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RESEARCH ARTICLE

Framework for performance assessment of storm water systems

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ABSTRACT

The integration of performance assessment may be determinant for water utilities and municipalities to improve their management practices regarding storm water systems (SWS). The use of performance assessment in the SW sector has been incipient, and the need to develop a performance assessment framework (PAF) that constitutes a reference for SWS was identified. The article aims to present a PAF, structured into eight objectives, 25 assessment criteria, and 80 performance metrics, namely performance indicators (PI), focusing on the assessment of SWS functioning, considering different performance dimensions and types of SWS. The PAF aims to promote the establishment of performance assessment systems in utilities, supporting the decision-making process and continuous improvement. The PAF was consolidated by incorporating the views and recommendations of two Portuguese water utilities during the validation process. Data collection process constitutes a barrier to the PAF application given the lack of financial and human resources in water utilities.

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Performance assessment; framework; storm water; performance metrics; water utilities

Introduction

Over the past decades, new approaches to storm water (SW) management have been put into practice in order to respond and adapt to the current challenges derived from the rapid urban development, climate change impact, aging infrastructure, complex urban infrastructure interactions, and changing regulatory environments (Eckart, McPhee, and Bolisetti 2017). Conventional SW infrastructure, comprising SW pipe systems, tended to manage water quantity by mainly draining water away from its source as quickly as possible and directly discharging it into receiving waters, as lakes and streams (Pazwash 2016). Water quality was of less concern to conventional storm water systems (SWS), and biodiversity and amenity have also been topics of minor importance (Charlesworth 2010). In addition to these shortcomings, the limited capacity and flexibility of the conventional SWS to adapt to future climatic variability and urbanisation (Zhou 2014) and the high construction and maintenance costs have urged the adoption of innovative sustainable drainage solution. These solutions aim to provide more functions to replace or complement conventional SWS while remaining cost-effective (Porse 2013).

In this sense, SWS that provide multiple functions have been developed and promoted in several countries. Several terms are used to describe them, differing in their primary focus and specificity, such as: SUDS (Sustainable Urban Drainage Systems), LID (Low Impact Development), BMP (Best Management Practices), SCM (Stormwater Control Measures), WSUD (Water Sensitive Urban Design), GI (Green Infrastructure), among others (Fletcher et al. 2015). Hereafter, the term SUDS is adopted in the present article. These systems may rely on diverse functions such as local treatment, retention, reuse, infiltration, and conveyance of water runoff (Zhou 2014). They may comprise the following types: swales, detention basins, permeable pavements, soakaways and infiltrations basins, and green roofs. If well designed and maintained, SUDS can provide means to simultaneously support national legislation, regulation requirements, and strategies related to the following areas: flood risk and water resource management, climate change resilience, green infrastructure, wetland creation, biodiversity and wildlife and carbon reduction (Woods-Ballard et al. 2015).

In a context of a paradigm shift in SW management, facing climate change and socio-institutional and financial constraints, the water utilities responsible for SWS management struggle to provide an adequate service. It becomes essential to develop tools that support the water utilities and municipalities in the different management stages of SWS (design, implementation, functioning, monitoring, rehabilitation), such as performance assessment.

For the last two decades, performance assessment has become a common practice in the water sector (Alegre et al. 2016), especially for water supply and wastewater systems. It can be described as the process of quantifying the efficiency and effectiveness of actions (Neely, Adams, and Kennerley 2002) using performance metrics, such as performance indicators (PI). The application of performance assessment systems (PAS) based on PI facilitates the communication among different stakeholders involved in water services, namely water utilities, consumers, policy-making bodies, regulatory agencies, financing agencies, and multi-lateral organisations (Alegre et al. 2016; Matos et al. 2003). The main potential benefits of performance assessment in the water sector are the following (Cabrera et al. 2011; Vilanova, Filho, and Balestieri 2015):

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motivation to collect the right information and to improve data quality; assessment of objectives or targets fulfilment; support of decision-making process; monitoring of performance trends over time and peer comparison; verification of the effectiveness of optimisation measures already implemented; and aid in the dissemination of organisational results via marketing. PAS can integrate broader management approaches, such as quality management programmes, risk management, benchmarking, and infrastructure asset management (Baptista and Alegre 2009).

Although performance assessment has revealed to be a remarkable management tool, leading to performance gains in the water sector, its application has been incipient regarding SWS. Santos, Galvão, and Cardoso (2019) carried out a performance assessment review based on PI for SWS. It was found that there were only a few projects and initiatives developed in this area. Some of the reviewed studies developed performance assessment methodologies with limited scope, dedicated to single SWS, in the case of infiltration systems by Dechesne, Barraud, and Bardin (2004) and Moura et al. (2010), or to some specific aspects of their performance, namely hydraulic, hydrologic, as proposed by Berggren (2008) and Nie et al. (2009), for example. Other studies presented unsuitable definitions and selections of PI, inaccurately identifying as PI single variables, restricting their further application.

Some water utilities and organisations have developed performance metrics for SWS to integrate into their asset management plans. It is the case of Auckland city (Auckland Council 2015) and the Wellington Water organisation (Wellington Water 2020), in New Zealand, and the Mitchell Shire Council (Mitchell Shire Council 2012) in Australia. Despite the significant effort by these countries, there is still a significant focus on SW pipe systems and flood control, public health protection, and, to some extent, environmental problems. In Canada, the Canadian National Water and Wastewater Benchmarking Initiative (AECOM 2018) has also developed performance metrics specifically for SWS. These metrics are mainly related to aspects of SWS service (funding, operation and maintenance works, human resources, etc.). Even though the service aspects are relevant to assess, these examples support the need to develop a performance assessment framework (PAF) to address other types of SWS and their multiple performance requirements. Its application may contribute to a better knowledge of systems' functioning and vulnerabilities, supporting the management, the planning, and decision-making processes in the definition of intervention and adaptation solutions. This PAF may constitute a reference in the field with the potential to promote, boost and support water utilities, municipalities, and other institutional organisations in the development and application of their own PAS. Therefore, PAF provides the basis from which each PAS may be derived, by selecting the adequate performance components that are applicable to a certain organisation.

The process of establishing a PAS in a water utility based on a PAF should comprise the definition of performance objectives with relevance to be achieved. Then, assessment criteria that better suit the objectives should be selected along with a set of PI, which provide an adequate quantification of the objectives' accomplishment. The selection of PI should consider technical conditions, data availability and costs, data quality, and comparability (Vilanova, Filho, and Balestieri 2015), being the most critical phase of PAS implementation. The selection and construction of PI often imply some bias (Cabrera et al. 2011), which reinforces the need for a PAF of reference, with properly designed performance metrics, for example.

