin.

Federal University of Rio Grande do Sul (UFRGS), Av. Osvaldo Aranha, 99, Porto Alegre, CEP 90.035-190, Rio Grande do Sul, Brazil.

Abstract: Although Water Distribution Systems (WDSs) have significant losses, the nature of their multiple contributing factors and their relationships are not well known. This gap hinders the identification of effective control measures and the anticipation of their impacts. This study presents a five-step framework for analysing losses in WDSs, which involves: (i) definition of the boundaries and characterization of the system; (ii) quantification of losses, identification and classification of contributing factors; (iii) modelling of the cause-effect relationships between the factors; (iv) identification of countermeasures to control the losses; and (v) comparison of the expected delays of the countermeasures, which supports the analysis of their implementation difficulty. The framework is based on the assumption that WDSs are socio-technical systems, and therefore loss control measures should not be limited to technical fixes . An application to a WDS of a large Brazilian city illustrates the use of the framework, shedding light on its strengths and weaknesses.

Keywords: Water Distribution Systems, Water Losses, Social-Technical Systems.

3.1. Introduction

Water distribution systems (WDSs) have high levels of losses (Trojan and Morais, 2015), which associated with the growing scarcity of water, have demanded more efficient operations. In fact, the reduction of losses can outweigh the benefits from the development of new water resources (Al-omari 2013). Kingdom et al. (2006) estimated that a 50% reduction of global water losses from WDSs would be sufficient to provide treated water for about 100 million people. The reduction of losses also has environmental benefits, such as lower greenhouse gas emissions (Prieto et al. 2015), lower energy costs (Teixeira et al. 2016) and the preservation of water sources. These benefits are particularly relevant in developing countries, where climate change, high population growth and urbanization can amplify water scarcity (Phan et al. 2018).

WDSs are dynamically interactive networks (Yazdani & Jeffrey 2011), composed by a large number of technical (e.g. pipes, pumping stations, and valves) and social elements (e.g. consumers, regulators). Indeed, WDSs are integrated with various aspects of human life, affecting users' comfort, leisure activities, and other personal goals. Thus, WDSs are socio-technical systems, which are those in which social and technical elements interact dynamically, subjected to the external environment as a permanent source of uncertainty (Dey & Lee 2017). As a result, WDSs might be analysed in light of socio-technical systems thinking (Clegg 2000), which is concerned with the joint optimization of the technical and social sub-systems (Dey & Lee 2017). A recent literature review carried out by Azevedo and Saurin (2018) indicated that, although the contributing factors to losses in WDSs have a socio-technical nature, this perspective has not yet been accounted for by loss control methods, neither in practice nor in theory.

Studies on losses in WDSs have focused on the technical infrastructure of these systems (Sheng et al. 2013) and the contributing factors to the losses are usually studied in isolation, which is in conflict with their interactive nature. For example, Hendrickson and Horvath (2014) analysed the role played by the WDS infrastructure in the losses, while Molinos-senante et al. (2016) investigated undetected leaks. Although other studies, such as Xin et al. (2014) and Karadirek (2012), addressed several factors (e.g. errors in water measurements, extensive distribution network, and network pressure), the relationships between the factors were not modelled.

Thus, the research question that guided this study is stated as follows: how to analyze, from a socio-technical systems perspective, the losses in WDSs? In order to answer this question, a framework to analyze the losses was developed. This framework is intended to play a complementary role to existing methods of loss control, and it foresees the development of a causal-loop-diagram, which allows for exploring the interactions between the contributing factors to losses. These diagrams have been widely adopted to model the behavior of socio-technical systems in general (Kumar & Yamaoka 2007; Tako & Robinson 2012), including some recent applications to the management of water resources. For example, Phan et al. (2018) employed that approach to assess the vulnerability of a freshwater system in Vietnam, demonstrating how the system is susceptible to global warming and may collapse under a number of future scenarios. Sahin et al. (2015) adopted causal-loop-diagrams to model urban water supply and demand planning by incorporating economic factors such as price adjustment, demand levels and funding capacity in Australia.

Thus, the objective of this article is to develop a framework for analyzing water losses that considers a perspective of socio-technical systems. An empirical study of a municipal water and sewage department, which is in charge of water supply to a large city in Southern Brazil, illustrates the application of the framework. The Brazilian context is relevant, since this country accounts for 12% of the world's water resources, and the volume of treated water per person is 19 times higher than the minimum recommended by the United Nations (Machado 2014). However, according to the national diagnosis of water and sewage services (SNIS 2015), there are large losses in distribution, ranging from 50.8 in the North region to 35.1% in South.

The rest of this paper is structured in five Sections. Section 3-2 presents an overview of the contributing factors to losses in WDSs. Section 3-3 presents the research method. Results are described in Section 3-4, while in Section 3-5 a discussion is made and a model of the relationships between the factors is presented. Conclusions and proposals for future studies are presented in Section 3-6.

3.2. Contributing factors to losses in WDSs

In WDSs, losses are usually classified as either apparent or real. Apparent losses correspond to the amount of water that is not billed due to unauthorized consumption and inaccuracies in the metering system. In turn, the real losses correspond to the physical quantity of water lost; this is treated water that never reaches the consumer and therefore also is not paid (Canto Ríos et al. 2014). The leaks are the most common cause of real losses and may represent up to 30% of the total volume of distributed water (Ferrandez-Gamot et al. 2015).

Table 3-1 presents contributing factors to losses in WDSs identified from a literature review conducted by Azevedo and Saurin (2018). These factors can interact with each other – e.g. high pressure in the network, when associated with undetected leaks, tends to amplify losses. These two factors, when combined, are cited by several authors as the main causes of losses (Lambert 1994; Choi et al. 2016; Al-omari 2013; Dube & Zaag 2003; Malm et al. 2015; Steffelbauer & Fuchs-hanusch 2016; Prieto et al. 2015; Bach 2000; Xu et al. 2014). The factors listed in Table 3-1 can be interpreted as underlying sources of both apparent and real losses, and their wide diversity mirrors the socio-technical nature of WDSs, as well as the influence of the external environment.

Tabela 3-1 - Contributing factors to losses in WDSs (adapted from Azevedo & Saurin, 2018)

Factor	What the factor looks like and/or its implications
Engineering attributes	High water pressure, large flow of water, leaks; materials of tubing, variations in soil conditions, location within a network, pumping dynamics
Large number of consumers	Rapid urbanization, large urban population concentrated in a small area
Extensive distribution network	Extensive distribution networks are harder to manage
Water supply pressure	High pressure leads to increased leakage
Leaks not detected	Unreported leaks that are not so easily detected
Climate changes	The city's water supply is highly sensitive to changes in weather conditions and rainfall
Variations in water consumption	The demand for water changes over time
Consumption of water not authorized	Abnormal use of water or water theft
Price of water	Rising water prices can lead to a decrease in daily water consumption. Consumers charged on a flat rate tend to waste water
Interconnection with other systems	Sewer and water distribution networks are often very close
Domestic use usually accounts for the majority of the demand	Small changes in residential water consumption can have a major impact on WDSs
Different categories of consumers	Residential, commercial, industrial, consumption meters of various sizes
Population's income	Changes in patterns of consumption and production

Institutional arrangements	Lack of qualified personnel, low level of public awareness, method adopted for controlling losses
Diversity of criteria for the assessment of losses and demand	Uncertainty in the judgment of decision makers, conflicting decision criteria, lack of established criteria to analyze water demand and losses
Different supply sources	Dams, groundwater, neighboring cities
WDS infrastructure conditions	The older the network , the greater the leaks, the pipe materials deteriorate over time and influence the amount of water lost
Errors in water measurements	Meters subject to wear and loss of accuracy over time, meter reading is susceptible to human error
Continuous Supply	Water supply designed to be larger than demand, in order to reduce the occurrence of supply disruptions
Intermittent Supply	Intermittent water supply is a common practice for dealing with water scarcity

3.3. Research Method

3.3.1. Epistemological approach

A case study was conducted to explore the nature and relationships between the contributing factors to losses in a real WDS. This approach is suitable for understanding complex and contemporary phenomena (Yin 2006), as well as for identifying empirical relationships between variables (Starman 2013).

Good practices for designing and conducting case studies (Yin 2006) were adopted, as follows: the definition of a research question and data collection protocols; the intentional selection of a relevant case, in which significant losses would exist, with non-trivial relationships; the triangulation of data collection methods, using interviews, observations and document analysis; the partial overlap between data collection and analysis activities, in order to identify the need to adjust the protocols if irrelevant or imprecise data were produced; and the development of a database (e.g. transcripts of interviews and notes from observations), which allowed for tracking the origin of the data as well as its reinterpretation if necessary.

3.3.2. Framework for the analysis of losses in WDSs

The proposed framework is comprised of five steps: (a) definition of the system boundaries and characterization; (b) quantification of losses, identification and classification of contributing factors; (c) modelling of the interactions between the contributing factors; (d) identification of loss control countermeasures; and (e) comparison of the expected delays of the countermeasures.

Step 1 (definition of the system boundaries and characterization) starts with the definition of the WDS boundaries, both structurally and functionally. This definition is arbitrary and it is up to the analyst to delimit a system that corresponds to the research objectives (Checkland 1985). As the main criteria to guide this definition, loss control in the selected WDS should be a practical concern for the water distribution company, as well as quantitative and qualitative data regarding the nature of the losses should be either available or feasible to be collected.

The structural boundaries of the WDS and its corresponding structural characterization should be based on the four subsystems of socio-technical systems, as proposed by Hendrick and Kleiner (2001): social, organizational, technological and external environment. The social subsystem encompasses the characteristics of the people who interact with the system (e.g. degree of specialization of workers), the organizational subsystem is concerned with the planning and management routines that meet a common goal (e.g. water distribution), the technological subsystem includes the equipment, software, tools, and machinery required to operate the system and, lastly, the external environment includes cultural, political, legal, social, and economic factors that, while outside of the system boundaries, interact with its elements. As for the functional boundaries, these are delimited by the interaction of the end users with the WDS (i.e. the actual water consumption). Although a functional modeling of the WDS is not a requirement for using the framework, this can be useful for the analysis of the loss control countermeasures more technically orientated.

Step 2 (quantification of losses, identification and classification of contributing factors) aims at shedding light on the extent of the losses, over several months or years if possible, and their multiple contributing factors. This sets the main empirical basis for all the following steps, and therefore a database should be developed based on multiple sources of evidence, such as existing databases of the amount of losses, as well as the network characteristics identified in Step 1. Qualitative data (e.g. from interviews and observations) can also be useful, since these support a holistic understanding of the mechanisms that link the causal factors, and of how these can change according to the context.

Then, the contributing factors are classified according to their association with real and apparent losses, acknowledging that a same factor can contribute to both types. This analysis is relevant since each loss type tends to require a greater emphasis on certain countermeasures. In principle, real losses, by being more visible and having clear immediate cause-effect links with technical failures, are relatively more amenable to technical countermeasures. In turn, apparent losses may require more socially oriented actions due to their dependence on agents´ behaviors. However, an integrated socio-technical approach is assumed to be relevant for both types.

In **Step 3 (Modeling of the interactions between the contributing factors)**, there should be developed a causal-loop-diagram, which allows for the schematic representation of the interactions between the causal factors (Love et al. 2013). The representation consists of a set of nodes and arrows, where nodes represent the variables and the arrows represent cause-effect relationships between them. A positive causal relationship means that the two nodes change in the same direction: thus, if the variable of the node in which the connection starts decreases (or increases), the variable of the other node also decreases (or increases). A negative causal relationship means that the two nodes change in opposite directions (Lee et al. 2014). The causal-loop-diagram of the contributing factors and their consequences, which was developed through the Vensim® software.

In **Step 4 (identification of loss control countermeasures)** recommendations for controlling the losses in the WDS are proposed based on insights from the previous steps. For instance, reinforcing loops that amplify the impact of losses, which can be identified from the causal-loop-diagram developed in Step 4, could be focused on by countermeasures clearly associated with the contributing factors (Steps 2 and 3).

Lastly, in **Step 5 (comparison of the expected delays of the countermeasures)**, countermeasures should be compared in terms of their expected delay from action to effect, by using the Path Analysis (PA) method (Montibeller & Belton, 2006). This analysis should be interpreted as a starting point for the prioritization of the countermeasures. A path is a sequence of connected variables in a causal-loop-diagram, starting with the causal variable, and ending with the outcome variable. The PA is operationalized by considering all possible paths from a given causal variable to a given outcome variable, and then comparing them in terms of their length and delay. The polarity of the path (i.e. the total polarity of a sequence of links) indicates the nature of the impact of a certain path on the outcome variable (Schoenenberger et al. 2016).

The relative delay of the paths allows for distinguishing between short-term and long-term effects of countermeasures. In this study, the procedure described by Schoenenberger et al. (2016) was adopted: a score of 1 indicates that there are no significant delay between pairs of adjacent variables, while a score of 4 indicates significant delays. The overall delay of a certain path is the sum of the delays of the individual links. In principle, priority should be given to countermeasures with lower delays if all other factors involved in the implementation decision are equal for all countermeasures.

3.3.3. Application of the framework

3.3.3.1. Data collection

Access to data sources was facilitated by the fact the first author has worked for the water distribution company as a Financial Administrator for five years. Table 3-2 lists the data collection techniques and the framework steps for which the data was useful. Interviews and observations played an important role in most steps, as these techniques provided rich information about the water distribution process and how losses occurred.

Tabela 3-2: Data collection techniques and their association with the steps of the framework

Data source	Steps of the framework: numbers correspond to those shown in Fig. 1					
	1	**2**	**3**	**4**	**5**	**Total**
Semi-structured interviews	x	x	x	x	x	4 h
Participant observation	x	x	x	x	x	20 h
Document Analysis	x	x		x	x	-

Semi-structured interviews were based on a script with 12 questions that addressed three themes: description of the nature of losses; causes and consequences; and possible countermeasures. The interviews were digitally recorded and resulted in 19,255 words transcribed in full. The four managers directly in charge of managing losses in the WDS were interviewed, involving: (i) two representatives from the operational area, which is responsible for all stages of water distribution; (ii) two representatives from the commercial area, which is responsible for marketing and service to users, reading and monitoring consumption, including the identification of unauthorized consumption.

Participant observations were recorded in a diary, organized according to the date, observed activities and insights associated with the research question. These observations occurred:

(i) During ten visits to the institution's operational facilities at different times of the day and days of the week, as part of audits of the ISO 9001 certification hold by the company. The first author was a member of the auditing team. These observations contributed to the understanding of technical aspects of the WDS, such as reservoir operation, network maintenance, hydrant inspection, and leak survey; and

(ii) During three meetings, in which the researchers presented and discussed their findings with the four interviewees. At the last meeting, when the final results were discussed, the interviewees were also asked about their perceptions about the practical implications of the study; and

(iii) During monthly meetings with top management that occurred over a 12-month period. These meetings focused on the strategic and operational planning of the company, and they contributed to the understanding of loss control measures under way, which had been devised independently on this study.

In turn, the **analysis of documents** was a relevant source of quantitative data, arising from the records of the "water balance". These records allowed for the quantification of water losses, since they provided data on the volume of water flowing into and out of the WDS, and compared the volume of water distributed with the total billed volume (Petroulias et al. 2016). Documents available on the institution' s intranet were also useful for the identification of contributing factors to losses and their interactions, such internal audit reports and minutes of the aforementioned meetings.

3.3.3.2. Data analysis

In order to analyze the qualitative data from all sources, the technique of content analysis was used (Bengtsson 2016). The analysis procedure starts with the identification of excerpts of text (e.g. sentences, terms) whose meaning is related to relevant data analysis categories. An excerpt may consist of several lines of text and be associated with one or more categories. Four main data analysis categories, which were associated with the steps for applying the framework, were defined: contributing factors to the losses (Step 2), their relationships, causes and effects (Step 3), and countermeasures (Step 4). Several rounds of reading the raw textual data, identifying relevant excerpts and data coding were conducted by the first author. Then, all codifications made by this researcher were reviewed by the second author and a consensus was reached for the final results presented in this study. Quantitative data were analyzed through a histogram by type of water loss. Only data from 2017 on were analyzed, since the company did not have records segmented by type of loss from previous years.

3.4. Results

3.4.1. Step 1: definition of the system boundaries and characterization

A WDS that supplies a large city in Brazil was selected for this study, based on the criteria mentioned in Section 3.3.2. The WDS was inaugurated in the late 1950's and treats 525,894 m³ of water / day on average, with a water supply network with about 4,000 km, in addition to a sewage network with almost 2,000 km. The company that operates the WDS is owned by the municipality, and is subject to significant political and social influence. According to historical data provided by the company, on average 60% of the total water treated is lost. Table 3-3 presents the main characteristics of the socio-technical sub-systems that form the WDS. This characterization provides useful contextual information for understanding the nature of the contributing factors to the losses, and their relationships.

