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Do resilience metrics of water distribution systems really assess resilience? A critical review

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ABSTRACT

Having become vital to satisfying basic human needs, water distribution systems (WDSs) are considered critical infrastructure. They are vulnerable to critical events such as extreme weather, natural and man-made disasters, armed conflicts etc. To account for critical events during design and operation of WDSs, the concept of resilience is frequently mentioned. How resilience of WDSs can be assessed using resilience metrics has been the subject of research of many publications. The aim of this paper is to inspect the alignment between a general understanding of resilience in WDSs and the metrics used for their resilience assessment. A novel framework for categorising resilience metrics for WDSs is presented. A literature review of resilience metrics for WDSs is performed and the results are analysed using the developed framework. The results show that the existing resilience metrics are not able to capture resilience in its complexityresilience metrics do not really assess resilience of the WDSs as a whole, but rather focus only on specific functions and properties which can make the WDSs resilient.

1. Introduction

Access to safe water belongs to the most fundamental human needs (United Nations Sustainable Development, 2022). It plays a pivotal role in the Sustainable Development Goal 6 (UN DESA, 2022). In many places on Earth, access to safe water is provided by water distribution systems (WDSs). Having become vital to satisfying basic human needs, WDSs are considered critical infrastructure that is vulnerable to extreme weather events, natural and man-made disasters, armed conflicts etc. Recent examples of this include the disruption of water supply as a consequence of the 2021 flood events in western Europe e.g. in Bad Münstereifel (Koks et al., 2022), several cases of direct attacks on pumping stations, pipelines and dams during the Russian invasion of Ukraine (Shumilova et al., 2023) as well as broken water pipes as a consequence of the 2023 earthquake in Turkey and Syria (Middle East Eye, 2023). The projected increase in frequency of extreme weather events as a result of the progressing climate crisis will continue to affect WDSs.

To account for critical events in the context of design and operation of WDSs, the concept of resilience is frequently mentioned (Ulusoy et al., 2018). WDSs are considered technical or socio-technical systems that need to be *resilient* with regard to critical events. While there is no scientific consensus about the definition of resilience, the aspect of guaranteeing minimum performance and the possibility of recovery can be found in several works (Pelz et al., 2021; Cassottana et al., 2021; Huizar et al., 2018; Cimellaro et al., 2016). Due to the difficulty of defining resilience as a result of its conceptual complexity, operationalising it and using it in academic studies is challenging (Fekete et al., 2020). These challenges will be illuminated in Section 3. The reasons for this are mainly the lack of scientific consensus regarding (i) the definition of resilience, and (ii) the quantification of WDS resilience.

These two challenges have been addressed in numerous scientific publications. In particular, numerous metrics have been proposed for resilience assessment of WDSs. The aim of the presented publication is to inspect the alignment between a general understanding of resilience in WDSs and the metrics used for resilience assessment. Specifically, the following research questions are addressed:

- How do existing WDS resilience metrics assess resilience?
- To what extent do the existing metrics assess resilience with regard to the functions and properties of resilient systems?
- How general are the existing resilience metrics with regard to different critical events?

To answer these questions, the remainder of the paper is structured as follows. First, an overview of existing review papers about resilience metrics in WDSs is provided in Section 2. In Section 3, the understanding of resilience within the scope of this study is presented, placed in the overall resilience discourse and its implications for the

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WDSs are illuminated. The novel framework for classifying resilience metrics is described in Section 4. Section 5 documents the literature search protocol. The results of the critical review and the discussion are presented in Sections 6 and 7, respectively.

2. State of the art

Several review studies aimed to categorise resilience metrics for water distribution systems in the past: Shin et al. (2018), Shuang et al. (2019), Liu and Song (2020), Gunawan et al. (2017), Gay and Sinha (2013), and Mohebbi et al. (2020). Each of the studies used their own unique framework for categorising metrics and the understanding of resilience also varied. In the following, the key structure of each of the frameworks is presented.

Shin et al. (2018) extend the system boundary considering not only WDSs but also water resource systems. While stating that resilience definitions in the domain of water infrastructures lack clarity, they determine four key capabilities of resilient systems - *withstanding* capability ("withstanding system disruptions and maintaining normal functionality under the disruptions" Shin et al., 2018, p. 5), *absorptive* capability ("immediately absorbing the disruptions and minimising system damage" Shin et al., 2018, p. 5), *restorative* capability ("quickly recovering to the normal or acceptable state" Shin et al., 2018, p. 5) and *adaptive* capability ("adapting to the changing conditions and uncertain disruptions" Shin et al., 2018, p. 5). These capabilities are considered as customer needs in a functional design process and can thus be understood as system functions. Shin et al. categorise resilience metrics according to two separate dichotomies: probabilistic vs. deterministic and dynamic vs. static. Unlike deterministic measures, the probabilistic measures "consider the stochasticity of system functions (or disturbances) and the probability-based formulation of the measures" (Shin et al., 2018, p. 19). Dynamic approaches "consider time-dependent functions of a system" (Shin et al., 2018, p. 3) while time-independent approaches do not.

Focusing solely on WDSs, Shuang et al. (2019) define WDS resilience as the "ability to absorb local failures, to quickly recover and maintain the essential service functions, and to adapt to long-term changes in the environment and uncertainty disturbances" (Shuang et al., 2019, p. 7). From this definition, they abstract three capabilities of a resilient WDS: absorptive, restorative and adaptive, omitting the withstanding capability of Shin et al. (2018). Analysing existing publications related to resilience assessment of WDSs, the authors identify four clusters of approaches for quantitative resilience metrics: surrogate measures, simulation methods, network theory approaches and fault detection and isolation approaches (Shuang et al., 2019). For each of the approaches, an overview of metrics, research progresses and limitations is provided. The clusters are, however, qualitatively different: while the first three focus on the methods behind the metrics, the last one covers an application area.

Liu and Song reviewed the body of research carried out on WDSs and five different types of urban networks (drainage distribution, gas distribution, transportation, electricity distribution and communication) (Liu and Song, 2020). For WDSs, Liu and Song identify two types of metrics similar to those of Shuang et al. (2019): surrogate-based evaluation metrics and recovery-based simulation metrics. According to the authors, the definition of resilience also changes based on which of the two types of metrics is used: in the first case, resilience "is considered a surrogate measure of [...] reliability, robustness, reserve capacity, and sustainability" (Liu and Song, 2020, p. 2) and is thus "static" (Liu and Song, 2020). In the second case, the resilience definition "[includes] adaptability, absorbability, and recovery capacity" (Liu and Song, 2020, p. 2), and is a "reflection of dynamic system performance before and after hazards" (Liu and Song, 2020, p. 2). However, the authors do not provide any sources for these definitions, neither do they explain their understanding of the terms "static" and "dynamic". They are also unclear on whether these terms relate to the concept of resilience, the resilience metric or the technical system itself.

Gunawan, Schultmann and Zarghami consider resilience itself to be one of the "indicators of system performance" (Gunawan et al., 2017), along with reliability, redundancy and robustness. They list 14 metrics, assigning each to one of the four "indicators" and dividing them into structural and functional metrics, where structural metrics can be understood as analogous to static metrics of Shin et al. and functional metrics as analogous to dynamic metrics (Shin et al., 2018). Resilience is mentioned only in connection with the dynamic metrics. Although this analysis provides an initial overview of different metrics, it does not systematically compare the individual indicators and elaborate in detail how they differ or what function of resilience they are related to.

Gay and Sinha performed a literature review of civil infrastructure system's resilience (Gay and Sinha, 2013). They offer an interdisciplinary perspective, distinguishing between engineering, ecologic, economic and societal resilience. However, they lack a resilience definition for the case of engineering resilience. They argue that while resilience in general cannot be measured, a system's capability for resilience can be assessed by concepts from graph theory. This resilience assessment should consider the previously stated four aspects of resilience during operation, design and analysis of infrastructures.

Mohebbi et al. (2021) evaluate resilience and its quantification in water, cyber, and transportation infrastructures, as well as their interdependencies. They distinguish between network-based, performance-based and technology-based metrics. They provide comprehensive lists for the different metrics (7 network-based, 6 performance-based and 5 technology-based). Nevertheless, similar to the reviews before, the authors do not go into detail about their understanding of resilience and do not describe which aspects of resilience each metric describes.

A major methodological problem in the review studies mentioned above is that little to no effort is made to link the resilience metrics to the definition or understanding of resilience. "Functions" or "capabilities" of resilient systems are mentioned, but not thoroughly reflected by the categorisation or analysis of the resilience metrics themselves. Other concepts such as redundancy, reliability and robustness are mentioned, but their relation to resilience differs in each paper and in some cases (Liu and Song, 2020; Gunawan et al., 2017) it is unclear whether they are the property of resilience or of a resilient system. Hence, more work is needed to improve the connection between the interpretation of resilience, other related concepts commonly mentioned in its context and the metrics used to measure it. The presented paper proposes a framework to address this challenge.

3. Resilience and water distribution systems

In this section, the understanding of resilience underlying this study is presented and placed in the overall resilience discourse. Certain functions and properties of resilient technical systems are introduced and the implications of this understanding within the studied domain of WDSs are illuminated.