In this sense, the aim of the present article is two-fold: i) to describe the development of a PAF and ii) to describe the validation phase of the PAF, which is based on a collaborative process with two Portuguese water utilities and the application to real case studies. The PAF intends to be comprehensive, flexible in its application, objective, and standardised. It is structured by objectives, assessment criteria, and performance metrics to support the integration of PAS into the management of SWS by water utilities, municipalities, and other institutional organisations. The PAF relies on a systematic approach, providing performance assessment of the SWS, not detailing the assessment of other service-related components.

1. Materials and methods

2.1. Method overview

The development of the PAF comprised the following steps (Figure 1): i) review of performance assessment methodologies applicable to water systems and more specifically to SWS, carried out in Santos, Galvão, and Cardoso (2019); ii) establishment of the assessment scope; iii) definition of the approach and structure of the PAF; iv) definition of its components based on SWS functions; and v) validation process of the PAF, as based on a collaborative process with water utilities.

2.2. Establishment of the scope of the performance assessment framework

The review carried out in Santos, Galvão, and Cardoso (2019) supported the establishment of the scope of PAF application. The most representative types of SWS in urban areas, on the public domain, managed by public or private water utilities and municipalities, excluding SWS in private properties, were selected. Two types of SWS were included: conventional pipe systems and SUDS. For conventional pipe systems, only separate systems were considered, which only convey SW in pipe networks. The separate SW pipe systems comprise pipes, manholes, inlets, drainage channels, pumping stations, storage, and flow control structures, among others. The SUDS group covers detention and retention basins, infiltration basins, constructed storm wetlands, bioretention systems, vegetated swales, permeable pavements, green roofs, soakaways, filter strips and drains, attenuation storage systems, and rain harvesting systems.

The focus of the PAF is on the SWS functioning. The framework is not extended to aspects that concern the water utilities or municipalities' management activity, such as human resources, financial management, and users' complaints management. These service aspects are covered by other frameworks for urban water services and may also be applied to SWS.

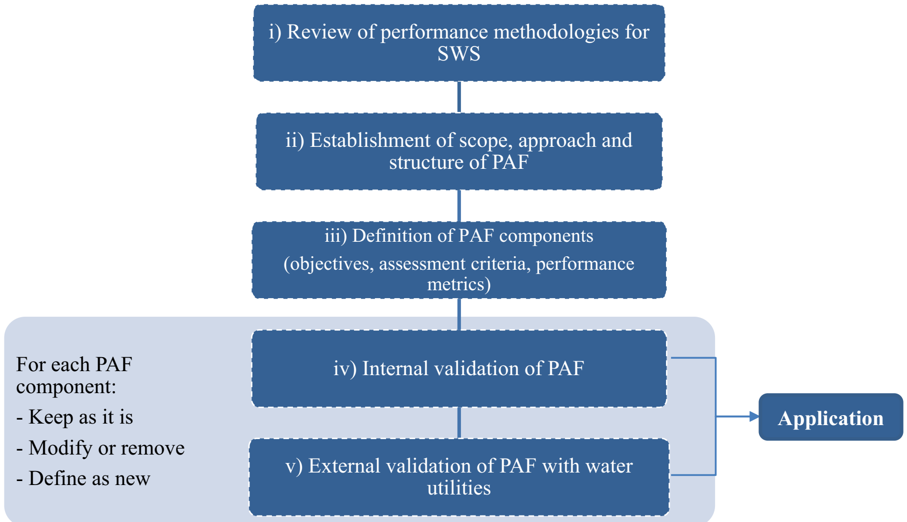

Figure 1. PAF development steps regarding the definition and validation of its performance components.

In contrast, there is a lack of reference frameworks that are meant to assess SWS functioning performance. The PAF can also be adapted by other institutional organisations, such as regulatory agencies and policy-making bodies.

2.3. Definition of the approach and structure of performance assessment framework

The approach and definition of the PAF structure followed the recommendations of the series ISO 24500 standards (ISO, 2007a, 2007b, 2007c) for the assessment, management, and improvement of drinking water and wastewater services. Beyond the ISO 24500 standards, the definition of the PAF structure also considered the sustainability framework structure for urban water cycle services that was developed under the scope of TRUST project (Transitions to the Urban Water Services of Tomorrow), which proposes dimensions, objectives and assessment criteria to facilitate the development of individual performance metrics (Alegre et al. 2012). Given the similarities between wastewater and SWS, namely regarding conventional piped systems, and the fact that many water utilities are responsible for managing both systems, the recommendations of ISO 24500 standards are applicable to SWS as well. These standards recommend an overall step-by-step assessment process, from the definition of a utility's objectives to the establishment of PI and assessment of performance, in line with the Plan-Do-Act-Check (PDCA) approach. The main steps are the following: i) identification of physical, management and/or service components; ii) definition of objectives; iii) definition of assessment criteria; iv) definition of PI; and v) comparison between the performance results and the objectives.

Based on these recommendations, the structure of the PAF relied on the definition of different types of components: objectives, assessment criteria, and performance metrics, namely PI. These components were defined according to the following concepts (Alegre et al. 2016, 2012; Matos et al. 2003; ISO 2007a, 2007b, 2007c):

- An objective is a result or a specific goal that a water utility aims to achieve with the resources at its disposal. The objectives need to be clear and concise, as well as ambitious, feasible and compatible. For each objective, it should be established assessment criteria;
- Assessment criteria are points of view that allow the assessment of the objectives and a perspective on which performance metrics, such as PI, are defined;
- Performance metrics are the specific parameters that are used to inform the assessment. There are different types of performance metrics: PI, performance indices, and performance levels. PI are metrics that allow the verification of the objectives' accomplishment through the quantification of the efficiency and/or effectiveness of an activity, process, or service. A PI consists of a value expressed in specific units along with a confidence grade, which indicates the quality of data represented. PI are typically expressed as ratios between variables that may be commensurate (e.g. %) or non-commensurate (e.g. €/m^3). Performance indices may result from the combination of other disaggregated performance metrics (e.g. weighted average of PI), and performance levels, which are performance metrics of a qualitative nature, are expressed in discrete categories (e.g. excellent, good, fair, unsatisfactory).

2.4. Definition of performance assessment framework components

The definition of objectives was based on the visions and principles articulated by the European Standard EN 752 (EN 752, 2017), the ISO 24511 standard (ISO, 2007b), the EU Flood Directive 2007/60/EC (European Commission 2007), the SUDS manual (Woods-Ballard et al. 2015), the Water, Wastewater and Stormwater Infrastructure Management manual (Grigg 2012) and the European Commission's Green Infrastructure Strategy (European Commission 2003; Table 1).