Tabela 3-3 – Characteristics of the studied WDS

Subsystems	Main characteristics
Social	1,939 employees, including key positions indicated by the political parties in charge of the municipality
	Diverse levels of education, ranging from employees with incomplete elementary education to employees with a MSc. There are professionals from several areas: engineering (civil, electrical, mechanical, chemical, cartographic), chemists, biologists, business administrators, economists, accountants, lawyers and psychologists
	22% of employees are on leave for health treatment
	107 days are lost per year due to work accidents
	52,000 overtime hours per month
Organizational	The main practice to measure the water losses is the "Water balance"

	The company is certified by the ISO 9001 and OHSAS 18001 standards
Technical	Operational control center that monitors the water supply of the entire city
	Various types of equipment used in supplying, such as pumps, valves, and water trucks
	Six water treatment plants
	86 treated water pumping plants
	6 pumping plants of raw water
	99 reservoirs, with a total capacity of 200,509 m³ of water
	Treated water volume: 191,951,205.00 m³ / year
	Volume of billed water: 107,881,649.00 m³ / year
	Total extension of the water network: 4,095 km
External environment	Average consumption per person of 145 liters water / day
	The city has a population of 1,409,351 inhabitants
	Demographic density of 2,841 inhabitants / km²
	681,157 water economies
	Supply of 258,492 households, 33,265 businesses, 1,960 public offices and 7 industries
	Several political aspects involved, due to the fact that the company is public and of great visibility to the population
	The city supplied by the WDS has a Human Development Index (HDI) of 0.805, 0.702 in education, 0.857 in longevity and 0.867 in income
	Greater influence of urban unplanned growth, estimating that 8% of treated water volume is used without authorization in the poorest neighborhoods

3.4.2. Step 2: quantification of losses, identification and classification of contributing factors

As for quantification, Figure 1 presents the percentage of losses in relation to the total volume of treated water in the WDS, over a 1.5 year period (2017-2018). The monthly average losses (60%, Coefficient of Variation, CV = 12%) are almost twice the average of Southern Brazil (35.1%), with apparent losses (34%, CV = 12%) being always higher than real losses (25%, CV = 12%). According to all of the four interviewees, the higher incidence of apparent losses is likely due to the disordered urban expansion, which in turn is associated with irregular housing and lack of monitoring of frauds that lead to water theft. The extent of identified losses is consistent with data from other developing countries, which experience levels of water losses greater than 50% of the total treated water (Kadu & Dighade, 2015), with apparent losses accounting for 30%–40 % of this total (Lambert 2003).

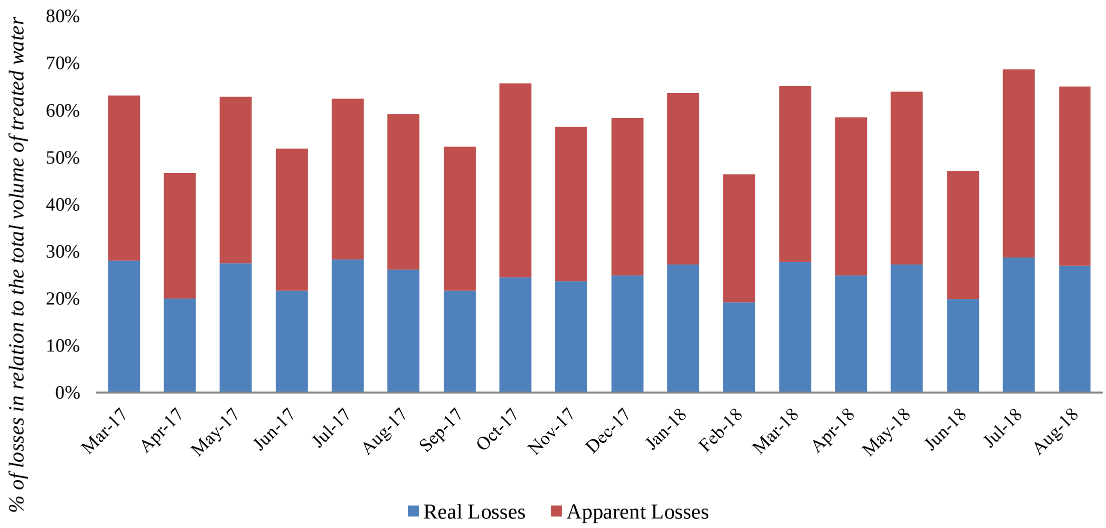

Figura 3-1 - Evolution of water losses in the studied company

Seventeen contributing factors obtained through interviews to the losses were identified and classified according to their association with real and apparent losses (Appendix 1, on-line). Most factors (11) are new in the sense that they had not been identified in a systematic literature review of losses in WDSs carried out by Azevedo and Saurin (2018), while others (6) correspond to different manifestations of factors mentioned by earlier studies.

An example of already cited factor (Smith et al., 2015; Marunga, 2006) refers to the networks portions that did not have District Metered Areas (DMA). This low sectorization creates too large networks, which amplify the impacts of repairs and leakages, implying financial losses due to non-billing, since more users have their supply interrupted.

In turn, "dead" networks can be cited as an example of new factor. These are obsolete networks that should have been deactivated, but they were not, due to the lack of effective organizational procedures for hiring contractors and the low quality of the service provided by these companies. These networks facilitate water theft and undetected leakages, because the customer is connected to the network without being billed. Although the company recently implemented new procedures to disable the old network when a new one is built, there is still a backlog of old networks that function in parallel with the newly built.

Another example of new factor refers to the outsourcing of the reading process, which has been in place since 2013. According to all of the interviewees, the low quality of the service provided by the outsourced companies is associated with a 37 % increase of user´s complaints due to inaccurate readings.

A competitive bidding process, which is mandatory by law, makes it difficult to hire the best qualified companies.

The two aforementioned examples illustrate the socio-technical nature of the problem of losses in WDSs, which is also indicated by the association between the seventeen contributing factors and the sub-systems of socio-technical systems, as follows (Appendix 3-1): 41% of the factors are associated with the work organization sub-system, 29% with the external environment, and 29% with the technical sub-system. This mixed nature is also consistent with the finding that 52.9% (n = 9) of the factors are associated with both apparent and real losses (Appendix 3-1).

3.4.3. Step 3: modeling of the interactions between the contributing factors

Figure 3-2 presents the causal-loop-diagram of the contributing factors and their consequences. Figure 3-2 indicates a salient reinforcement loop (R1) related to real losses. The model indicates that the greater the leaks the greater the costs associated with them. In turn, the greater the costs the lower the availability of financial resources for investments. Lower investments contribute to the deterioration of the WDS infrastructure, which then causes more leaks. This loop was perceived by the interviewees, as reported by one of the representatives of the operational area: "*If there is a cost and it is not in the tariff, we cannot invest so much…and if we cannot invest, we are returning to society less. This is a vicious circle*".

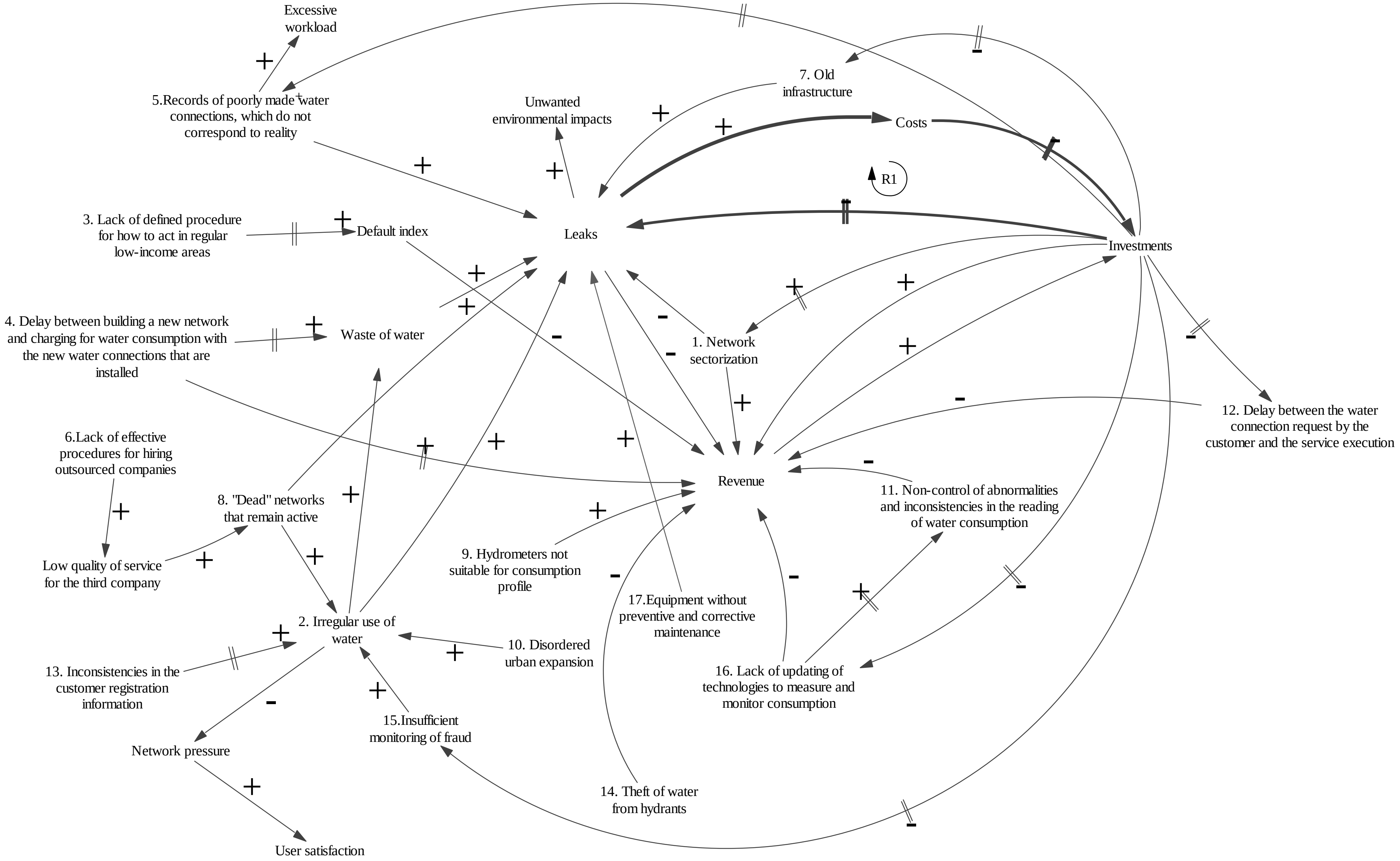

Figure 3-2 - Interactions between the contributing factors and their consequences

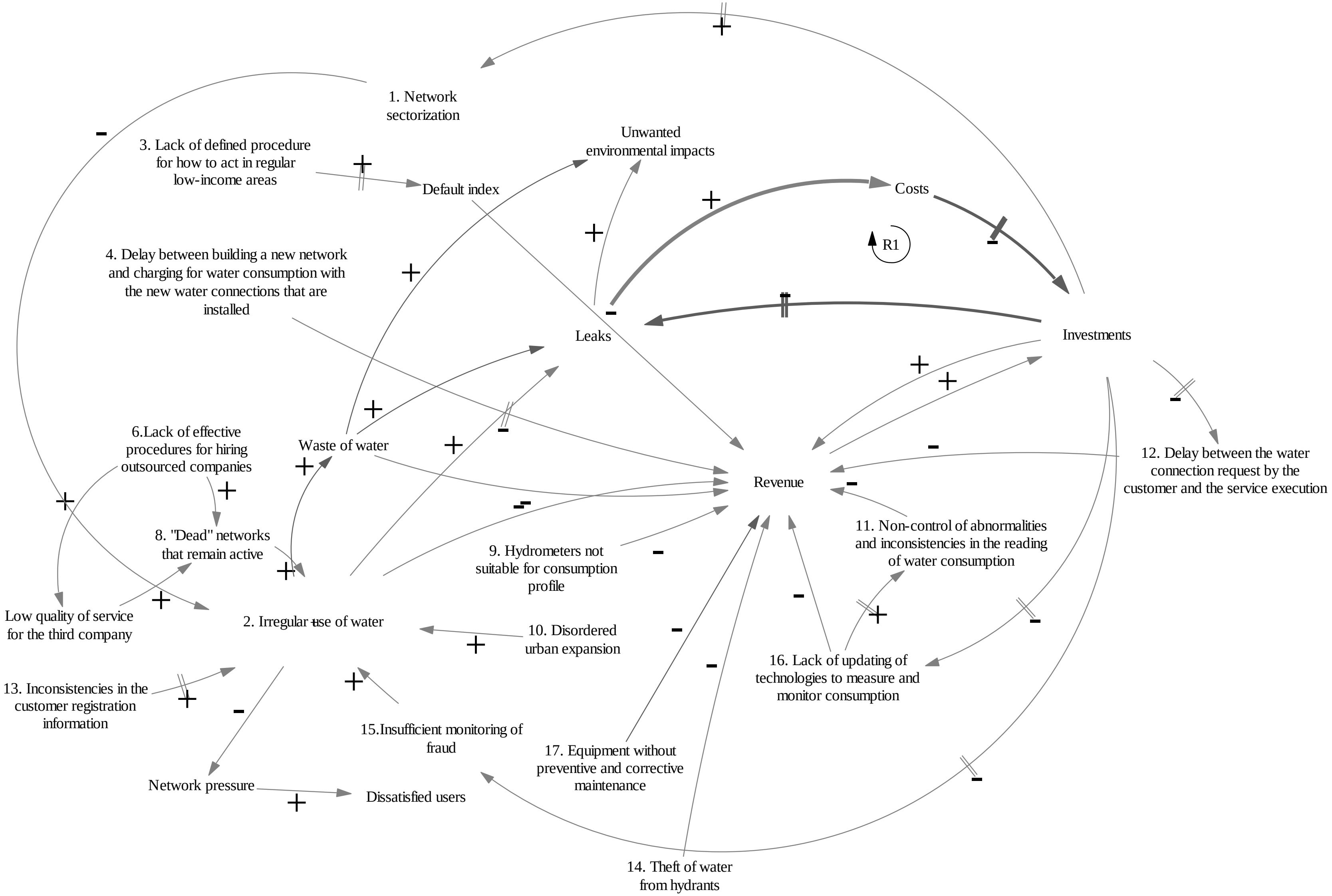

Figura 3-3 - Interactions between the contributing factors for **apparent losses** and their consequences

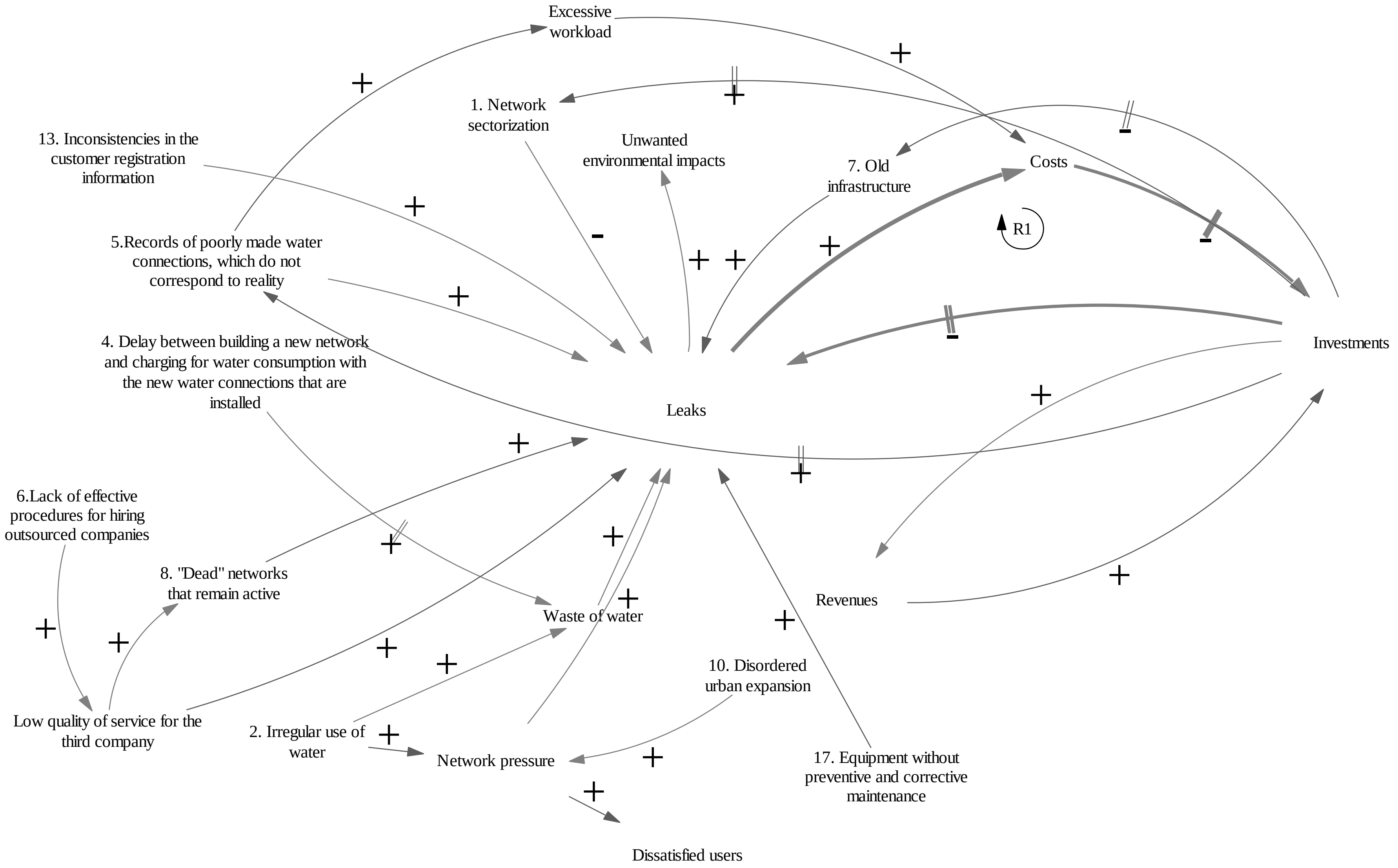

Figura 3-4 - Interactions between the contributing factors for **real losses** and their consequences

Notes: (i) variables identified by numbers correspond to the contributing factors listed in Appendix 1; (ii) the other variables are the consequences of the losses; (iii) the symbol —‖→ means that there is a delay in the cause-effect link.