3.1. Resilience of technical systems

While earlier mentions of the term resilience can be found, the first usage considered relevant for this work is by C. S. Holling in 1973 (Holling, 1973). Holling describes resilience as a measure of the ability of ecosystems "to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973, p. 17). In a later work, Holling distinguishes between engineering resilience and ecological resilience (Holling, 1996). The former focuses on efficiency, constancy, and predictability and aims for resistance of a (ecological) system to perturbation and return to an equilibrium steady state. The latter, in contrast, allows for multiple steady states to exist and considers the magnitude of disturbances that cause regimes changes in a system from one state to another.

Since then, the term resilience has been widely adopted and discussed in multiple scientific fields, as indicated by the scope of contributions to the Handbook of International Resilience (Chandler and Coaffee, 2016). According to Elsner et al. the concept of resilience owes its popularity in parts to a conjuncture of ecology, awareness of the dynamic nature of systems and the unavoidability of failures as well as a certain fatalism towards a loss of control (Elsner et al., 2018). In consequence, resilience has come under increased critical scrutiny. One point of criticism is the vagueness and ambiguity of its meaning (Cañizares et al., 2021) or even its haphazard usage (Elsner et al., 2018). This has not only put into question its usefulness for scientific study but raised the concern that as a normative term it transports a hidden agenda, as it does not capture aspects of political and economic power or interests, but instead is in line with neoliberal ideology (Elsner et al., 2018). More explicitly, it has been argued that calling for resilience is a strategy for the shifting responsibility of coping with critical events from large social institutions to individuals and that it can serve as an excuse for inaction with regard to mitigating the consequences of critical events or developments (Cañizares et al., 2021). The question whether the term is normative is not fully resolved, however, as the resilience of constellations or systems can be both desirable and undesirable (Cañizares et al., 2021). This is also reflected in the metaphors used for describing resilience, in that it allows systems to “bounce back” or “bounce forward”. Here, the former implies that a disrupted system returns to a prior, desirable state, reminiscent of Holling’s concept of engineering resilience and the latter that a disruption of the system leads to transformation and a new state of the system reflecting Holling’s concept of ecological resilience.

In spite of the critique, it has been acknowledged that the term is useful when studying complex, transient, adaptive systems (Elsner et al., 2018). Accordingly, from Holling’s concept of engineering resilience a paradigm of resilience engineering has developed for engineers concerned with complex systems (Woods and Hollnagel, 2017; Hollnagel et al., 2011; Hollnagel, 2016). Within this domain, the definition of resilience for the purpose of engineering of complex systems was gradually and systematically developed in order to include reactions to mishaps or continuous stress, to highlight the uncertainty of these events, and finally to incorporate aspects of the ecological engineering concept by focusing on adaptation to changed conditions (Hollnagel, 2016).

Pelz et al. drew on resilience as a strategy for coping with uncertainty when designing load-bearing systems in mechanical engineering (Pelz et al., 2021). Maintaining that systems ultimately serve to fulfil functions, they differentiate between three types of uncertainty these systems face: stochastic uncertainty, incertitude and ignorance. They further propose three design strategies for coping with uncertainty: (i) robustness, (ii) flexibility, and (iii) resilience. Here, robust systems are able to fulfil their designed functionality not only at the design point but within a given interval of operating conditions around the design point, whereas flexible systems can adapt to fulfil a given set of predetermined functionalities depending on the operating conditions. Both strategies are used for coping with incertitude. Resilience, in contrast, is a strategy for coping with ignorance, as it allows for systems to evolve their function beyond the predefined design point as an adaptation to changed conditions, while still fulfilling at least the function of its initial design. Accordingly, the authors give the following definition:

> A resilient technical system guarantees a predetermined minimum of functional performance even in the event of disturbances and failures of system components, and a subsequent possibility of recovering (Pelz et al., 2021, p. 411).

In this conceptualisation, resilient systems are a strict subset of flexible systems, which in turn are a strict subset of robust systems.

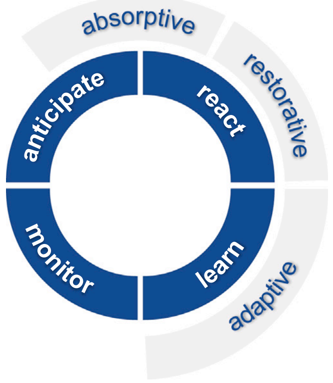

Fig. 1. Mapping of capabilities of resilient systems (grey) (Shin et al., 2018) to their functions (blue) (Hollnagel, 2016). While the absorptive capability can be mapped to both anticipation and reaction, the restorative and adaptive correspond to reaction and learning, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Within the scope of the presented work, resilience is understood as the property of technical systems according to the definition given above. However, the more general term *critical event* is used instead of the terms *disturbance* or *failure* to describe any event that requires the system to operate outside the designed operating conditions. In the following subsection, this broad definition is further detailed.

3.2. Functions and properties of resilient technical systems

Hollnagel speaks of four functions that make resilient performance possible (Hollnagel et al., 2011; Hollnagel, 2016). These functions of resilient systems are (Hollnagel et al., 2011):

- **monitoring** (knowing relevant internal and external critical parameters; supervising their values during operation)
- **reacting** (being able to respond to critical events by adjusting the current mode of functioning)
- **learning** (understanding what happened during a critical event and incorporate the knowledge during future critical events)
- **anticipating** (knowing the expected system’s behaviour when faced with critical events and being able to anticipate future developments such as changing operating conditions or new critical events)

Besides the functions of resilient systems, several other properties result from the definition of resilience in Section 3.1. Resilient systems are defined as having a predetermined (meaning required, acceptable) minimum of functional performance. This is e.g. the minimum of functional performance for emergency operation during or after a critical event. In resilient systems, the intrinsic minimal functional performance lies above the predetermined functional performance. It can be considered a baseline, hence it is referred to as *baseline functionality* in the context of this paper. Another important property of resilient systems is the possibility of *recovery*, reflected in the definition of resilience: despite the functional performance of the system being compromised, it should be possible for the system to return to a state in which a satisfactory functional performance can be guaranteed. Recovery is present in many other definitions of resilience as well (Ulusoy et al., 2018). A further property of resilient systems is *redundancy* (Ulusoy et al., 2018): by equipping the system with additional capacity, e.g. with duplicate components, a sufficient functional performance can be secured even in case of a critical event. However, it also increases costs and possibly the complexity of the system. Redundancy is generally considered tightly coupled with the concept of, but not sufficient for resilience. As such, it accompanies baseline functionality and the possibility of recovery.

Resilient systems are often described as those having the *adaptive*, *absorptive* and *restorative* capability (Liu and Song, 2020; Shin et al., 2018; Shuang et al., 2019; Hosseini et al., 2016; Ulusoy et al., 2018). These capabilities can be mapped to the functions of resilient systems as shown in Fig. 1. The *absorptive* and *restorative* capabilities – immediately reacting to critical events or restoring the system during or after a critical event – can be linked to reacting. Some authors also mention the *withstanding* capability (Shin et al., 2018), which is similar to the *absorptive* and can also be mapped to reacting. The *adaptive* capability can be mapped to learning as it describes changing the system according to experience from previous events or to expected circumstances. It is also possible to see a link between the capabilities and the properties of resilient systems mentioned above: recovery is reflected in the *restorative* capability, while *baseline functionality* as well as *redundancy* are important with regard to *absorptive* capability of the systems.

While the concept of resilience and the functions and properties of a resilient technical system have so far been presented in abstract terms of systems in general, in the following subsection, they are concretised for WDSs.

3.3. Resilience applied to water distribution systems

WDSs are large technical systems (LTS) with a socio-political dimension (Förster and Bauch, 2015; Moss, 2020). As infrastructure systems, they lie within the engineering domain as engineering knowledge is required for their design and operation (Hosseini et al., 2016). In the context of this work, the focus is on the technical character of WDSs. Of the overall water supply system of a city, WDSs are defined as the part that transports water from the outlet of the source or treatment plant to the point where the consumer's installation connects (European Committee for Standardization, 2022). WDSs consist of a network of pipes of various carrying capacity that covers the supply area but also of service reservoirs, pumping stations, valves, joints and fittings and further minor components (European Committee for Standardization, 2022).

Considering the adopted definition of resilience in the context of WDSs, the concepts minimum of functional performance, critical events, and possibility of recovery are to be clarified.

Functional performance of WDSs is determined by threshold values at the point of connection to the consumer's installation for the following quantities: service pressure, flow rate, continuity of supply, water quality (i.e. maximum threshold values for substances in the water) (European Committee for Standardization, 2022). Further criteria for functional performance include sustainable use of energy, minimising water loss, longevity of installations, minimising noise, and minimising risks to neighbouring buildings and the environment, and providing service in emergencies (Deutsches Institut für Normung e. V., 2021).

The minimum of functional performance can be defined by a further set of threshold values for the quantities enumerated above, according to national regulations. As an example for volume of water, the Federal Office of Civil Protection and Disaster Assistance (BBK) gives an estimation of 50 litres per day and capita to be provided by operators of WDS, even during critical events (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, 2022). This figure corresponds to the level 6B water restrictions enforced by the City of Cape Town during the drought in 2018 (Western Cape Government, 2018).[1] The threshold value in this case is a requirement defined for the operation of the WDS as a baseline functionality and is not equivalent to a predetermined minimum of functional performance as a characteristic of the WDS. Since WDSs are rarely designed from scratch but rather develop over generations, a predetermined minimum of functional performance cannot be implemented as a system characteristic and determining this characteristic is not trivial. Thus, defining threshold values for an acceptable minimum of functional performance for all operating conditions (i.e. a baseline functionality) is usually more relevant than determining the actual system characteristic "minimum of functional performance" of a WDS.