Table 1. Alignment between the visions and principles for SWS from standards, legislation and manuals and the derived objectives for SWS functioning.

	Standards, legislation, and manuals with visions and principles applicable to SWS					
Objectives for SWS functioning	EN 752:2017	ISO 24511:2007	EU Flood Directive 2007/60/EC	SUDS manual (Woods-Ballard et al. 2015)	Water, Wastewater and Stormwater Infrastructure Management manual (Grigg 2012)	European Commission' Green Infrastructure Strategy (European Commission, 2003)
2*Protection of public health and safety*	✓	✓	✓			
Protection of economic development			✓			
Protection of surface receiving waters quality	✓	✓		✓		
Protection of the natural hydrologic cycle			✓	✓		
Infrastructural sustainability of SWS	✓				✓	
Sustainable use of resources	✓	✓			✓	
Provision of ecological benefits				✓		✓
Provision of amenity benefits				✓		✓

Both European Standard EN 752 and ISO 24511 provide guidance, principles and recommendations applicable to urban drainage systems, including conventional SWS, despite the focus on wastewater systems. The EU Flood Directive provides support in what concerns flood protection. The SUDS manual constitutes a reference for SUDS, specifying how to design and implement these systems. The Water, Wastewater and Stormwater Infrastructure Management manual provides guidance on infrastructure management, including aspects related to water infrastructure integrity and financial management of water systems and services. The European Commission's Green Infrastructure Strategy reinforces the importance of implementing nature-based solutions, which can provide an alternative or complement conventional drainage solutions while delivering multiple environmental, social and economic benefits.

Table 1 presents the eight established objectives related to the protection of the public health and safety and economic development, improvement of SW quality and the natural hydrologic cycle, infrastructural sustainability, sustainable use of resources, and provision of ecological and amenity benefits in urban areas. These objectives are associated with social, economic, and technical performance dimensions. The technical dimension encompasses aspects related to hydraulic, hydrologic, structural, environmental, and ecological performance.

The definition of assessment criteria and performance metrics followed the recommendations presented in ISO 24500 standards (ISO 2007a, 2007b, 2007c) and the IWA *Manuals of Best Practices* regarding PI for water supply and wastewater services (Alegre et al. 2016; Matos et al. 2003). The initial selection of performance metrics was based on the review carried out in Santos, Galvão, and Cardoso (2019). Metrics that did not comply with the design recommendations were adapted in terms of variables composition. This adaptation was carried out for dimensional variables, such as volumes or masses, that were incorrectly classified as PI in some reviewed works. In the case of inadequate metrics or lack of specific metrics, new ones were proposed.

The modifications and the development of new metrics were based on the abovementioned review. They were complemented with extensive consultation of other documents about the functioning of different SWS in terms of hydraulic, hydrologic, pollution retention, structural condition and ecological processes, and the interactions between these systems and other urban infrastructures. Existing maintenance and monitoring techniques to assess SWS' performance were also analysed, along with established social and economic assessment methods. The consultation was based on journal articles, handbooks, academic thesis, water utilities reports and guidelines, regulatory agencies reports, and regulatory decrees concerning urban drainage systems. The references of the most relevant sources are further presented in the results section.

2.5. Validation of the performance assessment framework

The validation process of the PAF was adapted from the validation methodology proposed by Bockstaller and Girardin (2003) and Cloquell-Ballester, Monterde-Díaz, and Santamarina-Siurana (2006) for environmental and social quantitative assessment: i) internal (self-) validation; ii) external (scientific) validation; and iii) social validation. In the present article, internal validation and external validation were carried out to validate the developed PAF. The validation methodology proposed by the authors above applies to different fields, adapted, and applied to other sectors, such as the energy sector (Grafakos, Enseñado, and Flamos 2017).

Social validation was not included at this stage, but it may be carried out in further development stages. At the social validation, the views from the stakeholders of the SW sector should be incorporated to improve the set of PAF components, specifically assessment criteria and performance metrics. Stakeholders, such as institutional and policymakers, should be involved to contribute with their expertise, knowledge, and experience.

The internal validation phase was carried out, following the preliminary definition of PAF components. This phase consisted of a series of rounds to verify the quality of PAF components, focusing on performance metrics regarding their definition, relevance for the decision-making process and respective feasibility to be obtained. The application of the PAF to real case studies supported its validation at this phase, as presented in Santos, Cardoso, and Galvão (2022), to inform whether the obtained results are realistic compared to previous performance analysis of systems.

The external validation was carried out in a collaborative process with two Portuguese water utilities: SMAS de Almada and Águas de Coimbra, E.M. Both water utilities have a long experience in the use of PAS. Both water utilities had experience in developing PAS for their SW systems', not only within the scope of the National regulation of the sector but also as part of the development of infrastructure asset management plans. In both cases some difficulties arose during the process, mainly related to the lack of a reference assessment framework for SW systems, that exists for other urban water systems. Water utilities made a significant effort to adapt their former PAS for SWS from the PAS already established for water supply and wastewater systems. The result of this approach was an excessive focus on the assessment of conventional SW pipe systems and their hydraulic, infrastructural, and economic functions. The participation in the present work provided an opportunity to reflect on priorities for SWS management and, consequently, on objectives to be achieved, contributing to the improvement of each PAS.

The responsible for the SWS management team in each water utility participated in the validation process through email, videoconference, and face-to-face meetings. In these meetings, the proposed PAF was presented and discussed, and critical feedback was provided. The water utilities were asked if they agreed or disagreed with the PAF components and what suggestions could be made to reflect their concerns, leading to preliminary changes.

After this stage, according to the validation process proposed by Bockstaller and Girardin (2003) and Cloquell-Ballester, Monterde-Díaz, and Santamarina-Siurana (2006), in order to evaluate the proposed PAF components objectively, a questionnaire was sent to each water utility to evaluate the new set of performance metrics on a scale from 1 to 3 (1 – low, 2 – medium and 3 – high) in terms of their design, effectiveness to inform and translate the reality, and their relevance for the decision-making process

Based on the questionnaire results, on water utilities' additional comments and suggestions, and further internal discussions, some PAF components were reformulated and improved to approach the needs and expectations of water utilities. For some components, namely performance metrics, if there was misalignment between opinion of water utilities and the authors, the decision would be based on the scientific literature and experiences reported by organisations from different countries. The feedback from water utilities is presented in the results section (3.2).

2. Results and discussion

2.1. Developed PAF

The developed PAF for SWS is structured considering eight objectives, 25 assessment criteria, and 80 performance metrics, mostly PI. It is presented in Table 2., to support the establishment of PAS by water utilities, municipalities, and other institutional organisations. For each objective, the literature references, which supported the development of the assessment criteria and performance metrics, are presented. The metrics adapted from previous works and the ones developed in this work are also highlighted. The calculation formula and proposed reference values for each metric are presented in detail in the Supplemental Material.