In principle, undesirable reinforcing loops not subject to the influence of any external compensating variable could lead to system collapse. Since this has not yet occurred in the studied system, possible interpretations may be that the progress towards collapse is very slow (as indicated by the notation of delay over some of the arrows), and that there is substantial slack (e.g. surplus of sources of water), which keeps the system producing the required outputs. Also, long periods of drought are unusual in the geographical region of the water sources. This context can stimulate complacency from managers and government, which may not regard the losses as an urgent problem.

In fact, a similar reinforcing loop also occurs with apparent losses, since the lower the revenue the lower the availability of financial resources to tackle the causes of unauthorized use of water. The company's social function play a role in this loop, since this discourages aggressive policies of cutting-off unauthorized supply in socially vulnerable and irregularly occupied areas. Indeed, the company has no effective procedures to cope with frauds in these areas. As such, frauds are to some extent caused by the contributing factor "disordered urban expansion", since this might be followed by an increase in water theft, and crime in general. According to the two interviewed representatives from the operational area, there is a lack of security for the execution of services in these regions, which slows down the control of leaks and apparent losses.

In addition, it is possible that there are balancing factors that have not been identified in a long study, as they were not part of the questionnaire. An assumption is that the tariff charged for water consumption is a balancing factor that prevents or collapses the system, while the cost of use such as water losses may be included in the total tariff amount.

Figure 3-3 presents the causal-loop-diagram of the contributing factors for only apparent losses and Figure 3-4 presets the causal-loop-diagram of the contributing factors for only real losses. It is observed that the causal-loop-diagram of the contributing factors for apparent losses has more interconnections than the causal-loop-diagram of the contributing factors for real losses. Nine variables are not the causal-loop-diagram of the contributing factors for real losses: "Non-control of abnormalities and inconsistencies in the reading of water consumption"; " Delay between the water connection request by the customer and the service execution"; " Theft of water from hydrants"; "Insufficient monitoring of fraud"; "Lack of updating of technologies to measure and monitor consumption"; "Lack of defined procedure for how to act in regular low-income areas"; "Hydrometers not suitable for consumption profile"; "Default index"; and "Revenue".

This is due to the fact that 15 of the 17 (88.2%) factors found (available in Appendix 1) refer to apparent losses, while only 11 (64, 7%) refer to real losses. This reinforces the importance of understanding the causes of apparent losses for the management of water losses.

3.4.4. Steps 4 and 5: identification of loss control countermeasures and their delays

Table 3-4 presents the proposed countermeasures to cope with the contributing factors to losses. These countermeasures can cope with all of the contributing factors, and therefore they cover the four socio-technical sub-systems. Indeed, 67% (n = 14) of the countermeasures have a non-technical emphasis, which is consistent with the socio-technical nature of WDSs and losses.

Tabela 3-4 - Loss control countermeasures and the impacted socio-technical sub-systems

Nº	Factor	Countermeasures	Sub-systems impacted by the countermeasure
1	**Networks with little sectorization**	District Metered Areas (DMA)	Technical
2	**Irregular use of water**	Socio-educational work	External environment
		Apply fines for irregular use	External environment
3	**Lack of defined procedure of how to operate in regular areas of low income**	Negation of defaulting users	External environment
4	**Delay between building a new network and charging for water consumption with the new water connections that are installed**	Improvement of the technical registration process of water connections	Social
5	**Records of poorly made water connections, which do not correspond to reality**	Implementation of geo-referenced registrations	Technical
6	**Lack of effective procedures for hiring outsourced companies**	Requirement of higher qualification of contractors, with penalties for low quality services	Social
7	**Very old infrastructure**	Replacement of networks that have a higher incidence of water leaks	Technical
8	**"Dead" networks that remain active**	Identification and deactivation of inactive networks	Work organization
9	**Hydrometers not suitable for consumption profile**	Increased control of hydrometers	Technical
		Telemetry	Technical
10	**Disordered urban expansion**	Urban planning by the Municipality	External environment
11	**Non-control of abnormalities and inconsistencies in the reading of water consumption**	Software for analyzing reading abnormalities and inconsistencies	Technical
		Development of a task force to increase the frequency of inspections	Work organization
		Assessment of irregularities in property extensions	External environment
12	**Delay between the water connection request by the customer and the service execution**	Improvement in the process of commercialization of new water connections, so that the customer does not wait too long to start being supplied and charged	Work organization
13	**Inconsistencies in the customer registration information**	Development of an internal procedure to	Work organization
14	**Theft of water from hydrants**	Law enforcement	External environment

15	**Insufficient monitoring of frauds**	Increase of inspection frequency to identify frauds, regularization and customer notification	Work organization
16	**Lack of updating of technologies to measure and monitor consumption**	Use of technologies such as Telemetry and Radiofrequency to measure consumption	Technical
17	**Equipment without preventive and corrective maintenance**	Review of maintenance programs and plans	Work organization

A Path Analysis (PA) was carried out to compare the delays of a technical and a non-technical solution (Table 3-5): the implementation of DMAs as a technical approach; and the expansion of socio-educational work focused on changing the consumers' habits, as a non-technical approach. Figures 3-5 and 3-6 represent graphically the paths that countermeasures can take if implemented. In this case, the variables proposed as countermeasures for the variables that cause water losses act as leverage points that would boost part of the causal circuit diagram to reduce water losses. Countermeasure 1 (DMA) would be a leverage point for factor 1: Networks with little sectorization and countermeasure 2 (Socio-educational work) would be a leverage point for factor 2: Irregular use of water.

As for the DMA (countermeasure 1), it is expected to reduce water shortages, reduce water purge, and facilitate both repairs and the monitoring of water consumption (Smith et al., 2015; Marunga, 2006). Based on Figure 3-2, it is possible to observe that this countermeasure implies in two paths from cause to effect (these the two paths are summarized in Table 3-5 below): (i) through path (1), the DMAs imply in the reduction of networks with little sectorization (variable 1), and thus they have a direct effect in the reduction of leaks, and then on the reduction of unwanted environmental impacts – the delay of this path is three, since the implications of the countermeasures are fairly immediate and involve essentially technical links; (ii) through path (2), the DMAs contribute to the reduction of revenue losses, which then generates more resources for investments and the reduction of leaks. The delay of this path is seven, because the transformation of available resources for investments into practical actions may take time – non-technical factors play a role in this process.

As for the socio-educational work (countermeasure 2), there are two paths two. By focusing on socio-educational work in irregular areas of the city (variable 2), path (1) has a direct impact on the reduction of leaks, and then on the reduction of unwanted environmental impacts – the delay of this path is six, because it contains one significantly delayed cause-effect link. Regarding path (2), the revenue losses tend to be reduced, which contributes to an increase in the available resources for investments. The delay of this path is ten because it contains two significantly delayed cause-effect links: the one related to the transformation resources for investments into practical actions and the other related to the behavioural changes resulting from the socio-educational work. Regardless of the greater delay of the non-technical countermeasure, it certainly demands much less financial investment in comparison with the technical one. Therefore, in this case, it seems to be possible and desirable to apply both countermeasures jointly.

Table 3-5 - The relative impact of technical and non-technical countermeasures selected for analysis

Objective	Countermeasures	Path		Impact	Delay
Reduction of water losses	1. DMA	P1	C1 → 1→L→UEI	-	1+1+1=3
		P2	C1→1→ RL→RI→L	-	1+1+1+1+4=8
	2. Socio-educational work	P1	C2→2→L→ UEI	-	4+1+1=6
		P2	C2→2→ RL→RI→L	-	4+1+1+1+4=11

Notes: C1: countermeasure 1, DMAs; C2: countermeasure 2, socio-educational work; L: leaks; UEI: undesirable environmental impacts; RL: revenue loss; RI: reducing investments; 1: variable 1, networks with little sectorization; 2: variable 2, irregular use of water.

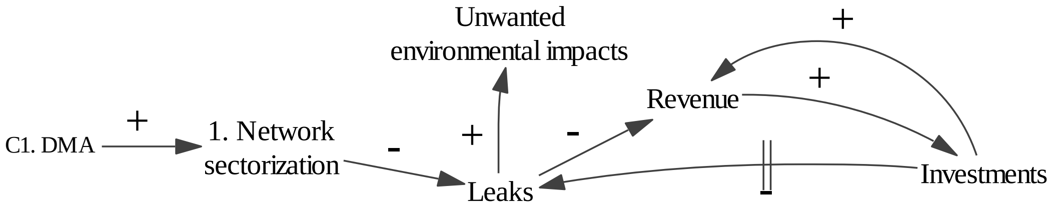

Figure 3-5 - Graphical representation of P1 and P2 for Countermeasure 1.

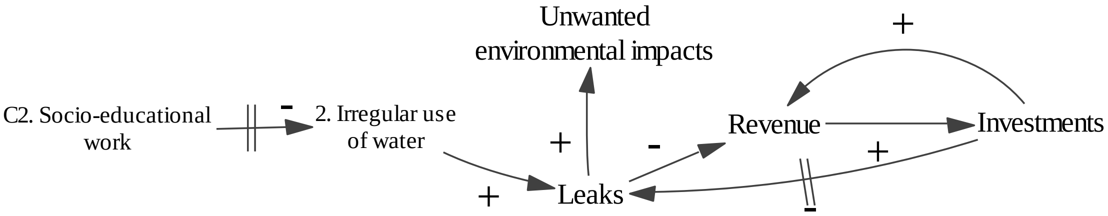

Figure 3-6 - Graphical representation of P1 and P2 for Countermeasure 2.

3.5. Discussion

3.5.1. Losses in WDSs as an emergent phenomena

The results of the empirical study indicated a wide range of contributing factors to losses in WDSs, also pointing out to the existence of dynamic interactions between these factors. Based on this, we propose to frame losses in WDSs as emergent phenomena, which are characterized by: (i) the impossibility of being fully controlled, but at best influenced to some extent (Buchli & Santini 2005); and (ii) arising from the interactions between several variables and having new properties, which do not exist in the individual parts (Cilliers 1998).

An immediate implication of the former characteristic is that losses, especially in highly complex WDSs, are impossible to be fully eliminated. Due to both the dynamics of the system and the strong influence by the external environment (as indicated by the empirical data gathered in this study), contributing factors will always find breaches in its defences. Thus, the design of strategies for minimizing the impacts of losses (e.g. through early warning systems) once these have occurred should be a concern, as a realistic complementary measure to the prevention of losses. However, what counts as the minimum tolerable level of loss for a certain degree of irreducible complexity is a question that requires further investigation. This insight also raises the question of how to reduce the portion of unnecessary complexity, through control actions that could be implemented given existing available resources – e.g. establishing a more rigorous process for hiring contractors in the studied company.

The second emergent characteristic aforementioned conveys that losses in WDSs have no single root cause. Although the literature stresses the role played by leaks and high network pressure, these are only the most visible outcomes of the interactions between a mix of several underlying socio-technical factors. Thus, it probably makes more sense to focus on bundles of countermeasures, which if applied together would have synergistic effects. The use of bundles of practices is a common and effective approach for coping with complex problems in other sectors, such as in the management of production in manufacturing plants (Shah and Ward, 2003) and patient care in hospitals (e.g. Miller III et al., 2013). The optimal mix of practices forming the bundles may be context-dependent to some extent, depending on the nature and intensity of the corresponding contributing factors.

3.5.2. Implications for the modelling and simulation of WDSs

The contributing factors and the correspondent countermeasures discussed in the previous Sections make it clear the socio-technical nature of WDSs and their losses. Furthermore, these factors evolve over time and their couplings are dynamic, which creates possibilities for non-linear interactions, when small changes in one variable may produce disproportionate outcomes. Thus, modelling and simulation approaches that consider only technical factors (e.g. Steffelbauer and Fuchs-hanusch, 2016, who studied the positioning of sensors to locate leaks), are likely to be too limited when attempting to predict the full impacts of contributing factors and control measures.

Thus, more robust modelling and simulation approaches for WDSs should account for their socio-technical nature. In this sense, hybrid modelling and simulation (Borshchev and Filippov, 2004) might be a more suitable approach, since it allows for the combined use of different models and simulations for different aspects of the WDS. For instance, while discrete-event simulation may be suitable for the technical aspects, agent-based-modelling or system dynamics may account more effectively for the social aspects. Although hybrid simulation has been a topic of growing practical and academic interest in several highly complex domains, such as logistics, transportation, and healthcare (Siebers et al., 2010), applications to WDSs are unknown so far.

3.6. Conclusions

3.6.1. Contributions of this study

The research question that guided this study was stated as follows: how to analyze, from a socio-technical systems perspective, the losses in WDSs? This question was answered by the framework proposed in Section 3.2, which allows for the identification of a broad range of socio-technical contributing factors, as well as for the exploration of their interactions. These characteristics of the framework were demonstrated through the study of losses in a real WDS, which provided empirical evidence of the need to model WDSs as socio-technical systems.

As such, in comparison with previous studies on losses in WDSs, a distinctive feature of this research is its holistic view. Losses in WDSs are framed as inseparable from their context, which is a result of thinking in terms of interconnections and causal links that are distant in space and time from agents' actions. Another original characteristic of this research study is the descriptive and contextualized presentation of the losses (in details, in Appendix 1), which should be mirrored by the loss control countermeasures.

Practical contributions should also be mentioned. In this sense, the framework can be a complement to the water balance method adopted by the company studied. Although the said method indicates the extent of the losses (see Figure 2), it gives little insight into the causal factors. Furthermore, the current loss control policies in the company are mostly limited to increasing the use of DMAs, while neglecting a broader range of socio-technical countermeasures.

3.6.2. Limitations

Two limitations of this research should be emphasized. First, there is a philosophical limitation in the sense that a complete description of complex socio-technical systems is impossible (Cilliers, 1998). Due to this, some contributing factors may not have been identified in the WDS studied. Second, the dynamic behaviour of the contributing factors and their interactions over time was not modelled and simulated.

3.6.3. Future research

Based on this study, some opportunities for further research can be mentioned, such as: (i) the application of the framework in other WDSs, in order to produce more generalizable qualitative and quantitative data on the nature of losses – this could shed light on the extent to which different contextual characteristics influences on losses; (ii) the development of computer simulations of the causal-loop-diagram, in order to explore the evolution of the variables over time and under different scenarios; (iii) to develop and assess the impacts of new practices to cope with the non-technical contributing factors to losses; and (iv) to assess the relationship between the complexity level of the WDS and the extent of losses.