As stated in Section 3, WDSs as technical systems can be subjects to critical events (failures of system components and disturbances). Failures of system components in WDSs include but are not limited to pipe bursts, leakages in pipes, joints, service reservoirs or fittings, faults in pumping stations and pump outages, as well as broken valves. Disturbances are considered to be changes to the operating condition deviating from that for which the WDS was designed, often without damage to components. This includes unexpected changes to consumer demand and demand patterns, changes to the available supply of water from the sources and treatment plants as well as contamination of the water sources, back flow, and stagnation.

Concerning the possibility of recovery subsequent to critical events, this can generally be understood as the WDS returning to the service levels determined by the functional performance after a period in which only at least the minimum of functional performance was fulfilled. Depending on the nature of the critical events, recovery is either achieved from within the WDS through the actuators (pumping stations, valves) or by human intervention (repair of pipes and other broken components, restoring supply through source or water treatment plant, and others). It is important to recognise that in the latter case, the system boundary is extended to include not only the WDS as described above but also the human agents required to operate it as well as spare materials.

The four resilience functions defined by Hollnagel referenced in the preceding section are proposed to be understood in the context of WDSs as follows:

- **monitoring:** using sensors to measure quantities for operation, e.g. service pressure and volume flow, as well as relevant external quantities, e.g. groundwater levels, precipitation, population dynamics
- **reacting:** mitigating the effects of critical events on functional performance after detecting them and returning the WDS to fulfilling service levels, e.g. using actuators in the WDS such as valves and pumps (when not including human agents in the system boundary) or deploying repair crews to restore failed components (when including human agents in the system boundary)
- **learning:** gathering operation data and information and analysing them to improve future operation. This can entail using the data to adapt models for control units of pumps or improving protocols for detecting critical events through monitoring, e.g. by improving data analysis methods of the sensor data
- **anticipating:** providing for likely critical events in WDSs, e.g. leakages, pipe breaks, pump outages, demand or supply variations, and others, as well as considering long term developments, e.g. demand level increase or decrease through migration into or out of the supply area and changes in supply due to dropping groundwater levels or droughts

Considering the properties of resilient technical systems given in the previous section, the following concretisations can be made in the context of WDSs.

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[1] The amount of water provided in emergencies may be lowered to the minimum of water required by humans as defined by humanitarian NGOs or governmental organisations tasked with civil protection, which is 15 litres per day and capita (McCann and Knudsen, 2018; Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, 2022). This is generally not distributed through the technical WDS but by different means, which is why this threshold value is unsuitable as a minimum of functional performance for the resilience assessment of WDSs.

- **Baseline functionality** is a set of threshold values of the functional performance of the WDS (service pressure, flow rate, etc.) that serves as a reference for the acceptable minimum of functional performance. The deviation from this can be measured.
- **Recovery** is reflected in the resilience definition and is closely linked to the resilience function **react**. If the threshold values of functional performance cannot be maintained due to critical events, the react function of the WDS needs to be fulfilled in order to return the operating point to a state where the threshold values are again met.
- **Redundancy** in WDSs is related to the resilience function **anticipate**. Redundancy in WDSs is achieved by, e.g., ensuring multiple supply paths for consumers in a network, using multiple sources, including surplus pumps in pumping stations as well as securing extra capacity both in terms of available volume of water and transportation capacity in the pipe network.

Having illustrated how the resilience definition, resilience functions and related resilience properties can be applied to WDSs as an instance of resilient technical systems, the next step is to construct a framework within which metrics for measuring resilience can be classified.

4. Framework for classifying resilience metrics

In this section, the categories used within the presented work for classifying resilience metrics are presented in detail, constituting the framework used for analysing resilience metrics.

In the past years, a plethora of metrics have been designed for the purpose of assessing resilience of water distribution systems. To inspect *how* the metrics approach the assessment of resilience, the current section presents a framework (Fig. 2) to classify them according to:

- system functions addressed (cf. Section 3.2)
- system properties addressed (cf. Section 3.2)
- dependence on time (cf. Section 4.1)
- mathematical characteristics (cf. Section 4.2)
- quantification type (cf. Section 4.3)
- scope of the metric (cf. Section 4.4)

An important distinction is that the first two categories refer to what characteristics of the system are addressed, while the rest of the categories are characteristics of the metrics themselves. Hence, the metric *assesses* a function or a property that a system *has*, but the metric *is* time-dependent or *has* certain mathematical characteristics.

As the system functions and properties have already been presented in detail in Section 3.2, this section will focus on the remaining categories of the framework.

4.1. Metrics according to their dependence on time

Resilience metrics can be differentiated based on whether they do or do not consider development of the functional performance of the WDS in time (Liu and Song, 2020; Shin et al., 2018; Hosseini et al., 2016). In this framework, the terms *time-independent* and *time-dependent* are used instead of static and dynamic (Shin et al., 2018) (as the metric itself is not static or dynamic) or structural and functional (Gunawan et al., 2017) (as metrics assessing structural or functional characteristics of a system can still either depend or not depend on time).

Time-independent resilience metrics aim to assess resilience without considering the development of the selected quantity in time and tend to focus on topology of the system and characteristics of its components.

Time-dependent resilience metrics account for the development of the functional performance or another selected quantity in time.

It is important to distinguish between time dependence as the property of resilience versus the property of the resilience metrics. In the understanding of the authors of this paper, it is the metrics that can be either time-dependent or time-independent, not resilience itself. Some authors speak of “static resilience” (Sweya and Wilkinson, 2021; Pelz et al., 2021), which would suggest its time independence. However, the authors of this paper are of the opinion that it would be more appropriate to discuss whether resilience is *time-invariant*. This discussion is, however, beyond the scope of the present work.

4.2. Metrics according to their mathematical characteristics

Resilience metrics are defined on various intervals. Unlike open intervals, closed intervals with an optimal value suggest that a WDS can achieve absolute resilience. However, no scientific consensus exists about whether this is possible. The main reason for this is that the resilience scholarship tends to think of resilient systems with regard to any (reasonable) critical events, not to a specific set of them (Mentges et al., 2023), and that it is impossible to account for all of these in the resilience analysis. Moreover, it is also disputed whether resilience is a continuous or a Boolean property: whether a system can be *only a little resilient* or whether it either is resilient or it is not.

Resilience metrics are developed with the goal of being able to compare various configurations of a single system or separate systems with one another. Resilience metrics normalised to a closed interval (such as $[0, 1]$) suggest that comparability within the system as well as between various systems is possible. Non-normalised metrics make comparison between separate systems more difficult.

4.3. Metrics according to their quantification type

Resilience metrics use different types of quantification. Cassottana et al. differentiate between *graph-theoretical* and *performance-based* resilience metrics (Cassottana et al., 2021). *Graph-theoretical* resilience metrics are based on measures developed in graph theory (Cassottana et al., 2021), such as betweenness centrality or shortest paths. As WDSs can be modelled as mathematical graphs, these metrics are a suitable tool for their resilience assessment. Graph-theoretical metrics often aim to express resilience in terms of values of each node or link. *Performance-based* resilience metrics assess resilience as based on a system output characterising the performance of the system (Cassottana et al., 2021). For example, they express the ratio of functional performance with a predefined reference value, such as the ratio between supply and demand during a critical event or between the available energy and the required energy. Another quantification type are *score-based* resilience metrics. *Score-based* resilience metrics rely on an qualitative or semi-qualitative assessment according to certain criteria, using e.g. a 5-point scale (from “very good” to “very bad”). Some metrics can also be composed of multiple weighted metrics – these will be referred to as *composite metrics*. This approach is recommended by Hollnagel for assessing the resilience of systems in general, as he disputes that resilience is a quantity which can be captured by a single measurement (Hollnagel et al., 2011).

4.4. Metrics according to their scope

The key advantage of using metrics is to have a relative assessment of a certain property of a system – either with regard to its own states or with regard to other systems. With the help of resilience metrics, specifically, it should be possible to distinguish whether a new state of the system is more resilient than a former one, but also whether one system is more resilient than another. Accordingly, metrics are classified with regard to whether they are evaluated *(i)* for different states of a single system in order to compare the resilience of the various states, and/or *(ii)* for different systems in order to compare the resilience of the various systems.