Objectives and assessment criteria are described on the following topics. The feedback provided by water utilities during the validation phase is also presented.

2.2. Objectives, assessment criteria and water utilities feedback

2.2.1. Protection of public health and safety

2.2.1.1. Overview. Protection of public health and safety constitutes a primary objective of SW management. Historically, SW management has been associated with flood control – by draining surface runoff away from structures and cities as fast as possible (Pazwash 2016). Without SWS functioning well, people are displaced, transportation is disrupted, and properties are damaged (Grigg 2019).

In this context, SWS shall function adequately in terms of SW conveyance and flood control to prevent and mitigate the associated risks to public health and safety (EN 752, 2017). The proposed assessment criteria aim to verify the accomplishment of this objective. The health and safety impacts criterion directly assesses the consequences of SWS performance failures by quantifying the number of people affected by injuries, diseases, and fatalities caused by flooding, collapses of SWS structures or accidents. Additionally, the quantification of temporarily and permanently displaced people due to flooding gives information on other types of consequences that may compromise safety. Built environment impacts criterion assesses the type of properties and the extension of roads affected by flooding and, to a lesser extent, by collapses of SWS structures. Basic services infrastructure disruption can also be quantified to inform on the effects of flooding on other urban systems infrastructure that support people's health and safety (e.g. water supply, wastewater collection and treatment, electric power supply, natural gas supply, and telecommunications). Flooding occurrences criterion relates to the hydraulic performance of SWS by quantifying the frequency and areas where flooding occurs with impacts on people and built environment as well as its magnitude. The

Table 2. Objectives, assessment criteria, and performance metrics proposed for PAF of SWS. In bold, it is identified the performance metrics that were developed in this work. The description of each metric is presented in detail in the Supplemental Material.

Objectives	Assessment criteria	Performance metrics	Units	References
Protection of public health and safety	Health and safety impacts	**Injured people** **People affected by flood-related diseases** **Fatalities** **Temporarily displaced people** **Permanently displaced people**	[no./1000 inhabitants/year] [no./1000 inhabitants/year] [no./1000 inhabitants/year] [no./1000 inhabitants/year] [no./1000 inhabitants/year]	Du et al. (2010), IRDR (2015), Menne and Murray (2013)
	Built environment impacts	Residential properties affected **Commercial facilities affected** **Industrial facilities affected** **Public services facilities affected** Road networks extension affected Traffic disturbances **Basic services infrastructure disruptions**	[no./1000 residential properties/year] [no./100 commercial facilities/year] [no./100 industrial facilities/ year] [%/year] [%/year] [km/interruption] [no./1000 residential properties/year]	Ashley et al. (2005), Auckland Council (2015), Beceiro (2016), Matos et al. (2003), and Hammond et al. (2015)
	Flooding occurrences	**Surface flooding with impacts on people and/or built environment** Area affected by flooding Duration of flooding	[no./km^2/year] [%/year] [%/year]	Berggren (2008), Cherqui et al. (2013), Dechesne, Barraud, and Bardin (2004), Matos et al. (2003)
	Users' complaints	Complaints related to SWS functioning	[no./1000 inhabitants/year]	Cherqui et al. (2013), Matos et al. (2003)
Protection of economic development	Business interruption	**Duration of business interruption**	[days/property/year]	Hammond et al. (2015), IRDR (2015)
	Economic losses	**Direct economic losses in relation to local GDP** **Indirect economic losses in relation to local GDP**	[%/year] [%/year]	IRDR (2015), Sultana et al. (2018)
Protection of surface receiving waters quality	Illicit domestic or industrial connections to SW pipes	Wastewater proportion regarding SW pipes capacity Wastewater flow in SW pipes **Wastewater volume proportion in SW pipes regarding total wastewater produced** **Detected wastewater connections to SW pipes**	[%] [m^3/day/m] [%] [no./100 km/year]	Cardoso (2007)
	Quality of discharged urban runoff	**Compliance of discharged runoff with quality permits** **Quality of discharged runoff** **Discharged runoff quality index**	[%] [%] [-]	Silva et al. (2014), SDD (1976), Spitzer (2007)

(*Continued*)

Table 2. (Continued).

Objectives	Assessment criteria	Performance metrics	Units	References
Protection of the natural hydrologic cycle	Control of urban runoff peak flow at SUDS	Duration of SUDS flow exceedance **Frequency of SUDS flow exceedance** Peak flow attenuation by SUDS	[%] [no./1000 m^3/year] [%]	Cherqui et al. (2013), Jefferies et al. (2004), Sun et al. (2014)
	Control of urban runoff volume at SUDS	Volume interception in infiltration-based SUDS	[%]	Cherqui et al. (2013)
	Groundwater recharge	**Variation of groundwater levels near SUDS**	[%]	Cameron and White (2004), Scanlon, Healy, and Cook (2002)
Infrastructural sustainability of SWS	Systems' hydraulic capacity	Surcharging in SW pipes High surcharging in SW pipes Flooding from SW pipe systems Manholes or inlets flooded **Effective storage volume in SUDS** **Frequency of overflow in SUDS**	[%] [%] [no./100 km/year] [no./100 km/year] [%] [no./1000 m^3/year]	Beceiro (2016), Berggren (2008), Cherqui et al. (2013), Dechesne, Barraud, and Bardin (2004), Matos et al. (2003) and Nie et al. (2009)
	Infiltration into SW pipes	Infiltration proportion in SW pipes capacity Infiltration flow in SW pipes	[%] [m^3/day/m]	Cardoso (2007)
	Operational condition of SWS	SW pipe blockages SW pipe blockage locations SW pumping stations blockages Blockages in SUDS structures **SW pipes without self-cleaning capacity** **SW pipes with abrasion potential** **Sediment accumulation rate at SUDS** **Saturated hydraulic conductivity evolution over time in SUDS** Dry solids removed from SW pipe systems **Dry solids removed from SUDS**	[no./100 km/year] [no./100 km/year] [no./no. SW pumping stations/year] [no./1000 m^3/year] [%] [%] [cm/year] [%] [ton/100 km/year] [ton/1000 m^3/year]	Erickso et al, (2013), Matos et al. (2003), and Moura et al. (2010)
	Structural condition of SW pipes	**SW pipes with a structural condition grade of 5** **SW pipes with a structural condition grade of 4**	[%] [%]	Davies et al. (2001), WRc (2001)
	Lifespan of systems' components	**Residual useful life of SW pipes** **Residual useful life of SUDS** Infrastructure value index of SWS (IVI)	[%] [%] [-]	Alegre, Vitorino, and Coelho (2014), Dechesne, Barraud, and Bardin (2004)
	Infrastructural integrity of SWS	Structural collapses in SW pipes Structural collapses in manholes **Structural collapses in SW storage devices**	[no./100 km/year] [no./100 km/year] [no./1000 m^3/year]	AWWA (2019), Danilenko et al. (2014), Matos et al. (2003)
	Rehabilitation of systems' components	Rehabilitation of SW pipes Rehabilitation of manhole chambers **Rehabilitation of SUDS**	[%/5 year] [%/5 year] [%/5 year]	Matos et al. (2003)

(*Continued*)

Table 2. (Continued).