3.7. Referências

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Appendix 3- 6- Contributing factors to water losses

N	Factor	Description	Real Losses	Apparent Losses	Socio-technical subsystems mostly associated with the origin of the factor	Authors who cited these factors in previous studies
1	**Networks with little sectorization**	Water networks that are too large (not sectorized) contribute to shortages of large areas, purging of a lot of water from the network, difficulty in monitoring the consumption in small areas, and greater complexity when performing repairs	Water leaks in non-sectorized networks tend to be larger than in sectoralized networks.	Difficulty in monitoring users' consumption, facilitating irregular use	Technical	Smith et al. (2015); Marunga (2006)
2	**Irregular use of water**	Irregular use of water has several undesired consequences, such as loss of revenues, uneven discharge of sewage into the soil, and leakages in the improvised water connections made by customers. In addition, users from higher regions of the city face low pressure in the water network, due to the irregular use of users from lower regions.	Excessive consumption amplifies the effects of water leaks.	Billing of these irregular customers is difficult	External environment	Xin et al. (2014); Marunga (2006); Agathokleous & Kourti (2016)
3	**Lack of defined procedure of how to operate in regular areas of low income**	The low-income areas, even in the regularized zones of the city, usually have higher default rates. According to the interviewees, this situation is encouraged by the non-inclusion of these customers in a list of defaulters. Legal and bureaucratic issues make it difficult the inclusion of customers in this list.		The increase in the default rate leads to increases in apparent losses.	External environment	
4	**Delay between building a new network and charging for water consumption with the new water connections that are installed**	There is a delay between the completion of the construction of new water networks and the charging for consumption. There are problems in the registration process of water connections due to bureaucratic issues, which generate billing losses and possible waste of water, since the user does not pay for consumption.	The possible waste of water due to non-billing amplifies the effects of leaks.	Due to bureaucratic internal problems of the company, the user obtains without paying for the consumption, generating apparent losses.	Work organization	
5	**Records of poorly made water connections, which do not correspond to reality**	Many water connections (registers, junctions, valves) are not georeferenced, which hinders	The difficulty in identifying the elements of the water network		Technical	

		their precise spatial location because they are underground.	delays the control of leakages.			
6	**Lack of effective procedures for hiring outsourced companies**	The company does not have effective procedures for hiring outsourced contractors who carry out works, which contributes to the poor quality of the delivered works, use of low-quality materials in the networks, and obsolete networks that should be deactivated but continue to operate in parallel with newly built networks	Poor quality materials generate leakage in the networks, which causes physical loss.	Obsolete networks that should be disabled generate irregular water supply.	Work organization	
7	**Very old infrastructure**	Networks that have a higher incidence of leakages and water shortages often take time to be replaced. This delay occurs mainly because of the lack of financial resources to update the infrastructure.	Old networks have a higher incidence of leaks.		Technical	(Wang et al. 2014; Kim et al. 2016; Gomes et al. 2013)
8	**"Dead" networks that remain active**	"Dead" networks are obsolete networks that should have been deactivated, but were not, due to factors 7 and 8 aforementioned. This situation facilitates water theft and leakages.	Irregular supply encourages excessive consumption, which in turn amplifies the effects of leaks.	Irregular water supply is not billed.	Work organization	
9	**Hydrometers not suitable for consumption profile**	Unsuitable hydrometers imply in imprecise measurements of consumption, which generate billing losses.		Imprecise measurements of consumption imply in imprecise billing	Technical	(Asadiyani & Burrows 2009; Kanakoudis et al. 2014)
10	**Disordered urban expansion**	The lack of an effective urban and housing planning on the part of the Municipality leads to a disordered and accelerated population growth in certain areas. Therefore, the water network becomes easily outdated, since the population density and growth are much greater than the company capacity of building new networks.	Disordered urban expansion stresses the infrastructure capacity in certain areas, thus amplifying the effects of leaks.	Water supply may become scarcer and irregular in disordered and crowded urban areas, thus encouraging illegal use by some customers	External environment	(Smith et al. 2015; Marunga 2006).
11	**Non-control of abnormalities and inconsistencies in the reading of water consumption**	Failure to track the origin of abnormalities and inconsistencies in reading		Failure to track the origin of abnormalities and inconsistencies in reading consumption makes it difficult to tackle apparent losses.	Work organization, Technical, External environment	(Mutikanga et al. 2011)

12	**Delay between the water connection request by the customer and the service execution**	Internal organizational processes are often slow and poorly designed, which contributes to delays in water connections requested by users.		The delay in serving the customer also delays the billing process	Work organization
13	**Inconsistencies in the customer registration information**	Due to the disordered urban expansion (factor 12) there is a conflict between the real customer's address and the address registered in the supply company. This implies in delays of several sorts, such as when performing a leak repair and when identifying water theft.	Leaks are amplified due to delays in repairs.	Delays in identifying water theft have financial implications	Work organization
14	**Theft of water from hydrants**	Law enforcement regarding stealing from fire hydrants is ineffective.	Stolen water is also a physical loss of water	Stolen water is not billed.	External environment
15	**Insufficient monitoring of frauds**	There is a lack of an inspection team to identify frauds and take appropriate measures regarding the offending user.		Failure to identify and control frauds encourages irregular water consumption.	Work organization
16	**Lack of updating of technologies to measure and monitor consumption**	The technological upgrade is difficult since new technologies are usually imported at a high cost. The current technologies in use by the company allow for consumption readings on a monthly basis, while recent technologies (still not in use by the company) allow for readings in much shorter intervals (e.g. every 15 min).		Outdated technologies used to measure user consumption make it difficult the identification of irregular consumption by the user.	Technical
17	**Equipment without preventive and corrective maintenance**	The lack of financial resources delay the effective implementation of an effective maintenance program of the company physical assets	Deteriorated physical assets are more prone to leakages	Pieces of equipment used to read consumption, if not properly maintained, can generate reading errors and imprecise billing.	Work organization

4. TERCEIRO ARTIGO: POPULAÇÃO URBANA E PERDAS EM SISTEMAS DE DISTRIBUIÇÃO DE ÁGUA: ANÁLISE SOB A PERSPECTIVA DE LEIS DE ESCALA EM CIDADES BRASILEIRAS

Bárbara Brzezinski Azevedo, Júlio Celso Borello Vargas, Tarcísio Abreu Saurin

Universidade Federal do Rio Grande do Sul (UFRGS), Av. Osvaldo Aranha, 99, Porto Alegre, CEP 90.035-190, Rio Grande do Sul, Brasil.

Abstract: Os sistemas de distribuição de água (SDAs) possuem altos níveis de perdas, as quais associadas à crescente escassez de água potável têm impulsionado esforços para operações mais eficientes. A literatura sobre as perdas em SDAs tem enfatizado atributos técnicos, tais como vazão e o tipo de solo no qual eles são assentados. O presente trabalho adota uma perspectiva mais abrangente, abordando os SDAs como sistemas sócio-técnicos complexos, que possuem relação de escala com sistemas de ordem superior, quais sejam as cidades em que estão localizados. Este trabalho apresenta a análise de SDAs de 968 municípios do sul do Brasil, avaliando a existência de relações de escala do tipo lei de potência entre a população urbana, o tamanho das redes de água e as perdas no abastecimento. Os resultados indicam que nas cidades com população a partir de 15.870 habitantes, seus SDAs seguem leis de escala, com as perdas crescendo de forma mais rápida que o crescimento populacional. Isso pode ocorrer em função do maior número de interações não completamente controláveis entre os elementos técnicos e sociais dos SDAs em cidades maiores.

Keywords: Water Distribution Systems, Water Losses, Complexity, Scaling laws, Socio-technical systems.

4.1. Introdução

Os sistemas de distribuição de água (SDAs), especialmente em países em desenvolvimento, apresentam altos níveis de perdas (Trojan & Morais, 2015), as quais associadas à crescente escassez desse recurso natural têm impulsionado esforços para operações mais eficientes. De fato, os benefícios obtidos com a redução de perdas em SDAs podem superar os benefícios obtidos com a ampliação de água tratada (Al-omari, 2013). Kingdom et al. (2006) estimaram que reduzir 50% das perdas de água no mundo seria suficiente para fornecer água tratada para mais de 100 milhões de pessoas por um ano.

Embora o Brasil conte com 12% dos recursos hídricos do planeta, ao distribuir água para garantir tal consumo, os sistemas sofrem perdas, que na média nacional alcançam 38,3% (Oliveira et al., 2018). Este é um tema de alta relevância no país frente a cenários de escassez hídrica e de altos custos de energia elétrica, além da sua relação direta com a saúde financeira dos prestadores de serviços (Oliveira et al., 2018).

Além disso, os SDAs estão profundamente integrados com vários aspectos da vida humana, incluindo o conforto do usuário, atividades de lazer e outros objetivos pessoais. Assim, pode-se considerar que SDAs são Sistemas Sócio-Técnicos complexos (SSTs), os quais são caracterizados pela interação dinâmica entre aspectos sociais, técnicos e econômicos, todos sujeitos ao ambiente externo como uma fonte permanente de incerteza (Dey & Lee, 2017). A perspectiva da complexidade tem sido amplamente utilizada para analisar sistemas sócio-técnicos de diversas naturezas, tais como sistemas de saúde, cadeias de suprimentos, sistemas de produção, sistemas aeronáuticos (Patorniti et al., 2017). Azevedo & Saurin (2018) realizaram uma revisão sistemática da literatura e identificaram 21 fatores que caracterizam a complexidade de SDAs, sugerindo que ela contribui para as perdas que ocorrem na distribuição de água. Até certo ponto, as perdas são inevitáveis, visto que *trade-offs*, grande número de elementos interagindo, variabilidade não antecipada e escassez de recursos não podem ser completamente eliminadas em SSTs.

De acordo com Sheng et al. (2013), a literatura sobre as causas das perdas em SDAs têm focado, por um lado, na estrutura física das redes (pressão e vazão d’água, por exemplo) e, por outro, na medição e faturamento do consumo, ao passo que as relações interdependentes entre as partes do sistema, bem como sua natureza sócio-técnica complexa recebem menos atenção. Skipworth et al. (1999) examinaram variáveis determinantes das perdas de água na Inglaterra, quais sejam: a pressão do sistema, a idade e o tipo de rede, o comprimento da rede de água, condição do solo, carga de tráfego e densidade das ligações de água. Güngör-Demirci et al. (2018) analisaram os fatores determinantes de perdas na Califórnia usando também um modelo de regressão de efeitos fixos. Esses autores concluíram que o tamanho da rede, a densidade de ligações de água e a receita operacional líquida estão associadas às perdas. Van den Berg (2015) analisou, por meio de um modelo de regressão em painel com efeitos fixos, perdas de água em 63 países em desenvolvimento. Os resultados apontaram a densidade populacional e o tamanho da rede de distribuição como os fatores que mais impactam nas perdas.

Por outro lado, pesquisas sobre sistemas complexos, tais como redes de distribuição de serviços básicos inseridas em cidades, consideram que uma de suas principais propriedades é a presença de *leis de escala* universais (Doctorale et al., 2015; Gleria et al., 2004; Newman, 2005). O termo escala, diz respeito à dimensão espacial ou temporal de um fenômeno de crescimento. Em sistemas urbanos, as leis de escala modelam, através de uma função do tipo lei de potência, como determinados fenômenos variam com o tamanho de uma cidade, geralmente medida por sua população (Barthelemy, 2019). Alguns autores indicam que existem relações quantitativas estáveis entre o ritmo da urbanização e o desenvolvimento socioeconômico, incluindo a implantação das infraestruturas, como energia elétrica, água e esgoto (Bettencourt et al., 2007; Meirelles et al., 2018).

Além disso, estatisticamente, os tamanhos de cidades e de SDAs apresentam histogramas com “caudas pesadas” que sugerem distribuições bastante assimétricas do tipo "lei de potência", também encontradas em muitos fenômenos naturais com propriedades análogas aos SSTs: inúmeros objetos pequenos e poucos objetos grandes; muitos eventos pequenos e raros eventos grandes (Salat et al., 2014). Essa estrutura pode ser detectada em sistemas que envolvem fluxos e interações, desde biológicos e geográficos até sociais e econômicos como estruturas pulmonares, bacias hidrográficas, redes de cidades e sistemas de distribuição de água (Salat et al., 2014).

Uma visão clássica da evolução espaço-temporal das cidades é que os espaços urbanos são o resultado de um planejamento urbano centralizado. Porém, a teoria de sistemas complexos indica que as cidades, assim, como os SDAs que são subsistemas inseridos em sistemas urbanos maiores, podem ser entendidos como resultado de processos descentralizados de auto-organização. Assim, parece promissor que as decisões de planejamento sejam embasadas em estruturas existentes e futuras (por exemplo, a expansão de uma rede de água que abastecerá uma nova população num futuro próximo) (Kühnert et al.,2006). Porém, para futuras expansões ou até mesmo o gerenciamento atual de SDAs é importante identificar os mecanismos que atuam por trás de estruturas urbanas e suas leis de dimensionamento, identificando como as perdas ocorrem nesse processo. Sendo assim, o objetivo principal deste artigo é estudar qual é a relação existente entre a população das cidades, tamanho dos SDAs e a quantidade de perdas na distribuição de água, verificando se essa relação obedece a funções de escala não-lineares como *leis de potência.*

Um estudo quantitativo com um banco de dados de 968 municípios da região sul do Brasil avalia a hipótese de que variáveis de tamanho de SDAs e suas perdas escalam conjuntamente com a população das cidades de forma não-linear obedecendo a uma lei de potência. O restante do texto é organizado como segue: a **seção 2** descreve a presença de leis de escala em SSTs. A **seção 3** apresenta uma introdução às variáveis causadoras de perdas de água. Na **seção 4** é apresentado o método empregado para a realização do estudo empírico. A

seção 5 apresenta os resultados obtidos, a **seção 6** faz a discussão destes e a **seção 7** traz a conclusão do artigo e sugestões para pesquisas futuras.

4.2. Leis de Escala

Nas ciências sociais, a ideia de concentração e hierarquia inerente aos sistemas complexos foi descrita por Pareto no início do século XX e por George Zipf na década de 1940. Em ambos os casos, a posição no *ranking* (ordem) de cada elemento (pessoa, palavra) tem uma relação com o valor a ele atribuído (fração das terras, frequência de aparição). Portanto, a distribuição segue uma lei que permite inferir o valor de um elemento a partir de outro, calculando a razão entre seus valores (Salat & Bourdic, 2011).

Em sistemas urbanos essa lei de escala é uma lei do tipo potência pode ser descrita pela equação (1)

$$Y \sim X^{b} \quad (1)$$

Onde Y é a variável, quantidade ou observação que se deseja analisar, X é a variável de tamanho que escala Y (por exemplo, a população de uma cidade) e b é o expoente, que geralmente é positivo (Barthelemy, 2019). A distribuição de frequência de variáveis que possuem a forma da equação (1) é dita "independente de escala" ou "invariante", pois resiste a transformações nos dados do tipo $Y \sim aX^{b}$ (a =1.000 ao passar de metros para quilômetros, por exemplo) sem perder a forma da equação (1). A equação 1 também implica que a quantidade per capita se comporta como $Y/X \sim X^{b-1}$ e, no caso linear (b =1) e Y/X é independente do tamanho da cidade. Nos casos em que $b \neq 1$ a quantidade per capita depende de X e, portanto, varia de acordo com o tamanho da cidade (medido em número de habitantes) e essa relação não é linear (Barthelemy, 2019).

West (2017) analisou o fenômeno da quantidade e escalamento de postos de abastecimento de combustível em cidades de diferentes tamanhos, concluindo que, quanto maior a cidade, menor o número de postos per capita: cada posto de uma grande cidade atende mais pessoas e vende mais combustível do que os de uma cidade pequena. Bettencourt et al. (2007) estudaram regimes de escala com dados de diversos países e estimaram três classes de variáveis de acordo com o valor de b. O suprimento de água, medido em habitantes com ligação ativa, foi enquadrado como variável do tipo “serviços básicos individualizados”, escalando de forma linear com a população. A extensão das redes de água foi considerada como variável de “infraestrutura”, apresentando consistentemente b <1 (relação sublinear). Por outro lado, indicadores de “atividade social” como número de diplomas universitários, patentes registradas ou ligação de água apresentaram b >1 (relação superlinear).

Redes de infraestrutura como as de distribuição de água são resultado de planejamento, investimentos centralizados e obras físicas, geralmente, longas, portanto, sua implantação se desenvolve de forma mais lenta em relação ao crescimento da população da cidade. Já indicadores socioeconômicos (como o número de depósitos bancários ou número de homicídios) tendem a se manifestar de forma mais rápida. Surge então a hipótese de que as dinâmicas baseadas em interação humana são vetores do crescimento das cidades, enquanto as redes de infraestrutura são consequências desse crescimento (Bettencourt et al., 2007; Meirelles et al., 2018).

No mesmo estudo de Bettencourt et al. (2007) foi analisada a variável "perdas em redes de distribuição de energia elétrica" de diversas cidades e encontrado b= 1,11 na escala com a população, considerando apenas as perdas reais por dissipação de calor em cabos e componentes. Portanto, as perdas de energia elétrica escalam com o tamanho da população urbana e apresentam uma relação superlinear, indicando que conforme a população cresce, as perdas em energia elétrica crescem de forma mais rápida. De modo similar, Meirelles et al. (2018) verificou, com base em estudo em 5565 cidades brasileiras, que as seguintes variáveis socioeconômicas analisadas seguem uma relação de escala superlinear com o tamanho da população, como: Produto Interno Bruto (b=1,15); número de Organizações não governamentais (b=1,19); número de habitantes atendidos por coleta de lixo (b= 1.12) e número de habitantes com medição de eletricidade (b= 1.08). Porém, no mesmo estudo os autores identificaram que as seguintes variáveis de infraestrutura apresentaram uma relação de escala sublinear com o tamanho da população, tais como: frequência de amostragem de efluentes de esgoto (b=0.91) e tamanho da rede de ruas (b=0.77).