Metrics also differ in their generality with regard to critical events. By definition, a system is resilient independent of a critical event, i.e. the resilient system definition from Section 3.1 should hold for

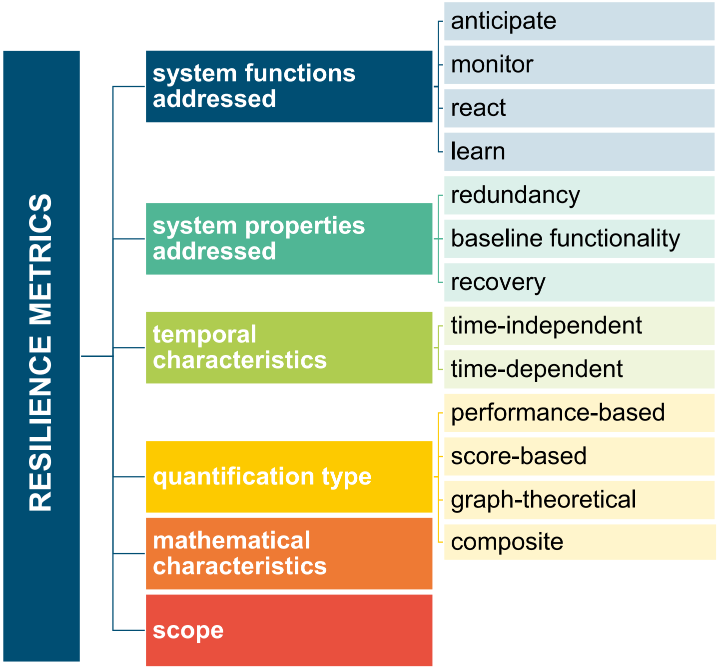


Fig. 2. Visualisation of the framework as described in Section 4.

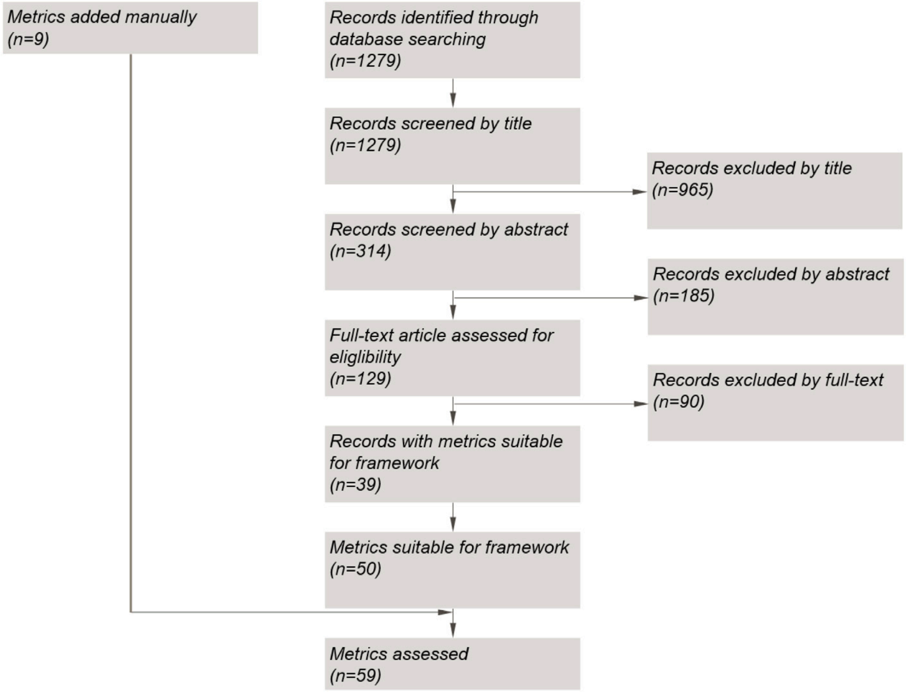


Fig. 3. Flowchart representing the step-wise filtering process according to the PRISMA guidelines.

all reasonable critical events. Accordingly, metrics are classified with regard to whether they are evaluated in view of critical events affecting the system as well as *which* and *how many* different types of critical events are considered.

5. Literature search protocol

The categorisation of currently existing resilience metrics using the framework presented above is based on a systematic search. Following the guidelines developed under the PRISMA concept (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), the following query in the Web-of-Science database was performed on March 10, 2022:

resilien AND (metric* OR indicator* OR quantitative* OR index OR indices) AND water AND (distribution* OR supply OR network* OR infrastructure*)*. Only papers written in English were included in the study. The workflow is shown in Fig. 3.

The initial search led to 1279 records. The titles of these publications were screened manually, after which 965 papers were filtered out,

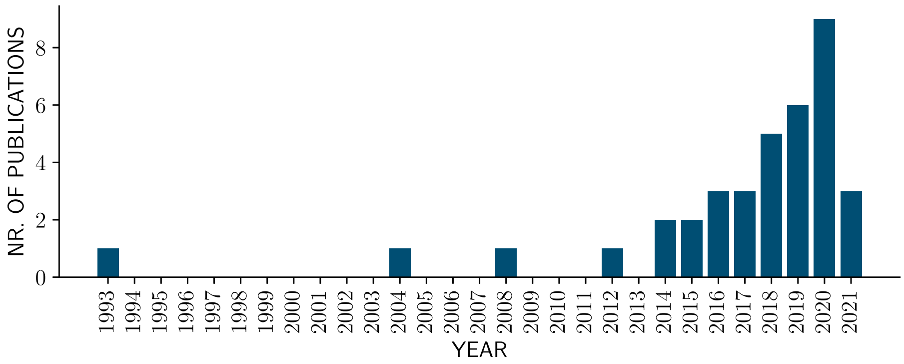


Fig. 4. A histogram of papers found in the literature search based on year of publication. After 2014, an increase in the number of publications is noticeable.

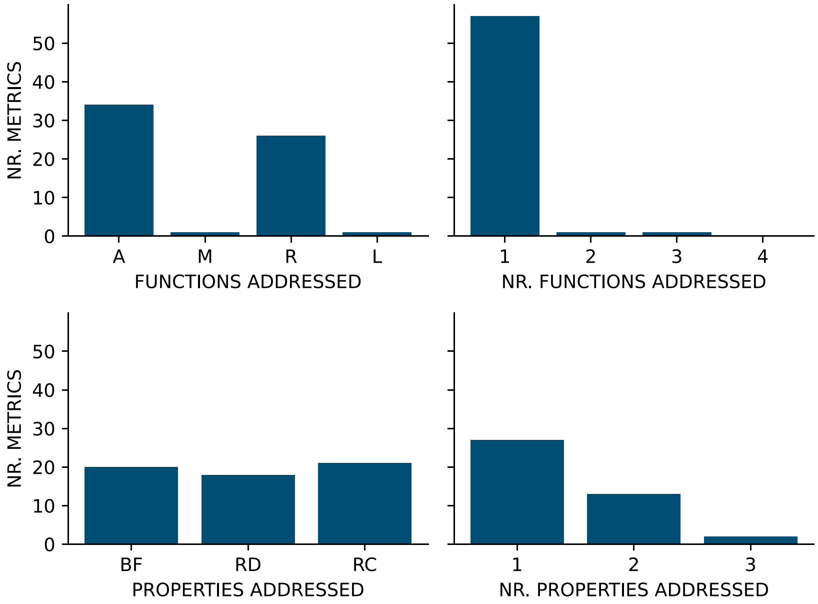


Fig. 5. Metrics by the functions and properties of resilient systems they address. Most metrics only assess either anticipating (A) or reacting (R); monitoring (M) and learning (L) is only assessed by one metric each. The properties baseline functionality (BF), redundancy (RD) and recovery (RC) are addressed by about 30% of the metrics each.

yielding 314 records. Subsequently, the abstracts underwent thorough screening. Whenever an abstract stated that a newly developed or adapted resilience metric was proposed or discussed within the paper, the paper was considered for further reading. Through this process, 185 papers were filtered out, leading to 129 papers.

Finally, full-text screens of all of the 129 papers were performed in order to assess whether the paper contains metrics that are presented as resilience metric, and whether the metrics are newly introduced or adopted from previous work. In this step, 90 papers were filtered out, resulting in 39 papers that contained suitable metrics. Most of the papers were published after 2014 as can be seen in the histogram in Fig. 4. Since some papers contained more than one metric, 50 resilience metrics were found through this search. Since several resilience metrics known to the authors were not captured by the search query, they were added manually (9 metrics). This has led to a total of 59 resilience metrics which are the research subject of this publication. The initial list of publications and all filtering steps can be followed with the help of the dataset linked in the supplementary material, c.f. Data and software availability section.

The resilience metrics were categorised using the framework introduced in Section 4 and subsequently used to answer the research questions from Section 1.

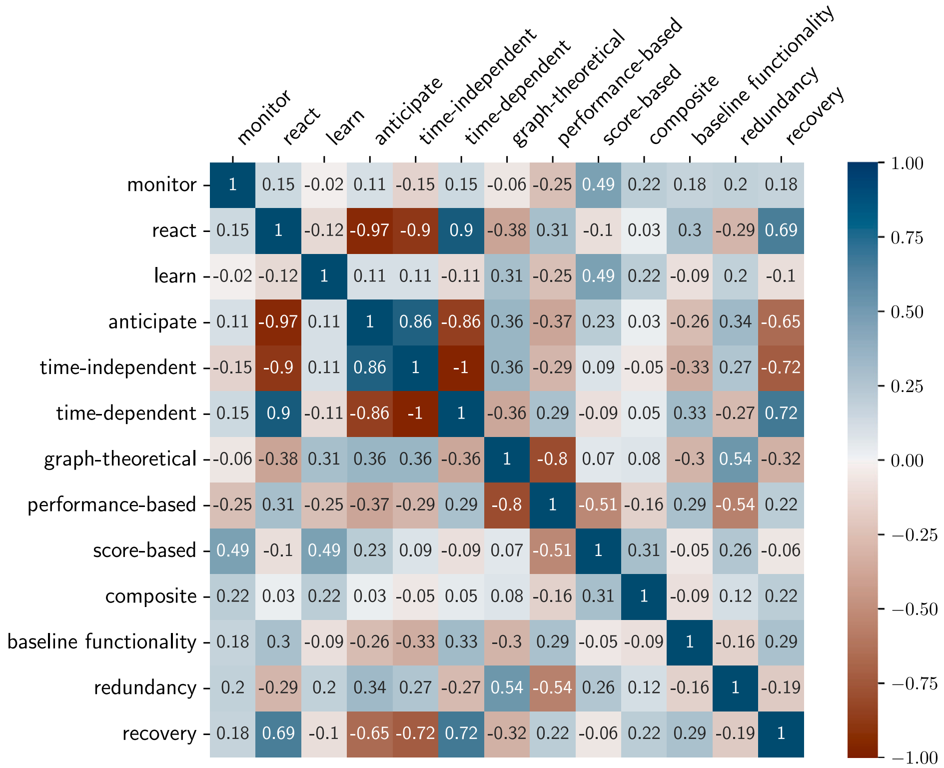
6. Results

This section presents the results of the literature review according to the framework described in Section 4. It is structured according to the three research questions defined in Section 1. The classification of metrics that this section is based on can be found in Appendix B, Table B.2.