Objectives	Assessment criteria	Performance metrics	Units	References
Sustainable use of resources	Efficient use of economic resources	**Costs of SW pipes new construction** **Costs of SUDS new construction** Costs of SW pipes rehabilitation Costs of SUDS rehabilitation **Costs of operation and maintenance works in SW pipe systems** **Costs of operation and maintenance works in SUDS** **Compensation costs for damages**	[€/m/year] [€/m^2/year or €/m^3/year] [€/m/year] [€/m^2/year or €/m^3/year] [€/m/year] [€/m^2/year or €/m^3/year] [€/1000 inhabitants/year]	Cherqui et al. (2013), Ossa-Moreno, Smith, and Mijic (2017)
	Efficient use of energy	Energy efficiency in SW pumping stations **Energy consumption in operation and maintenance works**	[kWh/(m^3.100 m)] [kWh/100 km/year or kWh/ ha/year]	Matos et al. (2003)
	Efficient use of water	**Water consumption in operation and maintenance works** **Water reuse in operation and maintenance works** **SW harvesting**	[m^3/100 km/year or m^3/ha/year] [%/year] [%/year]	Matzinger et al. (2014), Woods-Ballard et al. (2015)
Provision of ecological benefits	Biodiversity enhancement	Flora species richness Fauna species richness Species biodiversity index (Simpson's D index) Species evenness	[no. of flora species/SUDS site] [no. of fauna species/SUDS site] [-] [-]	Mak, Scholz, and James (2017), Matzinger et al. (2014), Moore and Hunt (2012), Woods-Ballard et al. (2015)
Provision of amenity benefits	Users' satisfaction	**Users' satisfaction with green spaces provided by SUDS** Users' willingness to pay	[-] [€/person/month]	Bastien, Arthur, and Mcloughlin (2012), Cherqui et al. (2013), Jarvie, Arthur, and Beevers (2017), Moura et al. (2010)
	Recreation opportunities	**Recreational, cultural and learning events**	[no./ha/year]	Mak, Scholz, and James (2017), Moore and Hunt (2012)
	Impacts of SUDS on microclimate	**Days with a positive difference in temperature between SUDS sites and city centres**	[%/year]	Matzinger et al. (2014)

*These PI can be disaggregated into more specific PI depending on the different chemical parameters proposed to analyse. GDP – gross domestic product.

assessment can be carried out with data from monitoring and/or mathematical modelling, in the latter case for rainfall events with specific return periods (e.g. 10-, 20-, 50- and 100-year). Users' complaints provide complementary information on how SWS performance affects people's lives and expectations.

2.2.1.2. Water utilities feedback. Both water utilities agreed on the importance of this objective for the SWS performance assessment. However, they questioned the relevance of some metrics to the decision-making process, namely the ones associated with the built environment impacts and complaints criteria. The fact that the quantification of some of those metrics requires information that normally water utilities do not own and the need to contact different institutions to obtain it, may represent a barrier for their application. Nonetheless, it was decided to keep the proposed metrics since they help identify vulnerable areas to the impacts of SWS failures, as studied in a previous study (Santos, Cardoso, and Galvão 2021). Water utilities or municipalities should develop methodologies to centralise the required information.

2.2.2. Protection of economic development

2.2.2.1. Overview. Urban flooding can cause massive disruption. SWS can play an important role in preventing and mitigating the effects of flooding events on the region's economy. SWS shall be maintained and operated to ensure that public and private properties and businesses are protected from flooding events. The proposed criteria allow assessing the magnitude and extent of the economic losses as resulting from these events, highlighting deficiencies in SWS performance and where interventions on these systems may be of high priority due to economic consequences. It is suggested the quantification of direct and indirect economic losses (IRDR 2015). Direct economic losses refer to the monetary value of physical damage to capital assets, including damages to residential, commercial, and industrial, public services facilities, infrastructure, and inventory. Indirect economic losses refer to damages to the flow of goods and services, such as losses due to business interruption. It is also proposed the quantification of business interruption that stems from operation and maintenance works, as well as from infrastructural integrity failure of SWS and the respective rehabilitation works.

2.2.2.2. Water utilities feedback. Although the economic impacts of SWS failures figure prominently in the media and, in many cases, it constitutes an incentive to dedicate more funding to SWS, water utilities classified this objective as moderately important in an assessment context. The respective metrics were considered difficult to apply, given the complexity involved in quantifying economic losses. Nevertheless, it was decided to maintain the proposal of metrics. They translate the reality with transparency, and they are applicable at a national level, despite the recognised difficulties. The fact that not all economic losses can be quantified should not be considered a weakness but rather an opportunity to improve data collection procedures continuously.

2.2.3. Protection of surface receiving waters quality

2.2.3.1. Overview. Several anthropogenic activities common to urban areas generate pollutants, contributing to the deterioration of surface receiving waters' physical, chemical and microbiological quality (Liu, Goonetilleke, and Egodawatta 2015). There is a high range of organic and inorganic pollutants entering SW that varies across and within catchments. The most common pollutant groups in SW are: solids, heavy metals, biodegradable organic matter, organic micropollutants, pathogenic microorganisms, and nutrients (Hvitved-Jacobsen, Vollertsen, and Nielsen 2010; Barbosa, Fernandes, and David 2012). Urban runoff quality monitoring constitutes a challenging tack given its intermittency, since it is dependent on the rainfall characteristics, including intensity and duration, and urban area surface, that influences the variation of pollutant load and composition (Liu, Goonetilleke, and Egodawatta 2015). The predicted impacts of climate change on the increase of antecedent dry period between rainfall events, increase in rainfall intensity and decrease in rainfall duration (Wijesiri and Goonetilleke, 2019), is expected to pose significant difficulties to the monitoring and mitigation of urban runoff quality.