4.3. Perdas em SDAs

Em SDAs, as perdas costumam ser classificadas como aparentes ou reais. As perdas aparentes expressam a quantidade de água não faturada devido ao consumo não autorizado e às imprecisões do sistema de medição. Assim, as perdas aparentes representam parte da água do sistema que realmente é consumida, mas não é paga. As perdas reais expressam a quantidade física da água perdida devido a vazamentos (Ríos et al., 2014). Globalmente, 48 bilhões de metros cúbicos /ano de água são distribuídos e não faturados como receita pelas empresas de saneamento, sendo que as perdas reais representam 66% desse montante (Kingdom et al., 2006; Mamade et al., 2015).

Quanto às causas das perdas em SDAs, uma revisão de literatura realizada por Azevedo e Saurin (2018) apresentou 21 fatores que causam perdas de água identificados em 49 artigos selecionados na revisão relacionados a cinco atributos de complexidade presentes em SDAs: grande número de elementos, interações não lineares, diversidade de elementos variabilidade não antecipada e resiliência.

O presente artigo ao analisar qual é a relação existente entre a população das cidades, tamanho dos SDAs e a quantidade de perdas na distribuição de água, verificando se essa relação obedece a funções de escala não-lineares como leis de potência, abordam-se os atributos de complexidade de grande número de elementos e interações não-lineares.

Relacionado ao atributo grande número de elementos (o sistema possui muitos elementos que interagem dinamicamente), os autores citam como fator causador de perdas o grande número de consumidores, que decorre da rápida urbanização gerando uma grande população urbana concentrada em espaços pequenos aumentando a pressão pela demanda de água e redes distribuição de água extensas, cada vez maiores e mais difíceis de gerenciar.

Relacionados ao atributo interações não-lineares (significa que pequenas mudanças nas condições iniciais podem causar efeitos dramáticos no comportamento do sistema), os autores citam como alguns fatores como exemplo: pressão na rede de abastecimento de água (a alta pressão leva ao aumento de vazamentos) vazamentos não detectados (vazamentos não relatados que não são tão facilmente detectados).

4.4. Método de Pesquisa

4.4.1. Coleta e preparação dos dados

Os dados foram extraídos da série histórica do Sistema Nacional de Informações em Saneamento (SNIS) e da base de dados do Instituto de Pesquisa Econômica Aplicada (IPEA) que correspondem à população de interesse, quais sejam os municípios da região sul do Brasil. A região é formada por três Estados – Rio Grande do Sul, Santa Catarina e Paraná – tem

29.754.036 habitantes e densidade populacional de 51,9 habitantes/km². Possui 19.801.709 veículos (0,66 automóveis por habitante), renda mensal domiciliar per capita de R$ 1.657,00. O índice de Desenvolvimento Humano (IDH) é de 0,75, sendo que 99,77% da população está abastecida com rede de água e 47,8% com rede de esgotamento sanitário (IBGE, 2019). Seus operadores prestam serviços de distribuição de água e saneamento básico para 23,5 milhões de habitantes, o que representa cerca de 90% da população total da região sul.

A base de dados do SNIS contém informações preenchidas pelos prestadores de serviço de saneamento em formulários específicos, disponíveis gratuitamente no sítio *www.snis.gov.br*. Os dados utilizados neste estudo foram coletados do componente “Água e Esgotos” que reúne informações e indicadores, informados pelos prestadores de serviço de saneamento anualmente. Foram usados os dados mais recentes disponibilizados na execução deste artigo, que são os do ano de 2017. O banco possui 214 campos, organizados em blocos como segue:

- 10 campos de identificação dos SDAs;
- 59 campos referem-se a dados, do tipo “quantidades”, relativos à distribuição de água dos SDAs, como perdas na distribuição, população total atendida, quantidade de economias ativas de água (casa ou apartamento) , quantidade de ligações (conjunto de economias) ativas de água micromedidas;
- 21 campos referem-se a dados sobre tratamento de esgoto, como população total atendida com esgotamento sanitário, quantidade de ligações ativas de esgotos, extensão da rede de esgotos;
- 49 campos referem-se a dados financeiros das prestadoras, tais como: créditos de contas a receber, despesa com produtos químicos, investimento realizado em abastecimento de água, tarifa média praticada;
- 19 campos referem-se a dados sobre qualidade na prestação do serviço em relação aos consumidores como quantidade de reclamações ou solicitações de serviços, quantidade de paralisações no sistema de distribuição de água; e por fim,
- 56 campos referem-se a indicadores de desempenho dos prestadores de serviço, tais como: índice de produtividade (economias ativas por pessoal próprio), despesa média anual por empregado, índice de macromedição (volume de água macromedida, valor da soma dos volumes anuais de água medidos por meio de macromedidores permanentes existentes nas estações de tratamento de água,

sobre o volume total produzido), Consumo micromedido por economia, Índice de tratamento de esgoto, Extensão da rede de água por ligação, Extensão da rede de esgoto por ligação, Consumo médio *per capita* de água, Índice de atendimento urbano de água (População urbana atendida com abastecimento de água sobre População urbana residente dos municípios com abastecimento de água).

Geralmente dados históricos contêm campos inválidos ou não informados pelo prestador de serviço. Neste banco de dados foram excluídas as observações incompletas, bem como as que não continham as informações de todas as variáveis de entrada no ano de 2017. Ainda, registros com valores 0 (zero) para população, perdas ou variáveis de tamanho da rede foram excluídos, bem como um único caso de município com prestador de serviço de natureza jurídica “OS” – Organização Social. Assim, a partir do conjunto de dados original com 1.190 SDAs do SNIS, duzentos e vinte dois registros (222) foram removidos devido aos critérios citados. A amostra final compreendeu 968 sistemas – cada um correspondente a um município da região sul do Brasil.

4.4.2. Análise dos dados e modelagem estatística

Foram encontradas baixas correlações de Pearson entre as perdas de água e as variáveis relativas a operação dos serviços em relação aos consumidores, como: quantidades de paralisações no sistema de distribuição de água (0,46); duração das paralisações (0,38), e quantidade de economias ativas atingidas por paralisações (0,29). Por outro lado, algumas variáveis pertencentes ao bloco das quantidades (59 campos) apresentaram correlações de Pearson mais altas com as perdas: volume de água produzido ($r=0,91$ $p<0,01$), extensão da rede de água ($r=0,93$ $p<0,01$), ligações de água ($r=0,96$ $p<0,01$), economias de água ($r=0,95$ $p<0,01$). Portanto, estas foram selecionadas como variáveis para a análise da lei de escala.

Essas variáveis foram classificadas nas categorias propostas por Bettencourt et al. (2007), quais sejam: *tamanho da cidade*; *prestação de serviços individuai*s e *infraestrutura*; conforme a Tabela 4-1.

Tabela 4-1- Variáveis selecionadas para ajuste dos dados a leis de potência

Categorias	Variável	Descrição	Unidade de medida
Tamanho da cidade	POP_URB	População urbana	Habitantes
Serviços básicos individualizados	LIG_AG	Ligações ativas de água	unidades
	ECO_AG	Economias ativas de água	unidades

Infraestrutura	EXT_RED	Extensão da rede de água	1.000 metros
	VOL_PROD	Volume de água produzido	1.000 metros cúbicos/ano
	VOL_CONS	Volume de água consumido	1.000 metros cúbicos/ano
	Perdas	Perdas na Distribuição	1.000 metros cúbicos/ano

A utilização da medida "população urbana", que corresponde àquela que ocupa a área legalmente definida pela administração do município como *urbana* foi priorizada em relação à população total nos modelos, pois os SDAs são implantados e operados predominantemente nas áreas urbanas. Em áreas rurais e semi-urbanizadas as soluções de abastecimento costumam ser individualizadas.

Para analisar as distribuições e estimar o escalamento conjunto entre as variáveis foram utilizados estimadores propostos por Gillespie (2014), com auxílio do código "*poweRlaw*", no software "R" (http://www.r-project.org/). O software "R" contém funções para ajustar, comparar e visualizar distribuições de "cauda pesada" e adequar funções a leis de potência, permitindo verificar, através da estimação do parâmetro "b", citado na seção 4.2, se a relação entre população das cidades, tamanho dos SDAs (definido pelas variáveis de serviços básicos individualizados e de infraestrutura) e quantidade de perdas na distribuição de água obedece a funções de escala não-lineares como uma **lei de potência.**

Para ajustar uma lei de potência a um conjunto de dados é necessário estimar um valor mínimo a partir do qual os dados apresentam esse comportamento (Barthelemy, 2019). Tradicionalmente, isto é realizado, plotando os valores em escala logarítmica - log_e das ocorrências no eixo Y e log_e das variáveis representativas de tamanhos em X e verificando o ajuste de uma reta aos pontos. Porém, a plotagem da *função de distribuição acumulada* (*CDF*) é superior, pois calcula em Y a probabilidade da variável X ser menor ou igual a um valor real *x*. Assim, Gillespie (2014) sugere plotar este gráfico acrescido das linhas de máxima verossimilhança estimadas e, a seguir, verificar o ajuste através de "*bootstraping*" para testar a hipótese de que os dados se ajustam a lei de potência. Esse teste de ajuste estima um valor-p que, se maior do que o nível de significância adotado impede de rejeitar a hipótese nula e descartar a lei de potência.

Dentre os parâmetros, estão: *xmin* que é o valor de base a partir do qual a lei de potência se ajusta aos dados, estimado via teste de Kolmogorov-Smirnov; *ntail* o número de casos na porção ajustada; *par* o parâmetro da distribuição power law ou expoente b; *gof* a melhor qualidade de ajuste ("goodness-of-fit"), correspondente ao expoente estimado e p-value, a estatística de teste da hipótese de que a distribuição segue a lei de potência, com alfa = 0,01. Os expoentes (b) consistentemente diferentes de "1" indicam que a relação ordem/tamanho de cada variável segue uma lei de potência. Assim, verifica-se que a variável efetivamente não segue uma distribuição normal e sim uma lei de potência.

Os expoentes (b) do escalamento conjunto das variáveis podem ser estimados através uma de regressão por Mínimos Quadrados Ordinários (MQO) entre o logaritmo de cada variável descrita na Tabela 4-1, log(Y) e o logaritmo da variável principal "população urbana" (X). Os expoentes que apresentarem valores acima de "1" indicam que a variável possui uma relação superlinear com a população, já os que apresentarem valores abaixo de "1" indicam que a variável possui uma relação sublinear (Meirelles et al., 2018).

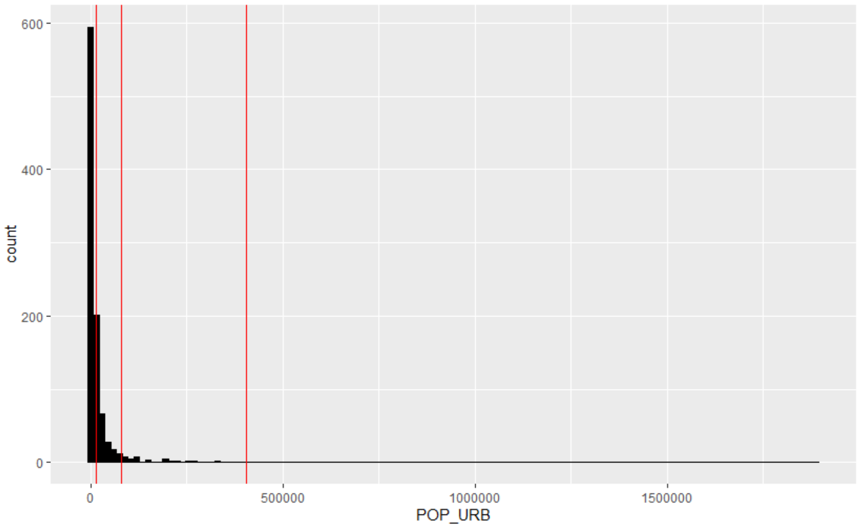
4.5. Resultados

4.5.1. Análise das variáveis selecionadas

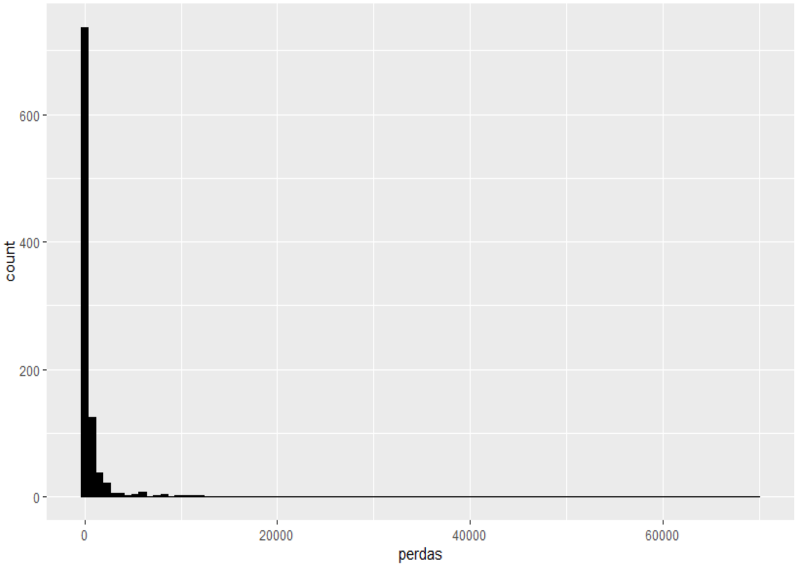
A Tabela 4-2 apresenta as estatísticas descritivas das sete variáveis selecionadas para ajuste a leis de potência.

Tabela 4-2 - estatísticas descritivas das variáveis selecionadas para análise das leis de potência.

Variável	**N**	**Média**	**Desvio Padrão**	**Coeficiente de Variação**	**Mínimo**	**Mediana**	**Máximo**	**Assimetria**
POP_URB	968	22.912	91.334	398,63	262	4.920	1.893.997	14,07
LIG_AG	968	7.133	22.823	319,95	132	1.947	478.832	12,62
ECO_AG	968	9.546	38.754	405,95	146	2.155	778.966	14,66
EXT_RED	968	124	338,7	272,96	1	43,8	7.327.5	12,82
VOL_PROD	968	2.248	10.146	451,31	19	371	194.926	13,76
VOL_CONS	968	1.441	6.474	449,13	13	269	119.131	13,15
Perdas	968	766	3.307	431,86	1	103	70.080	13,03



a)



b)

Figura 4-1- Histogramas de frequência das variáveis selecionadas a) População Urbana, b) Perdas Absolutas na Distribuição

Os resultados deixam evidente a grande variação dos valores, desde cidades com 262 habitantes urbanos e apenas 132 ligações ativas de água (Barra Bonita/SC), até metrópoles como Curitiba e Porto Alegre que têm populações acima de 1,5 milhão de habitantes e quantidade de ligações próximas a 500.000. Os histogramas das demais variáveis analisadas encontram-se no Apêndice 1. Na Figura 4-1a) estão plotadas três linhas tracejadas correspondentes a limiares dessas ordens de magnitude: 15.000 habitantes (com 75% das cidades abaixo desse valor), 80.000 habitantes (95%) e 400.000 habitantes (99,5%).

Para verificar se as variáveis possuem distribuições compatíveis com as leis de potência foram conduzidos os procedimentos descritos na seção 4-4. Os resultados são apresentados na Tabela 4-3, a qual apresenta também os parâmetros estimados de ajuste a leis de potência para cada variável da Tabela 4-1.