6.1. How do existing metrics assess resilience?

Most metrics (46; 78%) assess resilience based on the performance of the system, i.e. on system output (such as delivered head or volume flow). 4 (7%) metrics are score-based, evaluating resilience of a system using a score system, and 9 (15%) metrics are based on approaches from graph theory. There are 15 composite metrics that combine multiple metrics using normalisation and weighting factors. Composite metrics can be composed of metrics of one quantification type or combine multiple ones (e.g. graph-theoretical and score-based).

From a temporal perspective, the review shows that there are 34 (58%) time-independent resilience metrics and 25 (42%) time-dependent resilience metrics.



	monitor	react	learn	anticipate	time-independent	time-dependent	graph-theoretical	performance-based	score-based	composite	baseline functionality	redundancy	recovery
monitor	1	0.15	-0.02	0.11	-0.15	0.15	-0.06	-0.25	0.49	0.22	0.18	0.2	0.18
react	0.15	1	-0.12	-0.97	-0.9	0.9	-0.38	0.31	-0.1	0.03	0.3	-0.29	0.69
learn	-0.02	-0.12	1	0.11	0.11	-0.11	0.31	-0.25	0.49	0.22	-0.09	0.2	-0.1
anticipate	0.11	-0.97	0.11	1	0.86	-0.86	0.36	-0.37	0.23	0.03	-0.26	0.34	-0.65
time-independent	-0.15	-0.9	0.11	0.86	1	-1	0.36	-0.29	0.09	-0.05	-0.33	0.27	-0.72
time-dependent	0.15	0.9	-0.11	-0.86	-1	1	-0.36	0.29	-0.09	0.05	0.33	-0.27	0.72
graph-theoretical	-0.06	-0.38	0.31	0.36	0.36	-0.36	1	-0.8	0.07	0.08	-0.3	0.54	-0.32
performance-based	-0.25	0.31	-0.25	-0.37	-0.29	0.29	-0.8	1	-0.51	-0.16	0.29	-0.54	0.22
score-based	0.49	-0.1	0.49	0.23	0.09	-0.09	0.07	-0.51	1	0.31	-0.05	0.26	-0.06
composite	0.22	0.03	0.22	0.03	-0.05	0.05	0.08	-0.16	0.31	1	-0.09	0.12	0.22
baseline functionality	0.18	0.3	-0.09	-0.26	-0.33	0.33	-0.3	0.29	-0.05	-0.09	1	-0.16	0.29
redundancy	0.2	-0.29	0.2	0.34	0.27	-0.27	0.54	-0.54	0.26	0.12	-0.16	1	-0.19
recovery	0.18	0.69	-0.1	-0.65	-0.72	0.72	-0.32	0.22	-0.06	0.22	0.29	-0.19	1

Fig. 6. Pearson correlation matrix between the data categories “monitor”, “react”, “learn”, “anticipate”, “time-independent”, “time-dependent”, “graph-theoretical”, “performance-based”, “score-based”, “composite”, “baseline functionality”, “redundancy”, “recovery”. Positive values (blue) and negative values (red) suggest positive and negative correlation, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

All graph-theoretical metrics are time-independent. The point-based metrics are predominantly time-independent, and the performance-based metrics are about 50/50 split between time-dependent and time-independent.

In total, 36 metrics use normalisation to a certain interval, most commonly $[0,1]$. In most cases, the optimal value is 1. In some other cases, the metrics do not suggest an upper or lower bound to resilience.

6.2. To what extent do the existing metrics assess resilience with regard to the functions and properties of resilient systems?

As Fig. 5 shows, there is a strong tendency to address anticipating (34; 58%) and reacting (26; 44%) rather than monitoring (1; 2%) and learning (1; 2%), even though monitoring and learning are considered vital resilience functions (c.f. Section 3.2).

The vast majority of metrics assesses only one function (57; 97%). Only a single metric assesses 2 and 3 functions each; no metrics assess all four functions. A thorough assessment of resilience, considering all resilience functions, is thus missing.

Properties of resilient systems – baseline functionality, redundancy and recovery are addressed by 20, 18 and 21 metrics, respectively (about 30% each). Similarly to the functions, most metrics that address properties of resilient systems only address one of them (27; 46%). 13 (22%) metrics consider 2 properties, and two consider all three.

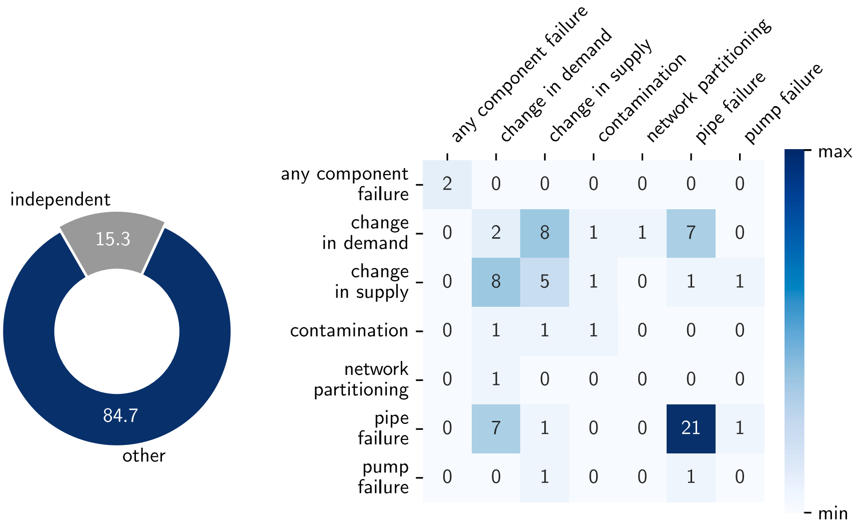
The functions and properties of the systems can be assessed by metrics with different temporal characteristics and quantification type. To investigate the relationship between the characteristics of the metrics (e.g., temporal characteristics or quantification type) and those of the systems (e.g., functions and properties), as well as between the functions and the properties themselves, the Pearson correlation coefficient was calculated using the data from Table B.2, see correlation matrix in Fig. 6. Fig. 6 shows that there is a strong positive correlation between time-dependence and the react function, and time-independence and the anticipate function, meaning that metrics that assess reaction tend to be time-dependent, while metrics that assess anticipation tend to be time-independent. This is in accordance with the expectations when considering the definitions of the functions provided in Section 3.3, as reaction is a highly transient function that arguably requires metrics that can capture development of the functional performance in time, while anticipation, defined as “providing for critical events”, can be also assessed without considering the development in time. Assessing anticipation and being graph-theoretical as well as assessing reaction and being performance-based correlate moderately, as expected due to the reasons mentioned previously. Assessing the recovery property correlates strongly with being time-dependent. The property redundancy correlates moderately with being graph-theoretical.

6.3. How general are the existing resilience metrics with regard to different critical events?

According to the resilience understanding in Section 3, a resilient system can keep its minimum functionality in any (reasonable) critical event. Hence, the metrics should aim for independence from the type of critical event, or for the consideration of a broad range of them.

The results of this study show that only about 15% of the reviewed metrics assess the resilience of WDS independent of the critical event (Fig. 7). Fig. 7 also shows that most metrics focus on a specific subset of critical events, most commonly only on one (pipe failure - 21, change in demand - 2, change in supply - 5). Two metrics consider “any component failure”, which is a relatively general category that can include pump failure, pipe failure, valve failure and other component failures. A commonly occurring combination is between change in demand and change in supply (8), as well as between pipe failure and change in demand (7). Only a single metric combines three critical events.

With this limited view, it can be argued that the metrics assess robustness of the system with regard to pipe failure or change in demand/supply, rather than its resilience.



	any component failure	change in demand	change in supply	contamination	network partitioning	pipe failure	pump failure
any component failure	2	0	0	0	0	0	0
change in demand	0	2	8	1	1	7	0
change in supply	0	8	5	1	0	1	1
contamination	0	1	1	1	0	0	0
network partitioning	0	1	0	0	0	0	0
pipe failure	0	7	1	0	0	21	1
pump failure	0	0	1	0	0	1	0

Fig. 7. Left: Metrics based on whether they assess the resilience of WDS independent of critical event (15.3% do). Right: Numbers of metrics based on which critical events they can capture. Most metrics can only capture one; combinations of change in supply and change in demand, as well as of pipe failure and change in demand are relatively common.