In this sense, surface receiving waters shall be protected from the pollution caused by discharges of SWS to meet national, local legislation or regulatory requirements. The illicit domestic and/or industrial connections to SW pipes criterion assesses the existence of unintended connections to the SW pipe network conveying untreated domestic or industrial effluents and the respective flow proportion. Infiltration and inflow of groundwater are not considered illicit discharges. The quality of discharged urban runoff criterion allows the assessment of the compliance of urban runoff with quality permits at both catchment and local scale, regarding monitored rainfall events or total runoff samples collected during the assessment period, at discharge points. The monitored pollutants may be selected according to the type of land use and their potential impacts on the chemical and ecological state of the receiving waters. A monitoring programme based on performance assessment may support the detection of critical areas and lead to implementing intervention solutions, such as the installation of SUDS, for example.

2.2.3.2. Water utilities feedback. The need to protect surface receiving waters quality was recognised as important by water utilities. Once again, their evaluation of the relevance of the proposed metrics was influenced by the perception of the necessary resources (financial and personnel-related) to monitor SW discharged runoff quality. In the case of Portuguese water utilities or municipalities, there is no legal or regulatory demand for monitoring the quality of SW runoff at discharge points. And this fact, in combination with limited financial resources and the perception that SW runoff is not as polluted as wastewater, contributes to the disregard of this objective. Nonetheless, it was stressed that lack of information should not guide the evaluation of some components' relevance. Since controlling pollution from SW sources is gaining increased attention and mobilising water utilities in other countries, it was decided to maintain the proposal.

2.2.4. Protection of natural hydrologic cycle

2.2.4.1. Overview. The increase of impervious surfaces leads to a higher urban runoff production than the site in its undeveloped state. It becomes crucial to protect and mitigate the impacts of urbanisation on the natural hydrologic cycle, by implementing SUDS that may complement or replace the conventional SW network, and support the flood risk management.

Urban runoff quantity can be managed by SUDS in terms of peak flow and volume control, both proposed as assessment criteria. The control of urban runoff peak flow criterion assesses the capacity of SUDS to attenuate the runoff flow on site and then discharge it at a specified maximum rate by quantifying the duration and frequency of flow exceedances and the degree of peak flow attenuation. The criterion control of urban runoff volume aims to assess how much runoff is intercepted at SUDS with infiltration capacity. Mathematical modelling may be used for rainfall events with specific return periods (e.g. 10-, 20-, 50-, and 100-year). The criterion groundwater recharge is proposed to assess the impact of SUDS, particularly applicable to systems that provide runoff infiltration, on the evolution of groundwater tables, in the medium and long terms.

2.2.4.2. Water utilities feedback. The protection of the natural hydrologic cycle was considered as moderately relevant for SWS performance assessment by water utilities. The quantification of this objective accomplishment was evaluated as challenging. It requires monitoring and mathematical modelling of SUDS to calculate the proposed metrics, which demands high investment. Although during the planning phase of SUDS, the control of volume and peak flow are crucial aspects, they are frequently overlooked once SUDS are installed. The focus is then the control of flooding events. It was decided to keep the proposed metrics because they address the assessment of important hydrological functions by SUDS.

2.2.5. Infrastructural sustainability of SWS

2.2.5.1. Overview. Infrastructural sustainability means that SWS characteristics are adequate and can face the impacts of various current and future stressors (Upadhyaya 2013). It is important to identify the factors that may influence the capacity of SWS to maintain their condition over time.

The proposed systems' hydraulic capacity criterion aims to assess whether SWS are adequately designed and maintained regarding conveyance and flood control. The occurrence of surcharging may also have undesirable structural impacts. Mathematical modelling may be used for rainfall events with specific return periods (e.g. 10-, 20-, 50-, and 100-year). Assessing infiltration indicates the existence of structural deficiencies associated with structural defects. It also informs on the hydraulic capacity that is unduly used, and that may lead to a hydraulic surcharge. With respect to the operational condition of SWS, it translates the effectiveness of operation and maintenance works or the effect of design or construction deficiencies in the system's functioning. The assessment of the structural condition of SW pipes enables to quantify the proportion of these components in critical condition. The assessment of the structural condition may be based on the EN 13508–2 standard (EN 13508–2 2003), which provides support for the codification of sewer pipes visual inspections, along with the protocol developed by the Water Research centre (WRc) for classification of the structural condition of sewers (WRc 2001). The service life of systems' components informs about which components are near the end or well past their expected useful life. The infrastructural integrity of SWS indicates the degree of deterioration of SWS based on the occurrence of collapses. The rehabilitation of SWS criterion informs if the rates of rehabilitation have been adequate.

2.2.5.2. Water utilities feedback. Infrastructure sustainability was recognised as a key objective by the water utilities. For assessing this objective, metrics with which water utilities are most familiar are proposed, related to infrastructural integrity, structural condition, and rehabilitation criteria, for example. Overall, the metrics were evaluated as moderately relevant for the decision-making process, being the worst classified the ones associated with SUDS. These results show that water utilities are still not prepared to assess SUDS as to conventional SW pipe systems. Given the current wide implementation of SUDS in cities, infrastructural assessment of these systems will also assume an increasing relevance.

2.2.6. Sustainable use of resources

2.2.6.1. Overview. The SW sector faces considerable financing and funding constraints with impacts on the management activity. Water utilities need to use their limited financial resources efficiently while ensuring the replacement of aging and failing infrastructure and the implementation of additional measures to address the continued degradation of SWS (WEF 2019). Moreover, energy and water are also important resources that support the operation and maintenance of SWS, and their efficient use is necessary to protect the limited natural resources.

The sustainable use of these resources over SWS' service life is then fundamental to ensure that current and future demands are met. The efficient use of financial resources criterion informs on the allocation of these resources to the different activities in the systems, and it detects inefficiencies in the management of SWS that should be addressed. The efficient use of energy criterion assesses its use within the system, such as in SW pumping stations and operation and maintenance works (e.g. cleaning, inspection, and monitoring). The efficient use of water assesses the amount of water used in operation and maintenance works, to maintain SUDS with vegetation, and the amount of water from SW harvesting. SUDS with vegetation may require watering during dry periods. This assessment may inform the need to change the type of vegetation to be adequate to the climate conditions of the site. Quantifying the SW harvesting helps determine the potential capacity to face water scarcity and reduce potable water use for non-potable uses.

2.2.6.2. Water utilities feedback. Water utilities considered the sustainable use of resources as an important objective for SWS performance assessment. High relevance was given to metrics related to the efficient use of financial resources criterion. Cost metrics are consensual, given that they are easily calculated and interpreted. Regarding the efficient use of energy and water criteria, there were some doubts about their applicability, being the respective metrics classified as moderately relevant.