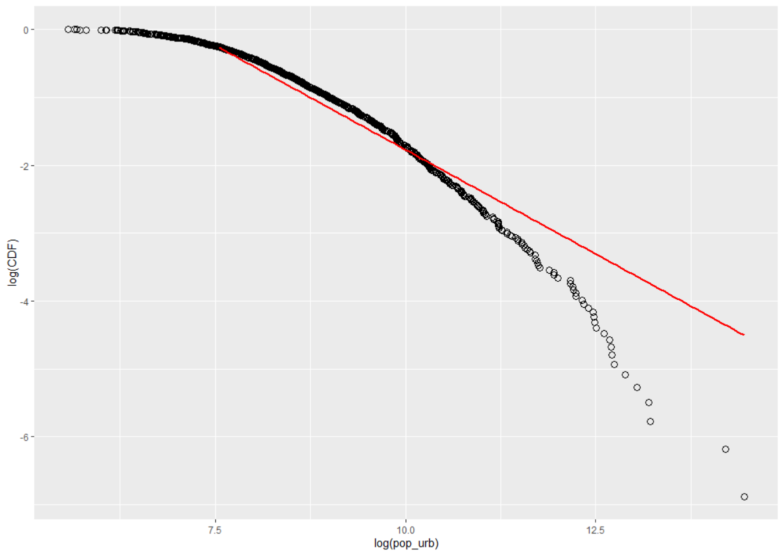
Tabela 4-3 - Parâmetros estimados para as distribuições de potência

Variável	Categoria	N	x min	par / b	gof	ntail	p-value
POP_URB	Tamanho da cidade	968	15.870	1,983	0,032	235	1,00
LIG_AG	Serviços básicos individualizados	968	4.399	2,020	0,044	291	1,00
ECO_AG		968	5.520	1,952	0,040	264	0,94
EXT_RED	Infraestrutura	968	115	2,210	0,033	236	0,97
VOL_PROD		968	650	1,789	0,043	351	0,94
VOL_CONS		968	903	1,915	0,034	215	0,96
Perdas		968	82	1,644	0,042	542	0,88

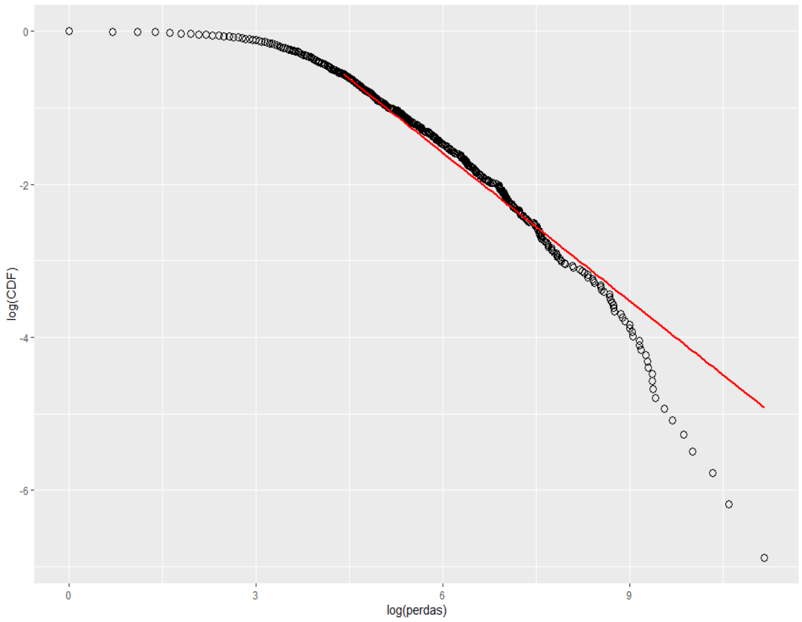
Onde *xmin* é o valor de base a partir do qual a lei de potência se ajusta aos dados, estimado via teste de Kolmogorov-Smirnov; *ntail* o número de casos na porção melhor ajustada; *par* o parâmetro da distribuição *power law*, ou expoente *b*; *gof* a melhor qualidade de ajuste ("*goodness-of-fit*"), correspondente ao expoente estimado e *p-value* a estatística de teste da hipótese de que a distribuição segue a lei de potência, com alfa = 0,01.

Os expoentes (par/b) consistentemente diferentes de "1" indicam que a relação *frequência/tamanho* de cada variável efetivamente não tende a um valor típico central, mas sim que o conjunto de dados possui alta frequência de cidades e redes pequenas, média frequência de cidades e redes médias, pequena frequência de elementos grandes (por exemplo, Joinville, Blumenau, Londrina, Caxias do Sul, Maringá, Pelotas) e mínima frequência de cidades muito grandes, os dois *hubs* regionais: Porto Alegre e Curitiba.

A Figura 4-2 apresenta os gráficos de probabilidade acumulada em escala logarítmica (log_e) das ocorrências no eixo Y e log_e das variáveis representativas de tamanhos no eixo X com reta de ajuste à distribuição potência das variáveis. A dispersão dos pontos nessa figura apresenta curvatura acentuada e relativo ruído nas extremidades, especialmente nos menores valores de log(X). Porém, os valores-p resultantes dos testes sumarizados na Tabela 4-3 permitem aceitar que as distribuições se ajustam a uma lei de potência para todas as variáveis e os parâmetros *xmin* e *ntail* mostram qual a porção da amostra onde se verifica o melhor ajuste. Essas porções (*ntail*) são relativamente pequenas em relação à amostra total de 968 cidades, devido à grande variação dos valores citada acima.


0
-2
-4
-6
log(CDF)
7.5
10.0
12.5
log(pop_urb)

a)


0
-2
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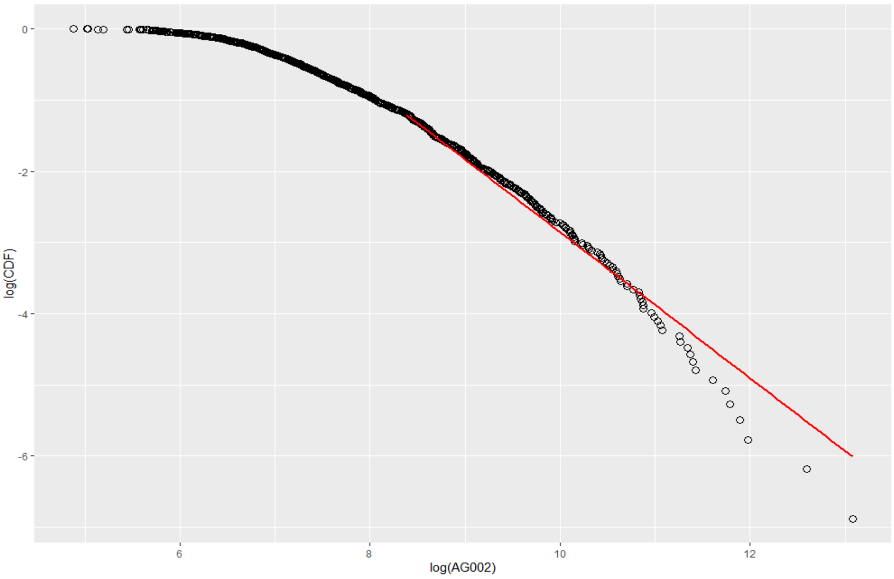
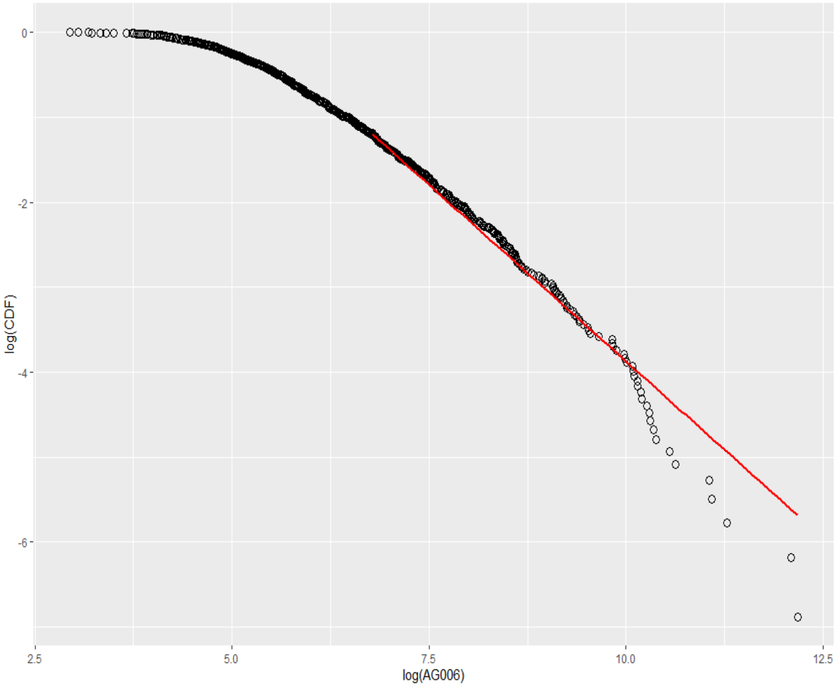
-6
log(CDF)
0
3
6
9
log(perdas)

b)



c)

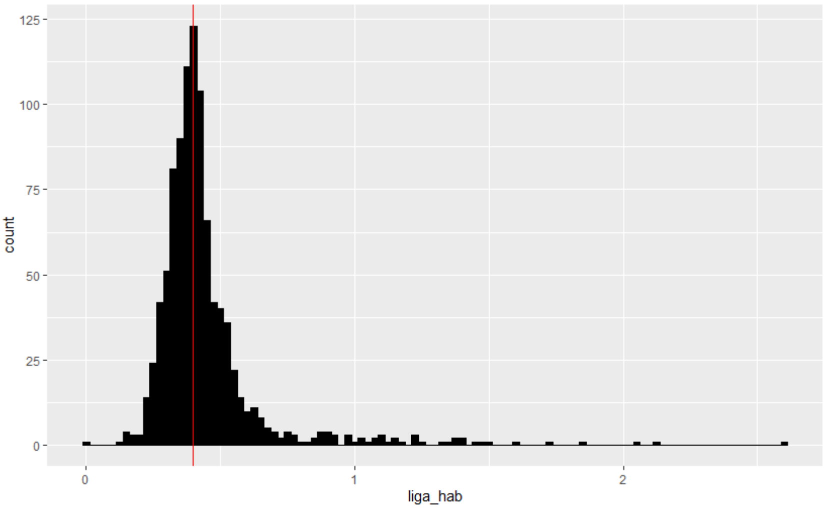


d)

Figura 4-2- Gráficos de probabilidade acumulada (log x log) com reta de ajuste à distribuição potência das variáveis a) População Urbana, b) Perdas Absolutas na Distribuição, c) Ligações ativas de água e d) Volume de água produzido

É importante frisar a diferença de comportamento das variáveis do tipo “per capita”, ligações ativas de água e economias ativas de água, analisadas nesse estudo. As variáveis referentes aos serviços básicos individualizados cujas medidas são em unidades (ligações, economias) poder-se-ia pensar, inicialmente, que apresentam uma relação perfeitamente linear com a população, no qual a cada adição de uma unidade de infraestrutura, corresponderia a adição de um domicílio. Neste caso o ritmo de desenvolvimento seria constante e trivial: a cada unidade de habitantes, uma unidade residencial, uma ligação de água, uma de esgoto e uma de energia. Portanto, em uma situação hipotética de atendimento total com abastecimento, as razões ligações por habitante e ligações por economia deveriam ser sempre iguais a 1 (um), com distribuição uniforme.

Porém, a Figura 4-3**Figura 4-2** indica que a distribuição da medida das perdas absolutas na distribuição tem um bloco concentrado com forma aproximadamente gaussiana em torno de valores abaixo de 1, mas a assimetria causada por algumas cidades com altíssimas perdas por economia lança a média para a direita e desvia a distribuição da normalidade. Já as perdas por economia deveriam, em tese, aproximar-se de uma curva normal, dado que são quantidades contínuas medidas em metros ou litros e cujo comportamento per capita, a princípio, não tem relação com o tamanho da cidade. No entanto, novamente o que ocorre é uma distribuição que parece se aproximar da lognormal, com cauda relativamente longa, o que pode indicar a relação de escala existente entre as perdas por economia e o tamanho da cidade.



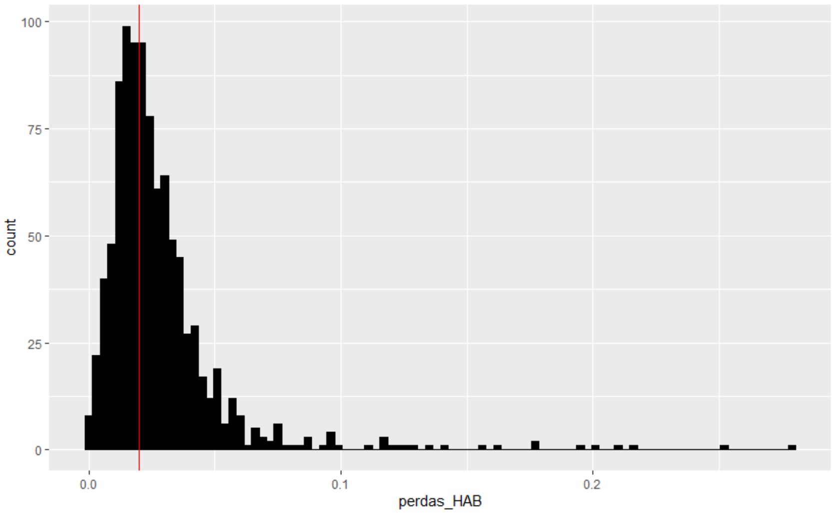


Figura 4-3- Histogramas de frequência das variáveis ligações por economia (acima) e perdas por economia (abaixo).

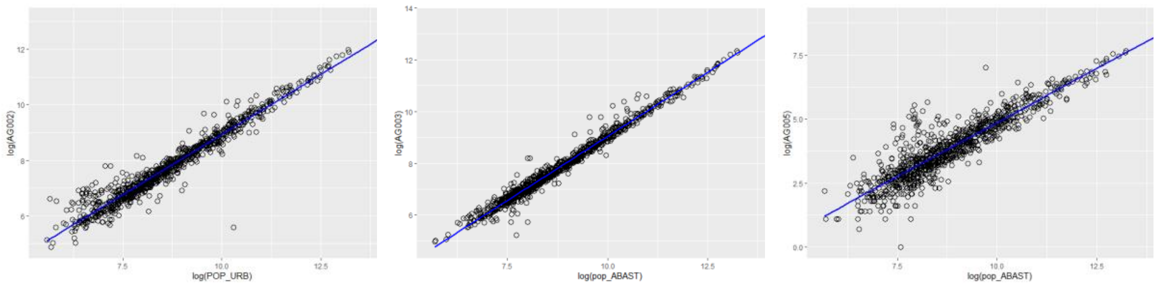
4.6. Modelagem das relações de escala

Através de regressão por MQO entre o logaritmo de cada variável descrita na Tabela 4-1, log(Y) e o logaritmo da variável principal "população urbana" (X), foram estimados os expoentes do escalamento (b) conjunto das variáveis. As estatísticas principais dos modelos estão na Tabela 4-4 e os gráficos de dispersão com retas de ajuste na Figura 4-4.

Tabela 4-4- estatísticas dos modelos de regressão linear entre a população urbana (logX) e as variáveis-chave dos SDAs (logY).

Y	Perdas	LIG_AG	ECO_AG	EXT_RED	VOL_PROD	VOL_CONS
Intercepto	*-4,461*	*0,292*	*0,071*	*-2,167*	*-2,224*	*-2,33*
X coeficiente (b)	*1,070*	*0,863*	*0,904*	*0,734*	*0,968*	*0,937*
R^2	*0,806*	*0,943*	*0,951*	*0,729*	*0,902*	*0,894*

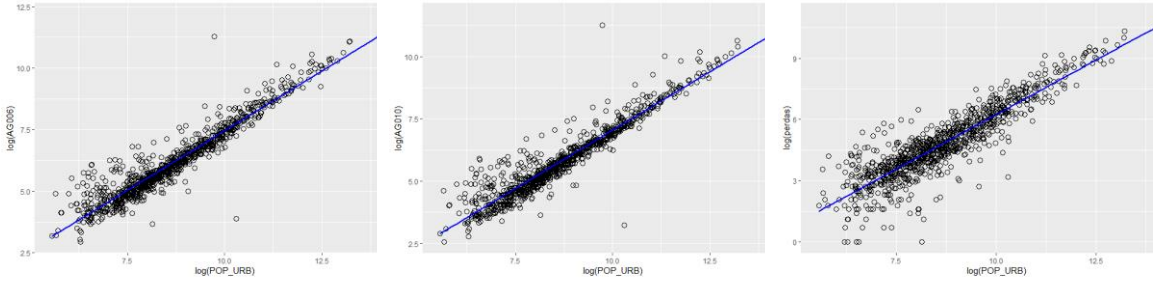
* Itálico indica p-valor < 0,01.



LIG_AG - Quantidade de ligações ativas de água

ECO_AG - Quantidade de economias ativas de água

EXT_RED - Extensão da rede de água



VOL_PROD - Volume de água produzido

VOL_CONS- Volume de água consumido

Perdas

Figura 4-4 - Gráficos de dispersão das regressões lineares entre logX (pop_urb) e logY (demais variáveis).

Todos os modelos têm bom ajuste geral, sendo os melhores os estimados com as variáveis LIG_AG- Quantidade de ligações ativas de água e ECO_AG - Quantidade de economias ativas de água, o que era de se esperar, pois os serviços individualizados são fornecidos aos domicílios como unidades (ligações, por exemplo) e, portanto, têm relação quase "um-para-um" com a população. Enquanto isso, a infraestrutura medida em metros lineares e metros cúbicos - EXT_RED, VOL_PROD e VOL_CONS - tem ajuste sensivelmente inferior. Essa diferença aliada ao valor dos interceptos evidencia a distinção entre os dois grupos de variáveis.