6.4. *Clustering reviewed metrics*

Hierarchical clustering has been performed on the reviewed metrics along the categories “system functions addressed”, “system properties addressed”, “dependence on time”, and “quantification”. More details on the clustering algorithm are provided in Appendix A. The results from the distance matrix are plotted in Table 1, forming 5 clusters (CLs). The clusters can be characterised as follows:

- CL1: reaction metrics considering recovery
- CL2: reaction metrics not considering recovery
- CL3: performance-based anticipation metrics
- CL4: non-performance-based anticipation metrics
- CL5: score-based resilience metrics considering all properties

6.5. *Categorisation of selected resilience metrics for WDS*

Below, selected metrics characteristic for each of the clusters specified in Section 6.4 are presented. The full list of reviewed metrics is presented in the Appendix B.

6.5.1. *Reaction metrics considering recovery (CL1)*

In CL1, all metrics are performance-based, assess reaction and consider recovery. Many of them also address baseline functionality.

Hashimoto et al. define the *system’s average recovery rate* as a measure of resilience (Hashimoto et al., 1982). For the system output X_t at time t, which can be in a satisfactory state S or failure state F, the metric can be expressed as follows:

$$\gamma = \frac{P(X_t \in S \text{ and } X_{t+1} \in F)}{P(X_t \in F)} = \frac{\varrho}{1-\alpha}, \tag{1}$$

where ϱ denotes the probability P of the system transitioning from the set S in the period t to the set F in the period $t+1$, and α denotes the probability of being in a satisfactory state: $\alpha = P(X_t \in S)$ (Hashimoto et al., 1982).

The metric is designed to aid in determining design and operating policies for WDSs (Hashimoto et al., 1982). In the understanding of Hashimoto et al. resilience describes “how quickly a system is likely to recover or bounce back from failure once failure has occurred” (Hashimoto et al., 1982, p.16). This measure assesses reaction, namely how likely the system is to transition back to a satisfactory state after failure. Hence, it considers recovery after the failure, and also requires baseline functionality to define the satisfactory/failure state. It is a time-dependent, performance-based metric. Hashimoto et al. do not prescribe what quantity the system output X_t should be expressed with; in their case study they work with volume.

The system’s average recovery rate is defined on the interval $[0, 1]$ with 1 being the optimum value. The use of the metric is illustrated on a water reservoir with seasonal changes in demand and supply.

Zhuang et al. define their resilience metric *integral water service availability* as “the percentage of water supplied to customers over a system failure period” (Zhuang et al., 2013, p. 532). It can be expressed as the ratio of delivered flowrate Q (supply) to required flowrate Q^* (demand) over the selected period of time when the critical event occurred (Zhuang et al., 2013). At system scale, it is formulated as

$$R_{\text{sys}} = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N} Q_{i,t}}{\sum_{t=1}^{T}\sum_{i=1}^{N} Q^*_{i,t}} \tag{2}$$

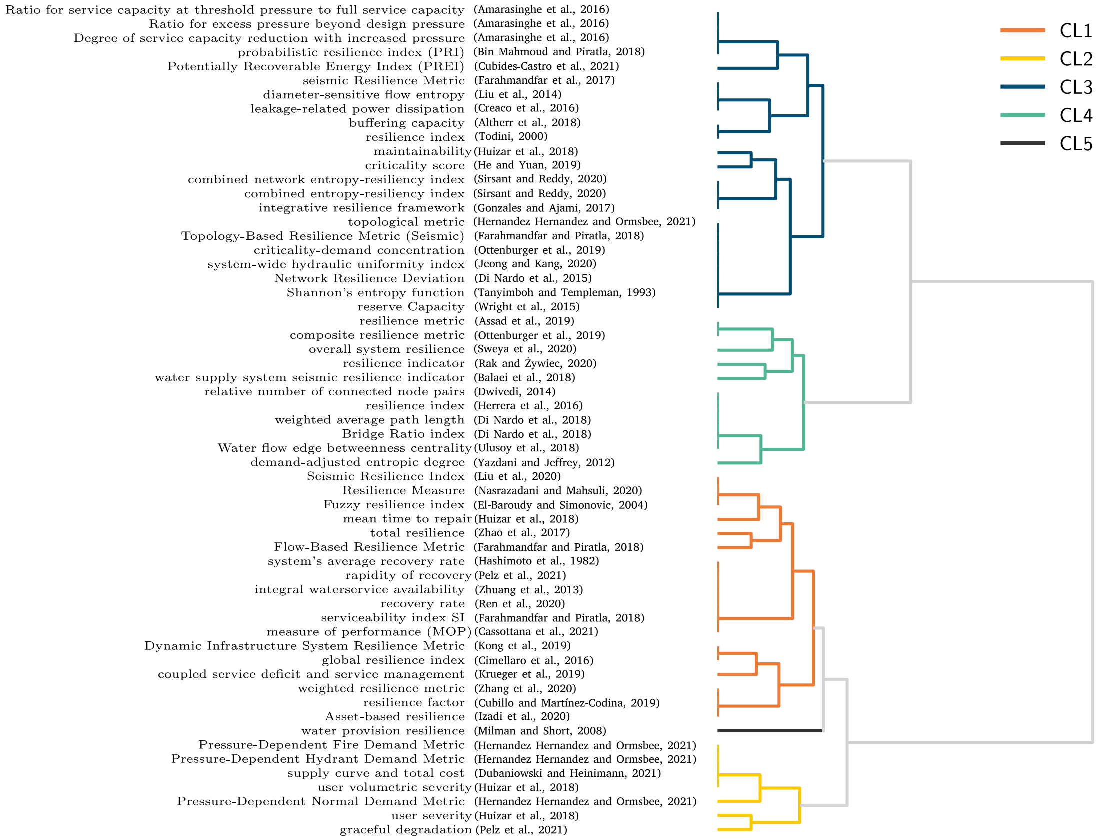
with T being the number of time steps when the system is subject to a failure and N the number of nodes (Zhuang et al., 2013). Using Monte-Carlo simulations, Zhuang et al. aim to assess the performance of the studied networks under various conditions. They aim to investigate what the critical factors affecting system resilience are. Moreover, they demonstrate how the expected costs for improving the WDS resilience can be determined. Zhuang et al. understand resilience as “the ability to recover from a failure to a satisfactory state” (Zhuang et al., 2013, p. 527). They consider the duration of recovery an important aspect of resilience. Considering Eq. (2) to be a resilience metric, they argue that it also provides an insight into the intensity of the critical event. This metric is a typical time-dependent resilience metric. It considers the time interval after the critical event, reflecting the focus on recovery. As such, it is capable of assessing the reacting function of the system. The authors use the metric to study the WDS performance when the current mode of functioning is adjusted, i.e. under operator intervention or under adaptive pump operation. Baseline functionality is reflected in the denominator (required volume flow Q^*). It is a performance-based metric defined on an interval between 0 and 1 with 1 being the optimal value at which the demand can be satisfied during the entire duration of failure. Performance of the system is measured using volume flowrate Q. The metric was applied to a medium-sized example network representing a primarily residential community. Comparisons are made between different reaction strategies. Zhuang et al. use the metric to study WDS resilience under randomly generated changes in demand and pipe failures.

Farahmandfar and Piratla define a *flow-based resilience metric* (Farahmandfar and Piratla, 2018) derived from Todini (2000):

$$\text{FR} = \frac{\sum_{t=1}^{td}\sum_{i=1}^{N_n}\left[\left(\sum_{j=1}^{N_i}(1-P_{fj})\right) q^*_{i,t}(h_{i,t}-h^*_{i,t})\right]}{4\times\sum_{t=1}^{td}\sum_{i=1}^{N_n} q^*_{i,t}h^*_{i,t}}. \tag{3}$$

Table 1

Dendrogram showing all reviewed resilience metrics grouped into 5 clusters (CL1–5). For assignment of metrics to clusters in text form, consult Table B.2.



Here, $q^*_{i,t}$ is the design demand at node i at time step t, $h^*_{i,t}$ is the minimum required total head at node i in time step t, and $h_{i,t}$ is the actual total head at node i in time step t. The factor $(1 - P_f)$ represents pipe reliability using pipe fragility P_f, which is computed for each pipe j as

$$P_{fj} = 1 - \exp(-\mathrm{RR}_j \cdot L_j), \tag{4}$$

with repair rate RR_j of pipeline j and length L_j of pipeline j. The quantities are summed over the number of time steps in the demand pattern td, the total number of nodes in the WDS N_n, and the node degree of node i N_i. The metric is used for making decisions in rehabilitation schemes with the objective of enhancing resilience within budgetary constraints. Farahmandfar and Piratla state that resilience refers to the ability of WDSs to "withstand stresses, mitigate failures, minimise consequences, and recover quickly in the face of abnormalities such as earthquakes" (Farahmandfar and Piratla, 2018, p.1). The metric assesses the reaction of the WDS. Similarly to the resilience index of Todini which it is based on, it considers the properties baseline functionality and redundancy (measuring the surrogate energy of the system). Summing up the values over time, however, makes it possible to also account for recovery. It is a time-dependent and performance-based metric, with performance being expressed in terms of power proportional to the product of the volume flow and head at node i and time t, $q_{i,t}h_{i_t}$. The metric is usually constrained to the interval $[0, 1]$ with 1 being its optimum value. The metric is evaluated for a single network and considers the scenario of pipe failures due to seismic events.