2.2.7. Provision of ecological benefits

2.2.7.1. Overview. SW infrastructure through SUDS can be designed to include the creation of habitats which in turn support biodiversity and stimulate a healthy and stimulating environment that add significant value to urban living (Woods-Ballard et al. 2015). The provision of these ecological benefits contributes to creating self-sustaining and resilient ecosystems, constituting a relevant performance objective for SUDS.

The proposed assessment criterion is the biodiversity enhancement, which intends to assess to what extent local species are being supported and enhanced at SUDS by considering species richness and diversity. It also assesses the creation and maintenance of habitat areas that contribute to habitat connectivity. The assessment will help to detect design malfunctions and limitations of SUDS that should be addressed.

2.2.7.2. Water utilities feedback. Water utilities identified the importance of providing ecological benefits by SUDS, but they revealed difficulties in evaluating metrics that are related to a different scientific field. The fact that the teams responsible for designing and managing SWS in water utilities have typically engineers, helps understand the low relevance provided to this area. It has been argued that the main challenges in the SW sector are not about advancing technology but about developing new working procedures and planning routines (Bohman, Glaas, and Karlson 2020) and integrating wider actor collaborations. The increasing adoption of SUDS in many cities and the need to provide several benefits beyond flood control will certainly motivate the integration of multidisciplinary teams in water utilities. It will help the redefinition of priorities in SUDS management, namely performance assessment.

2.2.8. Provision of amenity benefits

2.2.8.1. Overview. Amenity encompasses ideas related to greening urban landscapes, returning to nature, providing useful or pleasant services to the public, encouraging leisure activities and social interaction (Woods-Ballard et al. 2015). In this sense, SUDS shall be maintained and operated to ensure the provision of amenity benefits. The users' satisfaction criterion aims to assess the level of public acceptability regarding SUDS. The recreation opportunities criterion intends to assess the potential of SUDS sites to be used for organising activities related to sports and games, as well as to provide cultural and learning opportunities. The criterion of the impact of SUDS on microclimate assesses how green and blue spaces provided by SUDS buffer and moderate extreme temperatures.

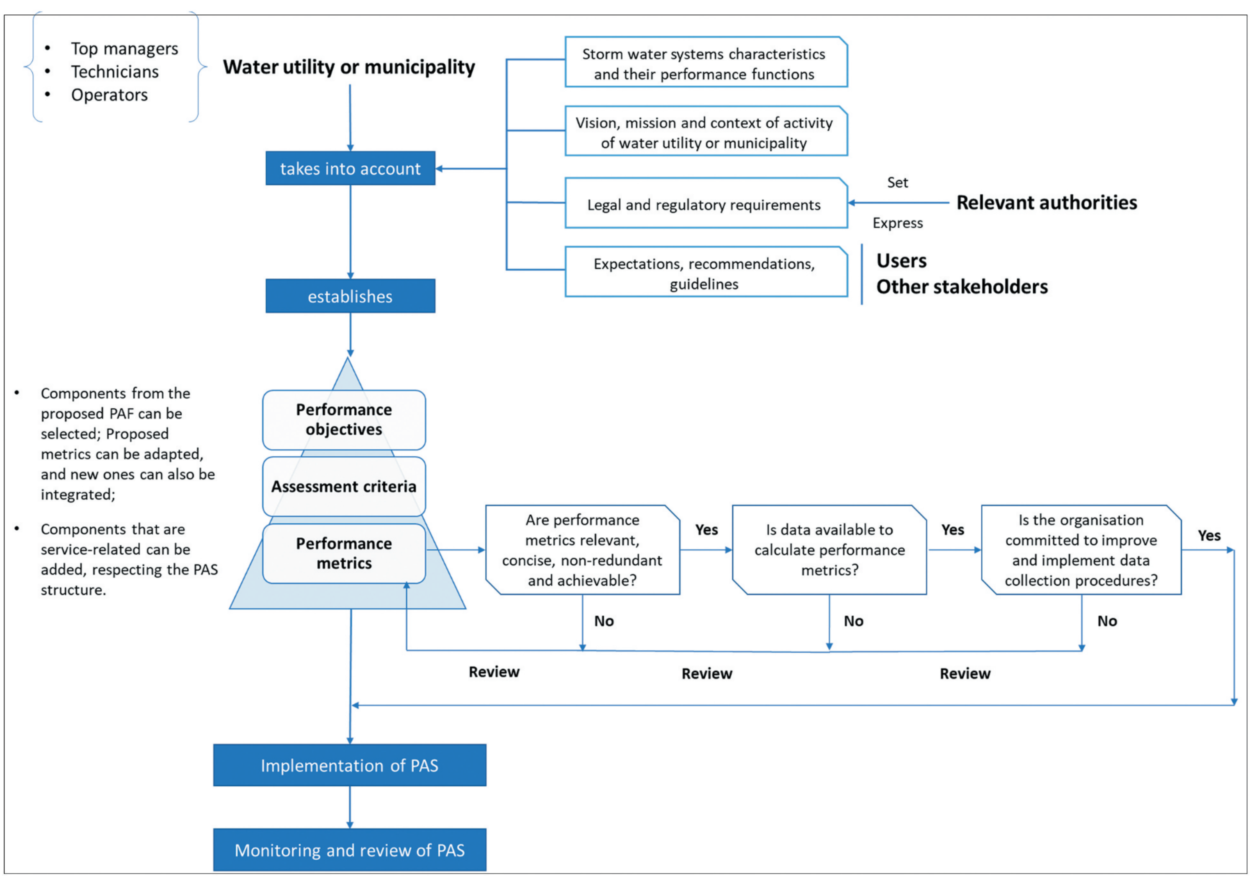

Figure 2. Schematisation of the establishment of performance assessment systems for SWS, which can be derived from the proposed PAF (adapted from ISO 24511 standard (ISO 2007b).

2.2.8.2. Water utilities feedback. The provision of amenity benefits was considered to have low relevance in SUDS performance assessment by water utilities. The SUDS potential to provide leisure areas was recognised, but the assessment of this objective was not viewed as a priority, besides being demanding in its implementation. Their evaluation was influenced by their lack of interest in this objective, being difficult to abstract from their specific context. Nonetheless, it was decided to keep the proposal since it has been increasingly recognised the capacity of SUDS to provide amenity benefits. As for the last objective, multidisciplinary teams could assume a strategic role in widening the SUDS assessment scope.

2.3. Performance metrics

For certain performance objectives, assessment criteria, and performance metrics there was a misalignment between water utilities and the authors opinion. On some occasions, it was decided to keep the initial proposal based on the scientific literature since it was thought to be of paramount importance. Additionally, the PAF must be applicable to SWS in diverse contexts and information maturity levels.