Porém, o mais importante é tratar os valores de (b) como *expoentes* para elevar a população urbana e estimar valores correspondentes dos demais indicadores, com base na equação (1). Embora todos estejam abaixo de 1 (ver tabela 4-5), com exceção das perdas, a diferença em relação à escala perfeitamente linear do tipo $logY \sim Y0$ + logX é em geral pequena. Isso não corrobora de forma taxativa as categorias propostas por Bettencourt et al. (2007), os quais concluíram que as variáveis referentes a serviços básicos individualizados apresentam valores b>1 e variáveis referentes a infraestrutura apresentam b<1.Quanto às variáveis de infraestrutura, todas corroboraram com Bettencourt et al. (2007), que analisou leis de escala nos EUA e China. O coeficiente da variável *Extensão da rede de água*, o mais distante de 1, demonstra a clara relação *sublinear* desta medida de infraestrutura com a população urbana, semelhante à encontrada no trabalho de Meirelles et al. (2018) com municípios brasileiros.

Já o resultado para as *perdas* mostra que seu escalamento em relação à população não segue o mesmo regime das variáveis de infraestrutura. Ao contrário dos volumes produzidos ou consumidos, a perda de água apresentou expoente pouco maior que 1, sugerindo - nesta amostra - uma relação *superlinear*. Este regime é semelhante àquele verificado em Meirelles et al. (2018) para indicadores socioeconômicos.

A exploração das relações entre as perdas e as demais variáveis adota a mesma abordagem, com os resultados da estimação da regressão MQO para cada uma das variáveis apresentadas na Tabela 4-5 e o gráfico de dispersão com reta de ajuste na Figura 4-4. Todos os ajustes podem ser considerados bons, mas o melhor é o do modelo com a variável VOL_PROD, o que indica que a medida que melhor explica o volume de perdas é exatamente o *volume produzido*.

Tabela 4-5- Estatísticas dos modelos de regressão entre as perdas (logY) e as variáveis-chave (logX)

x	POP_URB	LIG_AG	ECO_AG	EXT_RED	VOL_PROD	VOL_CONS
Intercepto	*-4,461*	*-4,588*	*-4,401*	*0,427*	*-1,091*	*-1,372*
X coeficiente (b)	*1,070*	*1,208*	*1,165*	*1,127*	*1,090*	*1,067*
R^2 ajustado	*0,806*	*0,813*	*0,821*	*0,660*	*0,869*	*0,789*

* Itálico indica p-valor < 0,01.

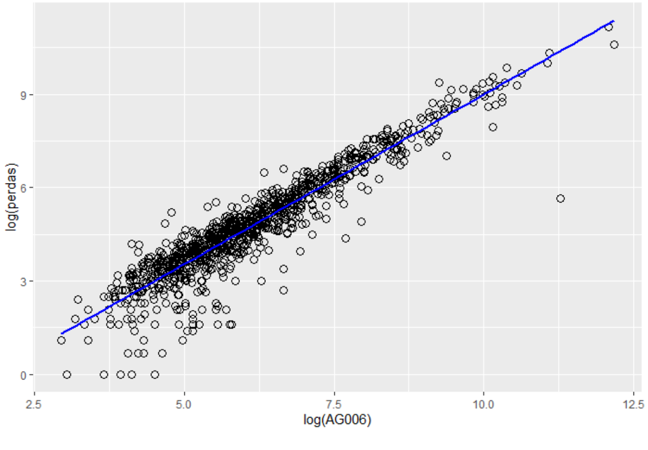


Figura 4-5 - Gráfico de dispersão com reta de ajuste das regressões lineares entre logY (perdas) e logX (Volume de água produzido).

A pequena variação nos valores dos coeficientes de X (b), todos pouco maiores do que 1, sugere relações na prática lineares entre as medidas das redes e as perdas, tal como entre as redes e a população. Porém, os maiores b foram encontrados justamente entre as perdas e as variáveis de serviços individualizados LIG_AG - Quantidade de ligações ativas de água - e ECO_AG- Quantidade de economias ativas de água.

Por fim, uma possível aplicação prática das distribuições potência e dos regimes de escala diz respeito à possibilidade de antecipar tamanhos de SDAs e de perdas em uma cidade, chamada aqui de 1, a partir dos dados de outra, chamada de 2, através da Equação (2).

$$Y_2 = Y_1 * \left(\frac{P_2}{P_1}\right)^b \qquad (2)$$

Onde Y é a quantidade da variável que se deseja analisar, P a população e b o expoente estimado para o escalamento de Y em função de P (Barthelemy, 2019).

Selecionando os modelos de regressão com melhor ajuste, foi conduzida a estimação dos valores de ECO_AG a partir de POP_URB (b = 0,904) e das perdas a partir de VOL_PROD (b= 1,09). Segundo Barthelemy (2019), uma boa estatística da qualidade dessa estimação é a diferença entre os logaritmos da variável calculada e da real (D). Nessa amostra foram encontradas diferenças em torno de 13%, com significativa variação. As correlações de Pearson entre os conjuntos de valores reais e os estimados foram de r=0,98, $p<0,01$ para ECO_AG e r=0,89, $p<0,01$ para perdas. Quando analisadas somente as cidades cujo volume de perdas absolutas de água estão acima do *xmin* estimado (82 m^3/ano), as diferenças caem para cerca de 11% e as correlações sobem para 0,98, $p<0,01$ e 0,90, $p<0,01$.

Uma exploração do potencial preditivo da relação de escala é apresentada a seguir, com o caso de quatro cidades da Região Sul com populações representativas das classes de grandeza indicadas na Figura 1a). A cidade de Santa Maria/RS foi tomada como referência escolhida arbitrariamente para calcular o volume de perdas e quantidade de ligações (LIG_AG) das demais, conforme dados da Tabela 4-6 e da Figura 4-6.

Tabela 4-6- Valores reais e estimados através de funções com expoentes de escalamento entre POP_URB e LIG_AG e entre VOL_PROD e Perdas.

Cidade	**POP_URB**	**VOL_PROD**	**LIG__AG**	***LIG_AG est***	***D***	**Perdas**	***Perdas est***	***D***
Barros Cassal	3.642	209	1.802	*2.410*	*12,6%*	70	*69*	*-0,4%*
Laguna	35.467	3.415	19.624	*18.398*	*-2,8%*	1.009	*1.455*	*15,9%*
Santa Maria	263.834	24.154	110.417			12.269		
Curitiba	1.893.997	178.005	778.966	*641.929*	*-8,4%*	70.080	*108.225*	*18,9%*

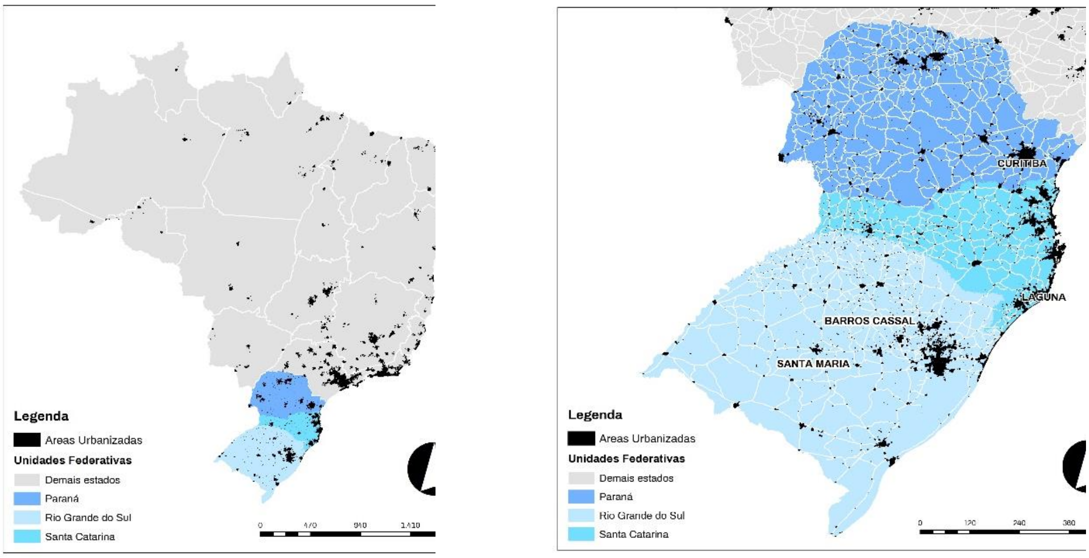


Figura 4-6 – Mapas com as manchas urbanas do Brasil (esq.) e da Região Sul (dir.) destacando as quatro cidades modeladas.

4.7. Discussões

O parâmetro *xmin* - valor inicial da quantidade em estudo a partir do qual a distribuição comporta-se como lei de potência - traz importantes insights sobre as relações de escala no SDAs estudados. Para estes SDAs, conforme resultados da Tabela 4-3, a partir de uma população de 15.870 habitantes e perdas anuais de 82.000 m^3 de água as distribuições seguem leis de escala. Esse resultado sugere que, a partir daqueles valores, as características de complexidade dos SDAs e de seu contexto social, são amplificadas. Por sua vez, isso pode ocorrer em função do maior número de interações não completamente controláveis entre os elementos técnicos e sociais dos SDAs em cidades maiores.

O valor encontrado para o expoente b da equação (lei de potência) que rege a distribuição do volume de perdas é maior que 1 (1,07), portanto demonstrou um comportamento superlinear, semelhante a outras variáveis socioeconômicas apontadas em Meirelles et al. (2018), como: Produto Interno Bruto (b=1,15); número de Organizações não governamentais (b=1,19); número de habitantes atendidos por coleta de lixo (b= 1.12) e número de habitantes com medição de eletricidade (b= 1.08).

Esses resultados corroboram quantitativamente com a revisão sistemática de Azevedo e Saurin (2018) que caracteriza qualitativamente os SDAs como sistemas que apresentam interações não lineares com um grande número de elementos que interagem dinamicamente.

Assim, este estudo evidencia matematicamente que SDAs são sistemas não lineares e por consequência as perdas de água também apresentam comportamento não –lineares a medida que há interação com elementos externos como a população urbana.

Assim, as perdas escalam, ou seja, crescem, com a população do mesmo modo que indicadores de atividade socioeconômica e crescem em proporção um pouco maior do que era de se esperar em uma relação linear com os volumes produzido e consumido. Isso pode ocorrer, devido à interação local com o usuário que surge durante o processo de distribuição de água que pode gerar mais perdas aparentes. Conforme apontado por Azevedo e Saurin (2020), em um estudo de caso com o objetivo de desenvolver uma *framework* para análise de perdas de água realizado no município de Porto Alegre/RS, isto pode ocorrer devido ao uso anormal de água ou furto com efeitos inesperados no sistema, pois o consumo da água furtada não pode ser acompanhada em tempo real pelos gestores, aumentando a pressão de rede de água projetada para um consumo menor, levando a maiores vazamentos.

Para este município com população de 1.481.019 habitantes (pertencente à amostra de municípios a partir da qual a distribuição de perdas se comporta como lei de potência) os autores analisaram duas contramedidas para redução das perdas de água: uma de caráter técnico (implantação de Distritos de Medição e Controle para reduzir o tamanho de rede em setores menores e facilitar o monitoramento das perdas de água) e outra de caráter sócio técnico (Trabalho socioeducativo com a população para redução de desperdício de água). Na análise realizada pelos autores, as duas contramedidas chegariam ao resultado esperado, porém a primeira contramedida traria resultados mais rápidos devido a uma menor demora entre a sua implantação e mudança no fluxo das variáveis envolvidas. Independentemente do maior atraso da contramedida sócio técnica, ela exige menos investimento financeiro em comparação com a técnica. Portanto, neste caso, parece possível e desejável aplicar ambas as contramedidas em conjunto em uma cidade na qual se verificou neste estudo que as perdas de água escalam de forma não linear com o tamanho da população.

Vale destacar a variável Extensão da rede de água que dimensiona o tamanho dos SDAs, classificada como de infraestrutura, apresentou b=0,734, conforme Tabela 4-5. Isso indica que variáveis infraestruturais associadas a decisões políticas e limitadas pelos orçamentos estaduais ou até mesmo federais, tendem a apresentar um comportamento sublinear em relação à população. Esse resultado é similar ao encontrado por Meirelles et al. (2018), os quais verificaram que a variável tamanho da rede de ruas apresentou b=0.77.

No Brasil e outros países em desenvolvimento a natureza informal de muitas cidades e partes de cidades somadas às deficiências das políticas de infraestrutura levam a um descompasso entre os fenômenos de crescimento populacional e suprimento de infraestrutura. Mesmo que, ao atingir um determinado tamanho, as cidades passem a se comportar de forma "viva", quando suas dinâmicas de auto-organização – extensões e ligações individuais regulares e irregulares, furtos, fugas e etc. - passam a ser tanto ou mais importantes para o funcionamento do sistema, inclusive as perdas de água, do que as decisões de cima para baixo.

Uma visão clássica da evolução espaço-temporal das cidades é que os espaços urbanos são o resultado de um planejamento urbano centralizado. Porém, com a teoria de sistemas complexos, verificamos que as cidades, assim, como os SDAs, são SSTs, assim, pode-se interpretar que as estruturas das cidades, incluindo aí os SDAs, são resultado de processos de auto-organização, onde os usuários têm papel fundamental. Portanto, pode ser útil ao gestor analisar as relações de escala existentes entre perdas de água e crescimento populacional quando da execução de planejamento urbano como resultados das estruturas existentes e futuras (por exemplo, que população será abastecida com água em um novo loteamento habitacional e o quanto poderá haver de perdas de água, nesse novo espaço urbano). Dentro deste contexto de planejamento de SDAs, as perdas de água, que apresentaram, nos resultados deste estudo, o mesmo comportamento que indicadores socioeconômicos tendem a crescer de forma mais rápida que o crescimento populacional, ou seja, cresce mais rápido que o tamanho da cidade onde o SDA está inserido, pois são decorrentes de processos de interação humana.

Conforme resultados apresentados na Tabela 4-7, estimativas de perdas de água e de quantidade de economias ativas podem ser feitas de uma cidade a partir dos dados de outra, o que pode auxiliar os gestores públicos quando da implantação de um novo SDA. Decisões *top-down* sobre expansão e funcionamento de SDAs deveriam ocorrer considerando o comportamento das perdas como variável superlinear resultante de processos de auto-organização desenvolvidos pelos próprios usuários a medida que as cidades vão crescendo.

4.8. Conclusões

4.8.1. Contribuições

Este trabalho avaliou se as variáveis de tamanho do SDA e das perdas escalam conjuntamente com a população das cidades obedecendo a um regime de potência. Os resultados apontaram que as *perdas na distribuição de água* apresentaram expoente pouco maior que 1, sugerindo - nesta amostra - uma relação *superlinear*. Este regime é semelhante àquele verificado na literatura para indicadores socioeconômicos. Isso significa que as perdas possivelmente escalam com a população do mesmo modo que indicadores de atividade socioeconômica, cujas quantidades per capita são maiores do que se esperaria em uma relação linear trivial. Além disso, o melhor modelo identificado para previsão de perdas é o modelo com a variável volume de água produzido.

Este estudo contribuiu para verificar que em redes de SDAs pertencentes a um mesmo país, que obedecem às mesmas lógicas de distribuição de população e infraestrutura como é o caso da região sul do Brasil, existe uma faixa de tamanho populacional que obedece muito claramente às leis de potência e, portanto, pode ter seu comportamento aparentemente "caótico" previsto. Existe uma ordem subjacente que indica hierarquia e regularidades quantitativas que podem ser apropriadas, por exemplo, por agências reguladoras ou órgãos de controle para estabelecer o planejamento de novas redes e monitorar o desempenho da prestação de serviços de abastecimento de água, considerando assim, o tamanho da cidade, o tamanho da rede, quantidade de ligação e economias de água, volume de água produzido e perdas de água.

4.8.2. Limitações

Três limitações desta pesquisa devem ser enfatizadas. Primeiro, há uma limitação filosófica no sentido de que uma descrição completa de SST complexos como SDA é impossível; caso contrário, o sistema não seria complexo. Assim, alguma variável geradora de perdas de água pode não ter sido identificada, pois o banco de dados utilizado não possui variáveis correspondentes a todos os fatores apresentados na seção 3 deste artigo. A segunda limitação refere-se às características próprias da amostra de SDAs utilizada para análise do modelo de regressão MQO realizada, no sentido de que variáveis causadoras de perdas que foram significativas para os SDAs estudados, podem não ser para outros SDAs e vice-versa.

Finalmente, do ponto de vista dos métodos quantitativos, o trabalho se ressente do aprofundamento de algumas análises estatísticas. Uma delas é relativa aos regimes de escala para cada categoria de variável, considerando sua flutuação através das cidades da amostra e os pontos de eventual transição ao longo do tempo, nesse estudo avaliamos somente 1 (um) ano. Expoentes locais para cada cidade podem ser estimados de forma relativamente simples, permitindo identificar com maior robustez a cidade de "referência" para calcular com o menor erro possível as quantidades para as demais (Barhelemy, 2019).