6.5.2. Reaction metrics not considering recovery (CL2)

In CL2, all metrics are performance-based and assess reaction. None of them consider recovery. They are predominantly time-dependent, and a few consider baseline functionality.

Huizar et al. propose a resilience metric called *user severity*, defined as "the minimum ratio of supply to demand, or minimum functionality, during the analysis period" (Huizar et al., 2018, p. 6). For the ith user, it is defined as

$$\mathrm{US}_{i,t} = \min_{T_0 \le t \le T} \{f_{i,t}\}, \tag{5}$$

where T_0 and T are the beginning and the end of the analysis period and $f_{i,t} = S_{i,t}/D_{i,t}$ is the user functionality, defined as the ratio of supply S to demand D at time t (Huizar et al., 2018).

The metric was developed along other metrics for the purpose of measuring water system security. Huizar et al. understand resilience as "the ability to mitigate and recover from failure" (Huizar et al., 2018, p. 1). User severity assesses the reaction of the system to a failure. It is time-independent and performance-based; the performance is expressed in terms of volume supplied. For non-zero demand D, user severity can attain values between 0 and 1, with 1 being the optimal value. The metric is sensitive to changes in supply and demand.

6.5.3. Performance-based anticipation metrics (CL3)

In CL3, all metrics assess anticipation and are performance-based. They are predominantly time-independent and consider baseline functionality or redundancy, in a few cases also recovery.

Todini's resilience index for looped water distribution networks (Todini, 2000), which is one of the most commonly used resilience metrics for WDSs, belongs to this cluster. It was formulated as

$$I_\mathrm{r} = \frac{\sum_{i=1}^{n_\mathrm{n}} q^*_i (h_i - h^*_i)}{\sum_{k=1}^{n_\mathrm{r}} Q_k H_k + \sum_{j=1}^{n_\mathrm{p}} (P_j/\gamma) - \sum_{i=1}^{n_\mathrm{n}} q^*_i h^*_i}, \tag{6}$$

with q^*_i and h^*_i being the design demand and head required at the node i, h_i being the available head at the node i, Q_k and H_k being the flow from and total head in the kth reservoir, P_j is the power introduced to the network by the jth pump, γ being the specific weight of water, and n_n, n_r, n_p being the number of nodes, reservoirs and pumps, respectively (Todini, 2000).

Todini understands resilience as the "capability of overcoming stress or failure conditions" or "the capability to allow to overcome local failures and to guarantee the distribution of water to users" (Todini, 2000, p. 116).

The resilience index is a time-independent resilience metric. It is performance-based, comparing the required power with the available power in the WDS. It can have values between 0 and 1, with 1 being the optimum value. Todini illustrates the use of the index on optimisation problems with three simplified looped networks with the aim of minimum cost design. He uses the resilience index in the design phase in order to develop a heuristic optimisation approach to arrive at a Pareto set of solutions in the cost vs. resilience space.

While Todini compares the values of resilience index for different states of a specific WDS, he does not make comparisons between different systems. The resilience index is independent of critical events. It assesses the anticipating function of the system. It is not necessary for the critical event to occur in the analysis or in the real world in order to be able to assess it.

Altherr et al. bring the *buffering capacity* into resilience engineering (Pelz et al., 2021). This metric was first described by Woods as "the size or kinds of disruptions the system can absorb or adapt to without a fundamental breakdown in performance or in the system's structure" (Woods and Hollnagel, 2017). Altherr et al. understood the buffering capacity as "a measure for the amount of structural change after which the fulfilment of a predetermined required minimum of functional performance can still be guaranteed" (Altherr et al., 2018, p. 190). In WDSs, buffering capacity can be expressed using discrete values - the number k of components that can fail while the minimum of functional performance can still be guaranteed. The system is then called *k-resilient*.

6.5.4. Non-performance-based anticipation metrics (CL4)

In CL4, all metrics are time-independent and assess anticipation. They are graph-theoretical or score-based. Composite anticipation metrics also belong to CL4. Most of these metrics address redundancy.

Herrera et al. base their resilience index on a common graph-theoretical algorithm, K-shortest paths (Eppstein, 1998). The index is also extended to WDSs sectorised into district metered areas. The measure of resilience is first computed for each node by determining the K-shortest paths between the node and each source. To account for hydraulics, the paths are weighted by energy loss associated with the flow resistance along the path. The resilience index of Herrera et al. for a node i is mathematically defined as

$$I(i) = \sum_{s=1}^{S} \left(\frac{1}{K} \sum_{k=1}^{K} \frac{1}{r(k,s)} \right) \tag{7}$$

with S being the total number of sources, K the number of shortest paths and $r(k,s)$ being the measure of the energy loss for the path k to source s (Herrera et al., 2016). It can be expressed for example as follows:

$$r(k) = \sum_{m=1}^{M} f(m) \frac{L_m}{D_m} \tag{8}$$

with M being the number of pipes on the path k, f the friction factor and L and D the pipe length and diameter, respectively (Herrera et al., 2016). As Lorenz and Pelz show, the index can be additionally weighted by the relative node demand q/Q where q is the node demand and Q the total demand in the network (Lorenz and Pelz, 2020).

For a district metered area, Herrera et al. propose aggregating the resilience indices of each node j into a single resilience index for all n nodes using the trimmed mean (García-Escudero et al., 2003):

$$I^* = \sum_{j=1}^{n^*} \frac{I(j)}{n^*} \tag{9}$$

in which nodes of very high or very low values are discarded before computing the mean ($n^* < n$) (Herrera et al., 2016). The purpose of the work of Herrera et al. is to develop a resilience assessment framework. The index is shown to be consistent with other alternative approaches. Herrera et al. understand resilience as "the ability of a system to maintain and adapt its operational performance in the face of failures and other adverse conditions" (Herrera et al., 2016, p. 1686). The resilience index of Herrera et al. addresses anticipation. It is a measure of the system's expected behaviour during a critical event. It quantifies redundancy in connectivity and supply (Herrera et al., 2016). It is not capable of considering recovery. It is a time-independent metric that only considers the topology of a network and hydraulic properties.

Herrera et al. validate the metric on the C-Town network (Ostfeld, 2016) and they use it to analyse the resilience of two networks with 4820 and 106,115 nodes, respectively. Comparisons are made between the resilience of various DMAs, not between the networks. The considered disruption event is pipe failures.

Balaei et al. developed a framework for assessing resilience, leading to the *water supply system resilience indicator* that aggregates several weighted and scaled metrics:

$$R = \frac{1}{\sum_{j=1}^{N} w_j} \sum_{j=1}^{N} w_j i_j^2, \tag{10}$$

where the weights are denoted by w and the indicators by i for N indicators in total (Balaei et al., 2018). The indicators are scaled by the respective maximum value. The indicators are "operational representations of serviceability, quality, or a characteristic of a system" (Balaei et al., 2018, p. 5) that satisfy the criteria of validity, sensitivity, objectivity and simplicity (Balaei et al., 2018). A specific set of indicators must be chosen for each use case under the consideration of data availability. Examples of indicators provided in the paper are physical vulnerability, knowledge of the emergency response plan, social participation rate, GDP per capita and median household's income. The purpose of the resilience indicator and the proposed framework is to assess seismic resilience based on data and information from past earthquakes. The framework is aimed at researchers, planners and decision makers. The metric considers the anticipating function. It is a time-independent and score-based metric. It has been evaluated on one example without comparisons. It has a strong focus on earthquakes but as the choice of indicators has to be determined for each individual system, there is potential to adjust it to other critical events as well.

6.5.5. Score-based resilience metrics considering all properties (CL5)

Among the metrics found in the presented study, CL5 contains only one score-based metric that considers three system functions (monitor, react and anticipate) and all three properties. It is thus the closest to being a resilience metric.

The *water provision resilience (WPR)* was proposed by Milman and Short (2008). Rather than giving a single equation for calculating it, WPR is an aggregate of points that the considered WDS scores in the categories supply, finances, infrastructure, service provision, water quality, and governance. In each of these categories, there are different numbers of criteria for which a binary decision is made whether they are fulfilled or not, each fulfilled criterium yielding a point. The sum of points gives the score of WPR. The purpose of this metric is not, as the authors state, to "measure the adaptive capacity related to catastrophic events" (Milman and Short, 2008, p. 756). Instead, the focus lies on measuring "the ability of a city or water district to maintain or improve access to safe water" (Milman and Short, 2008, p.760). In their understanding of resilience, the authors refer to Folke (2006, p.259) seeing resilience as "the capacity of the system 'to absorb disturbance and re-organise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks'", emphasising that the definition includes the ability of the given system "to adapt to stresses and changes and to transform into more desirable states" (Milman and Short, 2008, p.759). The variety of criteria included for the resilience evaluation allow the metric to cover three of the resilience functions: monitor, react and anticipate. The properties baseline-functionality, redundancy and recovery are also considered within the criteria. As the criteria include the development of the WDS within the following 50 years, the metric is time-dependent. It is a score-based and composite metric. In total, 36 criteria are included, i.e. the maximum achievable value of WPR is 36, the minimum being 0. The metric is used by Milman and Short to assess the resilience of the WDS of three municipal areas and to compare the resilience of these. Critical events considered in the criteria are change in demand, change in supply, and water resource contamination.