There is a certain degree of subjectivity during the proposal, design, and implementation of PAS. It is recognised as an intrinsic aspect of performance assessment that is not always controllable. Water utilities tended to consider relevant objectives and metrics the ones that would likely fit into their context. Most attention was paid to hydraulic, structural, and economic performance dimensions. It is then important to emphasise that lack of data should not justify discarding important aspects to assess.

Most proposed performance metrics in the PAF quantify past performance, using data collected from operation and maintenance routines, monitoring and rehabilitation works, records of incidents, complaints, and questionnaires to the public. Metrics can also be used to predict future performance using mathematical modelling, such as hydraulic modelling. In this case, the future performance of a SWS for different return periods of rainfall and climate scenarios can be studied, helping to anticipate performance failures and supporting the decision-making process regarding the selection of intervention solutions.

Depending on the assessment purpose, metrics can be aggregated into indexes to provide the overall SWS performance. Nonetheless, care should be taken when using indexes, otherwise important information may be lost. Metrics can also be disaggregated into sub-metrics to analyse different sub-systems or categories in detail. It is the example of some metrics that aim to assess SUDS. When the assessment of SUDS is carried out in multiple sites, the metrics of each component may be integrated into a performance index through weighted average, for example, considering area or volume. If disaggregation is required, metrics can be adapted to consider different systems configurations, such as surface or volumetric (e.g. €/100 m^2 or €/100 m^3).

The recommended assessment period for most metrics is one year to facilitate comparison over time. However, some metrics may be calculated for shorter periods, such as the case of modelling simulations, depending on the assessment requirements and existent technical and financial constraints. In this case, careful interpretation is recommended, or, if applicable, the transformation to a 1-year duration may be used.

Preference was given to the proposal of metrics composed of quantifiable variables, given the ease of interpretation, comparison, and objectivity. However, at the initial phases of PAS implementation, it may be acceptable to use qualitative information and classify it by performance levels when quantitative information is incipient or not available. It may help identify data gaps and the definition of methodologies for information collection to be used in a later phase of PAS implementation while considering the experience knowledge of the managers or operators.

Performance metrics results need to be compared against reference values. An interval of values may be defined, for which limits for good, acceptable, and unsatisfactory performance, for example, are established. Establishing those limits may be based on legislation requirements, literature references, historical data, or other water utilities' data. Most proposed reference values in the Supplemental Material were derived from legislation requirements and literature references from Table 2. Others were proposed within the scope of this work.

2.4. Recommendations for PAF application

The developed PAF intends to support water utilities, municipalities, and other institutional organisations responsible for SWS management, in defining their PAS (Figure 2).

The selection of objectives constitutes a crucial phase that will influence the definition of the PAS. The vision and mission of the organisation should be reflected in the selection of objectives, considering the context of the activity. Additionally, legal and regulatory requirements should be taken into account, as well as the users and other stakeholders' expectations, recommendations and guidelines.

In the next phase, assessment criteria and performance metrics, such as PI, should be selected, enabling the verification and quantification of objectives' accomplishment. It is fundamental to integrate those criteria and metrics that reflect the organisation main concerns in the PAS, even if they could not be calculated at the beginning of the assessment process. They may guide the relevant system information to be collected.

The PAF is flexible, allowing the addition of new metrics (e.g. service-related metrics) or the adaptation of the proposed ones, as long as the structure is maintained to guarantee a coherent PAS. The selection of performance metrics constitutes an iterative process. Their selection should follow the requirements proposed by Alegre et al. (2016) and Matos et al. (2003): well-defined and concise; reasonably achievable, simple and easy to understand; quantifiable; and non-redundant within the PAS.

Different professionals from organisations should be involved, including the top hierarchical managers, to ensure that the final PAS is robust and can translate reality and support the decision-making process. Over time, the PAS will need to be reviewed and updated to keep up with the evolving SW sector challenges.

4. Conclusions

The present article aimed to describe the development of a PAF that intends to fill the gap in the SW sector regarding the application of performance assessment. The PAF was based on the best practices and recommendations to establish a reference basis and to facilitate the integration or improvement of PAS into the management practices of water utilities, municipalities, and other institutional organisations. The views and contributions of two Portuguese water utilities during the validation phase were included, providing important insights to the authors about the difficulties that the water utilities face in the daily management of the SWS.

The PAF was designed to be comprehensive, flexible, objective and standardised, to support the establishment of a PAS. Eight objectives, 25 assessment criteria, and 80 performance metrics were proposed. These PAF components are in line with the structure of PAS in other urban water systems and broader management programmes. Therefore, it supports continuous improvement and preparation of SWS for the present and future challenges.

According to the water utilities' feedback, the major constraint to the development and application of PAS based on the proposed PAF is the lack of data and difficulty to be obtained, mainly related to the lack of financial and human resources. Water utilities also revealed to not be prepared to assess SUDS, especially considering the performance objectives related to discharged runoff quality, biodiversity and amenity benefits. Nonetheless, water utilities recognised as highly relevant performance components that, in their perspective, are attainable to apply in their context or that they are already applying.

Data availability may constitute a significant barrier to the application of PAS in many water utilities, given that some performance metrics are demanding in terms of data collection and analysis. Despite the difficulties, data gaps should not interfere with the selection of performance assessment components, since it is possible to carry out the assessment process as well. When performance metrics cannot be quantified, they may be replaced by a qualitative analysis based on the existent expert knowledge of systems functioning. This analysis can help to identify the needs of collecting quantitative data, supporting water utilities in improving information. After this phase, it is recommended that the water utilities invest on the collection and organisation of quantitative data for the selected PI, to ensure a more objective SWS performance analysis, improving reliability and quality.

It was conjectured that multidisciplinary teams, with staff with a complementary scientific background, would play a crucial role in how SWS are designed, managed, and assessed. It would help redefine priorities and urge the assessment of different systems' functioning requirements and data collection. In this sense, it is important to have the commitment of high hierarchy management levels of water utilities to support this paradigm shift successfully.

For future work, it is proposed the application of the PAF to additional real case studies, as in Santos, Cardoso, and Galvão (2022), to consolidate the proposal of PAF components and reference values. Soil and groundwater pollution was not addressed in the PAF. The approach to analyse the impact of SUDS on groundwater quality by water utilities should be further studied, given its complexity. The definition of a PAS based on the present PAF complemented with components focused on assessing service aspects is also proposed. The authors suggest extending PAF evaluation to other water professionals from different work contexts and scientific backgrounds engaged in the SW industry, to consolidate the external validation phase, to reduce the bias that exists during the process. Furthermore, the social validation phase should be carried out with relevant stakeholders in the SW sector. The contribution of more professionals would be an enrichment process since the proposed performance components are neither final nor exhaustive; the PAF will evolve as knowledge develops and data availability improves.

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