4.8.3. Pesquisas Futuras

Com base nas lacunas teóricas e práticas quanto à análise de perdas em SDAs verifica-se a oportunidade para o desenvolvimento de um modelo mais abrangente para analisar as perdas em SDAs, considerando um maior número de variáveis sócio-técnicas e a realização de estudos similares em outras regiões do Brasil e outros países, verificando como as perdas escalam com a população urbana nesses outros locais. Oportunidades de estudos também surgem analisando-se um banco de dados com séries temporais de vários anos, identificando assim possíveis mudanças nas características populacionais e consequentemente nas perdas de água. Este tipo de estudo longitudinal pode identificar os mecanismos em ação durante a evolução dos sistemas, permitindo entender como se complementam o planejamento centralizado e as decisões individuais.

Os métodos de coleta e preparação dos dados podem ser aperfeiçoados, buscando refinar os indicadores já testados e modelar as relações de escala entre outras variáveis de ordem econômica e/ou social. A expansão da amostra para, por exemplo, todos os municípios brasileiros, pode ajudar também a aperfeiçoar os modelos e compreender as flutuações dos expoentes e seus desvios dos regimes esperados.

A Análise Envoltória de Dados surge também como oportunidade de estudo ao passo que essa técnica avalia a eficiência relativa de unidades comparáveis, com o objetivo de melhorar o desempenho, utilizando um modelo matemático não paramétrico de programação linear. Assim, as cidades poderiam ser comparadas utilizando as perdas de água como variável de eficiência.

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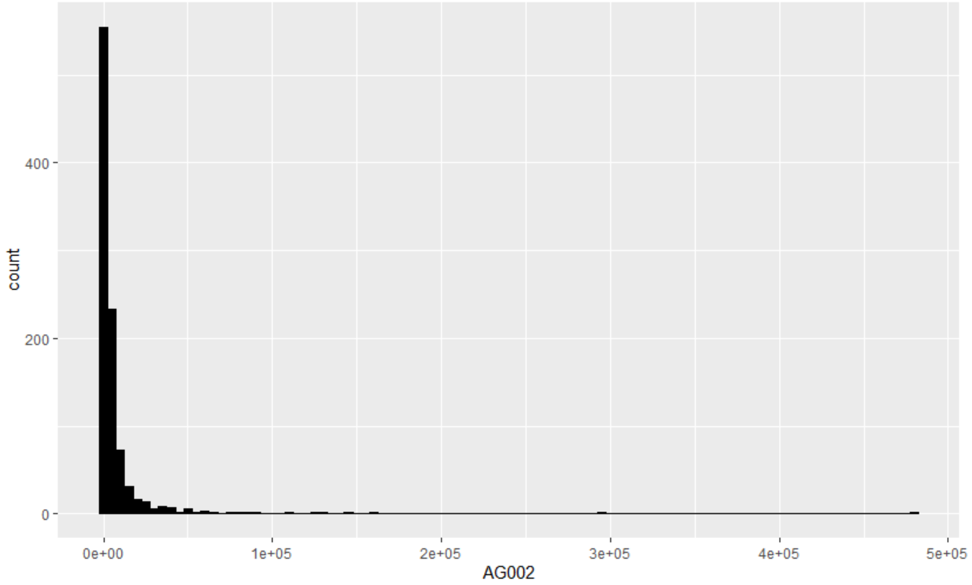
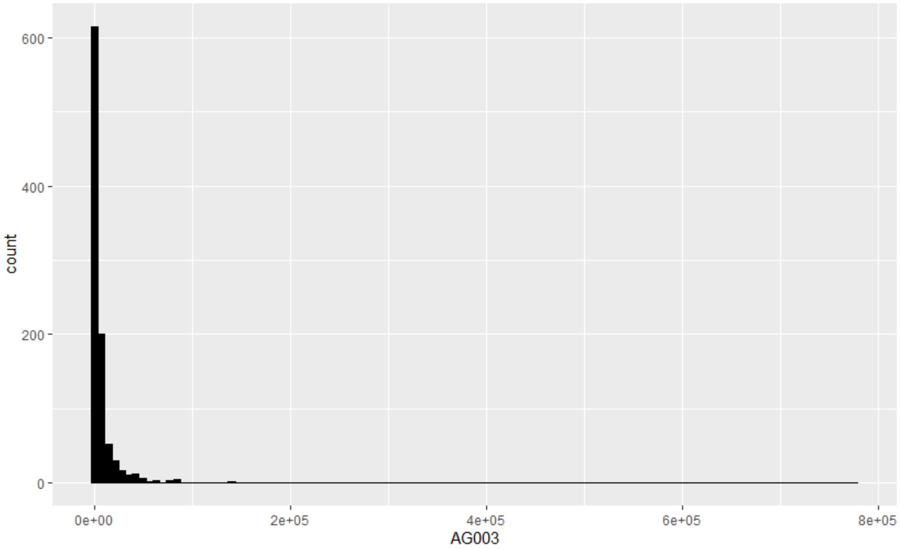
4.10. Apêndice:

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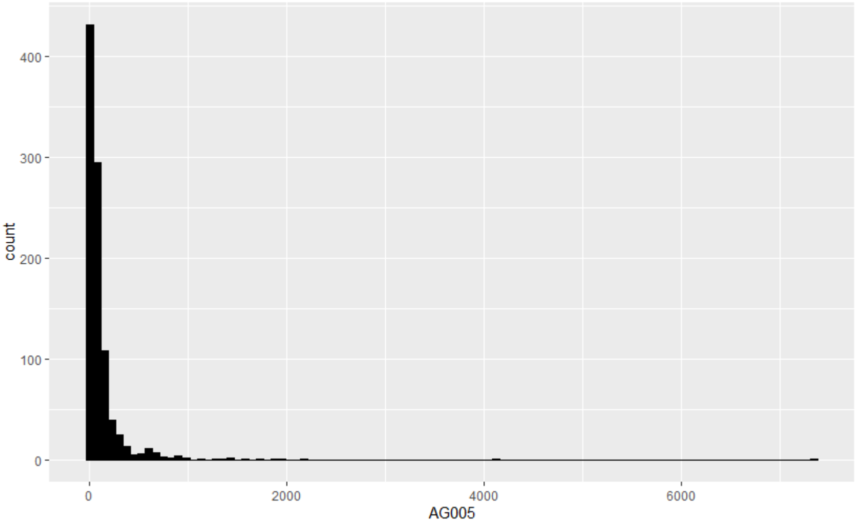
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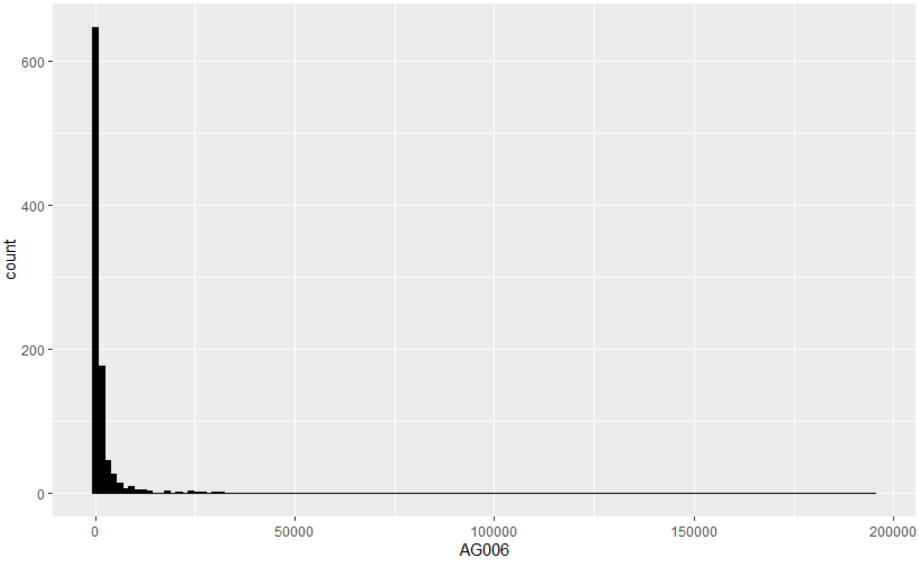
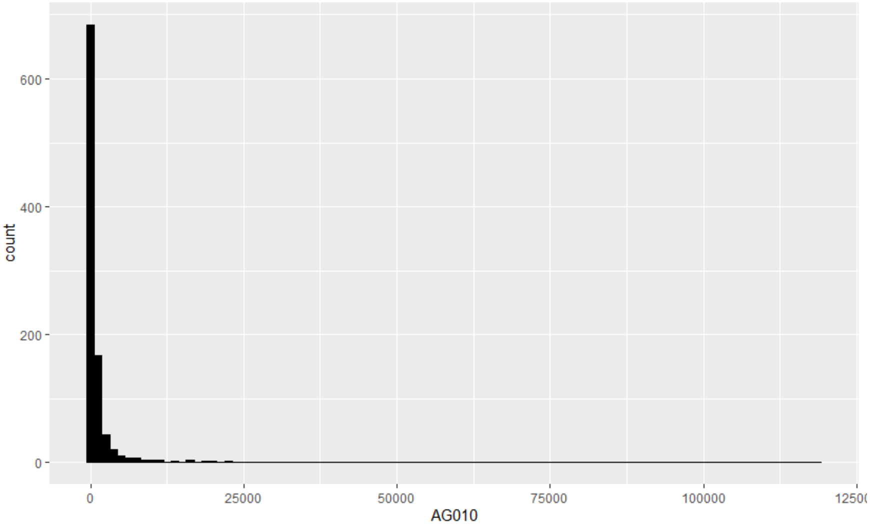
AG005





Apêndice 4-7- Histogramas de frequência das variáveis selecionadas: AG002 - Ligações ativas de água; AG003 - Quantidade de economias ativas de água; AG005 - Extensão da rede de água; AG006 - Volume de água produzido e AG010- Volume de água consumido

5. CONCLUSÕES

5.1. Contribuições da tese

A pesquisa apresentada nesta tese de doutorado originou-se da constatação de que as linhas de pesquisa atuais sobre perdas em SDAs geralmente versam sobre aspectos técnicos, não considerando o comportamento complexo desses sistemas (SHENG *et al.*, 2013). Como SDAs são SSTs complexos, inseridos em sistemas urbanos, resultados de processos descentralizados de auto-organização e regidos por leis de escala, a teoria de sistemas complexos pode contribuir para a interpretação do comportamento de SDAs, identificando como ocorrem as perdas de água. Assim, esta tese foi motivada pela seguinte questão de pesquisa: como a teoria da complexidade pode contribuir para a compreensão e controle das perdas em SDAs?

Para satisfazer este questionamento, a pesquisa foi conduzida através de três fases, sendo inicialmente realizada uma revisão sistemática da literatura com o objetivo de identificar o estado da arte referente aos fatores que influenciam a complexidade de SDAs e impactam nas perdas de água. Na sequência, um estudo de caso foi conduzido e proposta uma *framework* para analisar, segundo a perspectiva de sistemas sócio-técnicos complexos, as perdas em SDAs, no qual um diagrama de causa e efeito apresentou o relacionamento entre variáveis que causam perdas. Por fim, um estudo com dados quantitativos de 968 SDAs foi realizado para estudar a relação existente entre o tamanho de sistemas urbanos, tamanho de SDAs e quantidade de perdas nesses sistemas, verificando se essa relação obedece a funções de escala não-lineares.

Os resultados encontrados, a partir de diferentes fontes teóricas e empíricas ao longo das três fases da pesquisa, permitiram contribuições práticas e acadêmicas. Uma das primeiras contribuições foi a identificação de 21 fatores inter-relacionados que influenciam a complexidade dos SDAs e as suas perdas, relacionados aos cinco atributos de complexidade identificados por SAURIN e GONZALEZ, (2013). Essa visão geral permitiu nos artigos subsequentes o aprofundamento de alguns atributos.

No segundo artigo a framework proposta para a compreensão das interações entre os fatores causadores de perdas de água enfatizou o atributo de complexidade de grande número de elementos que interagem dinamicamente, trazendo uma visão holística sobre as perdas de água, em comparação com estudos anteriores. Em consonância com o pensamento sistêmico, entender as perdas de água como inseparáveis de seu contexto é resultado do pensamento em termos de interconexões e elos causais que estão distantes no espaço e no tempo das ações dos agentes. Este estudo também é original por apresentar as perdas de modo mais descritivo e contextualizado que em artigos anteriores, apresentando a interação entre os fatores geradores de perdas de água

Esta tese também contribuiu para o aprofundamento do atributo de complexidade de não linearidade em seu terceiro artigo através do estudo de relações não lineares entre o tamanho de cidades, tamanho de SDAs e quantidade de perdas. Esse artigo identificou que existe uma faixa de tamanho populacional (a partir de 15.870 habitantes) que obedece às leis de escala não lineares (leis e potência). Portanto, o comportamento aparentemente “caótico” das perdas em SDAs, com população a partir deste tamanho, pode ser previsto. Existe uma ordem subjacente que indica hierarquia e regularidades quantitativas que podem ser apropriadas para estabelecer o planejamento de SDAs, considerando assim, o tamanho da cidade, o tamanho de SDAs, suas perdas de água e sua não linearidade.

Com base nas contribuições apresentadas, pode-se concluir que o objetivo geral e os específicos desta tese foram cumpridos. A abordagem metodológica pluralística, associada ao uso da teoria da complexidade, permitiu uma compreensão holística das perdas em SDAs.

5.2. Limitações

As limitações desta pesquisa devem ser ressaltadas. Primeiro, há uma limitação filosófica no sentido de que uma descrição completa de SST complexos como SDAs é impossível; caso contrário, o sistema não seria complexo. Assim, alguma variável geradora de perdas de água pode não ter sido identificada no primeiro e segundo artigos. A segunda limitação refere-se ao estudo aprofundado dos cinco atributos de complexidade e dos fatores relacionados a estes atributos que causam perdas em SDAs. A revisão sistemática de literatura realizada no primeiro artigo encontrou 21 fatores inter-relacionados que influenciam a complexidade dos SDAs e as suas perdas, relacionados aos cinco atributos de complexidade identificados por SAURIN e GONZALEZ, (2013). No entanto, no segundo artigo a framework proposta para a compreensão das interações dinâmicas entre os fatores causadores de perdas de água enfatiza o atributo de complexidade de grande número de elementos que interagem dinamicamente. Similarmente o terceiro artigo enfatiza o atributo de complexidade de não-linearidade, através do estudo de relações não lineares entre o tamanho de cidades, tamanho de SDAs e quantidade de perdas. Assim, os outros três atributos de complexidade (diversidade dos elementos, variabilidade imprevista e resiliência) não foram aprofundados.

Outra limitação refere-se às características próprias da amostra de SDAs utilizada para análise do modelo de regressão MQO realizada no artigo 3, no sentido de que variáveis causadoras de perdas que foram significativas para os SDAs estudados, podem não ser para outros SDAs e vice-versa.

Do ponto de vista dos métodos quantitativos, o trabalho se ressente do aprofundamento de algumas análises estatísticas. Uma delas é relativa aos regimes de escala para cada categoria de variável, considerando sua flutuação através das cidades da amostra e os pontos de eventual transição ao longo, nesse estudo avaliamos somente um ano. Expoentes locais para cada cidade podem ser estimados, permitindo identificar com maior robustez a cidade de “referência” para calcular com o menor erro possível as quantidades para as demais (BARHELEMY, 2019).

Por fim, esta pesquisa traz no segundo artigo um único estudo de caso. Esta limitação impõe restrições quanto à generalização dos resultados, uma vez que se trata de evidências particulares do sistema sócio-técnico abordado.

5.3. Pesquisas Futuras

Como consequência dos resultados e limitações desta tese, diversas oportunidades de pesquisas futuras são vislumbradas, quais sejam:

a) Desenvolver métodos de controle de perdas que considerem os cinco atributos de complexidade analisados, reconhecendo o papel desempenhado por fatores sócio-técnicos;
b) Investigar empiricamente qual seria o nível e a natureza ideais de resiliência em um SDAs, a fim de manter o suprimento continuamente, minimizando as perdas de água;
c) Desenvolver um Modelo de System Dynamics simulando quantitativamente um sistema real com base no modelo apresentado neste estudo, no qual o diagrama de enlace causal desenvolvido nesse estudo poderá ser transformado em um diagrama de estoque e fluxo, com o apoio de um software que permita desenvolver modelos de SD.
d) Aplicar a *framework* desenvolvida em outros SDAs, a fim de produzir dados qualitativos e quantitativos mais generalizáveis sobre a natureza das perdas - isso poderia lançar luz sobre a extensão em que diferentes características contextuais influenciam as perdas;
e) Analisar um banco de dados com séries temporais de vários anos, a fim de identificar possíveis mudanças nas características populacionais e consequentemente nas perdas de água. Este tipo de estudo longitudinal pode identificar os mecanismos em ação durante a evolução dos sistemas, permitindo entender como se complementam o planejamento centralizado e a auto-organização característica de sistemas complexos.