7. Discussion

In a systematic review of resilience metrics for WDSs, the presented results show that most metrics, regardless of what their characteristics are, only focus on a single function and/or property of resilient systems, rather than on their resilience as a whole. The review bridges a gap in research about resilience metrics for WDSs as it provides a comprehensive framework for categorising metrics and juxtapose them with a general understanding of resilience.

Most often, the functions “anticipate” and “react” are assessed. While generality with regard to critical events is often stressed when speaking about resilience, it is not reflected in the metrics which tend to focus on specific critical events such as pipe failure and changes in demand or supply. Moreover, that the metric is defined on a specific interval with an optimal value suggests that the system can achieve perfect resilience. Once the system achieves it, there is no more room for improvement with regard to resilience. It is, however, questionable whether such a state is achievable for real-world networks, and whether the resilience metrics are really capable of capturing this.

Strictly speaking, the presented assessment framework shows that there is no metric among the existing metrics reviewed that can be called a *resilience metric*, as no metric addresses all 4 functions of a resilient system. Moreover, the existing metrics tend to focus on a small range of critical events. This is not to say, however, that the metrics are not useful for certain purposes, even for those related to resilience assessment, or e.g. optimisation for resilience. Resilience is a complex concept that is difficult to capture by quantitative and even qualitative metrics, whether they are composite or not; composite metrics bring a new challenge, namely determining the scaling and weighing factors. Instead of focusing on finding an all-encompassing resilience metric, the authors propose that a more precise differentiation is made among metrics related to resilience assessment in WDSs: for example, to speak of anticipation metrics or reaction metrics rather than of resilience metrics, and to explicitly state which critical events can be captured by them and which cannot. This will help prevent conceptual stretching of the term resilience, already criticised nowadays for being a buzzword or an umbrella term particularly difficult to work with in academia (Fekete et al., 2020; Bogardi and Fekete, 2019). The presented framework can be used for this purpose.

The design of the presented framework depends strongly on the selected definition of resilience. As no scientific consensus with regard to the definition of resilience exists, the authors have selected a definition that is well-known and general enough to cover most other definitions present in literature. Assessing whether functions and properties are addressed by metrics has been a challenging task during the review that is necessarily prone to a certain amount of subjectivity. By providing both the data and the code used for the analysis (Data and software availability section), the authors hope to lay ground for a discussion of the framework and resilience understanding in the domain of WDS.

A further limitation of the presented study is that it is restricted to resilience metrics for WDSs as isolated “complex systems”, thus disregarding the interdependencies WDSs have with other infrastructure systems, e.g. power grid, communication and transportation networks etc. It would be a more holistic approach when assessing resilience of urban infrastructure to consider the multiple infrastructure systems and their interdependencies as a “system of systems”. However, it is common engineering practice to draw a limited system boundary in order to reduce complexity while dependencies of the considered system with its environment (e.g. other systems) are reflected in boundary conditions or flows across the system boundary. Extending the system boundary for it to encompass multiple infrastructure systems increases the complexity and makes resilience assessment an altogether more challenging task. Open questions with regard to resilience assessment in the domain of WDS identified in this study need to be resolved before addressing the more formidable challenge of assessing the resilience of a “system of systems”.

While difficult to capture by metrics, the authors are of the opinion that the understanding of resilience should not be limited in order to make it easier to quantify, but rather that new metrics should be developed in order to improve its quantifiability. Especially the functions “learn” and “monitor” are largely ignored by the existing metrics for WDS. Existing frameworks such as the Resilience Analysis Grid (Hollnagel et al., 2011) or water provision resilience (Milman and Short, 2008) can be used as a guideline; while having a thorough resilience understanding, these frameworks, however, lack quantitative metrics and are thus currently difficult to implement in studies commonly performed in the field of resilience engineering of WDSs, such as optimisation problems or Monte Carlo simulations.

The presented results also prepare ground for further research in the domain of WDS resilience. As mentioned in Section 1, WDSs can be considered socio-technical systems. However, during the presented analysis it became apparent that the “social” part of the socio-technical system remains largely ignored in the resilience assessment of WDSs. The interlinkage between the “social” and the “technical” in WDS resilience assessment should be subject of further research, ideally building upon recent advances in formalising social resilience (Copeland et al., 2020). A big challenge remains to systematically incorporate climate change effects into resilience metrics for WDS, as climate change is not only causing critical events that affect water distribution, but is also a critical event itself. With progressing droughts, it will be necessary to extend the system boundary of WDS to include water resource management and/or other infrastructure that can be used for delivering water to citizens, such as the transport network. Moreover, like other disciplines (Fekete et al., 2020; Cai, 2020; Cañizares et al., 2021), WDS research should also take a critical look on resilience, evaluating the weaknesses and strengths of the concept and reflect these in the metrics.

8. Conclusion

The presented publication assessed the alignment between a general understanding of resilience in water distribution systems and the metrics used for their resilience assessment. For this purpose, a systematic review of resilience metrics for WDSs was performed, showing that:

- most metrics are performance-based rather than graph-theoretical or score-based, and time-independent rather than time-dependent (RQ1)
- most metrics, regardless of what their characteristics are, only focus on a single function and/or property of resilient systems, rather than on their resilience as a whole (RQ2)
- most metrics focus on a specific set of critical events, resulting in a lack of generality inherent to the understanding of resilience (RQ3)

To summarise and answer the title question, the results show that resilience metrics do not really assess resilience, but rather specific functions and properties of systems which can make them resilient. To prevent further conceptual stretching of the term resilience, the authors propose that a stronger differentiation is made among metrics related to resilience assessment in WDSs: for example, to speak of anticipation metrics or reaction metrics rather than of resilience metrics.

CRediT authorship contribution statement

Michaela Leštáková: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Data curation, Project administration. **Kevin T. Logan:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Data curation, Project administration. **Imke-Sophie Rehm:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Peter F. Pelz:** Funding acquisition, Supervision. **John Friesen:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data and software availability

The data for this study (a table with categorisation of all reviewed metrics as well as a table with the literature search procedure) is available under https://doi.org/10.48328/tudatalib-1179.

The corresponding code in the form of Jupyter notebooks is available under https://doi.org/10.48328/tudatalib-1180.

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Appendix A. Clustering

The hierarchical clustering was performed in Python utilising the methods `scipy.cluster.hierarchy.linkage` (method: `‘ward’`, metric: `‘Euclidian’`) and `scipy.cluster. hierarchy.fcluster` (number of clusters: 5, criterion: `‘maxclust’`).

The dendrogram was created with the method `dendrogram` from `scipy.cluster.hierarchy`.

The code including an Anaconda environment file with all necessary Python packages is available in the Jupyter Notebook the link to which is provided in Data and software availability section.

Appendix B. Categorisation of metrics

See Table B.2.

Table B.2
Categorisation of the existing resilience metrics. M: monitor, R: react, L: learn, A: anticipate, TI: time-independent, TD: time-dependent, GT: graph-theoretical, PB: performance-based, SB: score-based, CM: composite, BF: baseline functionality, RD: redundancy, RC: recovery, CL: cluster.

Metric	M	R	L	A	TI	TD	GT	PB	SB	CM	BF	RD	RC	CL
Measure of performance (MOP) (Cassottana et al., 2021)		1				1		1			1		1	1
Dynamic infrastructure system resilience metric (Kong et al., 2019)		1				1		1		1			1	1
Total resilience (Zhao et al., 2017)		1				1		1				1	1	1
Serviceability index (SI) (Farahmandfar and Piratla, 2018)		1				1		1			1		1	1
Flow-based resilience metric (Farahmandfar and Piratla, 2018)		1				1		1			1	1	1	1
Coupled service deficit and service management (Krueger et al., 2019)		1				1		1		1		1	1	1
Weighted resilience metric (Zhang et al., 2020)		1				1		1		1	1		1	1
Resilience measure (Nasrazadani and Mahsuli, 2020)		1				1		1					1	1
Seismic resilience index (Liu et al., 2020)		1				1		1					1	1
Resilience factor (Cubillo and Martínez-Codina, 2019)		1				1		1		1	1		1	1
Global resilience index (Cimellaro et al., 2016)		1				1		1		1			1	1
Recovery rate (Ren et al., 2020)		1				1		1			1		1	1
Fuzzy resilience index (El-Baroudy and Simonovic, 2004)		1				1		1					1	1
Mean time to repair (Huizar et al., 2018)		1				1							1	1
Integral water service availability (Zhuang et al., 2013)		1				1		1			1		1	1
System’s average recovery rate (Hashimoto et al., 1982)		1				1		1			1		1	1
Rapidity of recovery (Pelz et al., 2021)		1				1		1			1		1	1
Asset-based resilience (Izadi et al., 2020)		1				1		1		1	1		1	1
Supply curve and total cost (Dubaniowski and Heinimann, 2021)		1				1		1						2
User severity (Huizar et al., 2018)		1			1			1						2
User volumetric severity (Huizar et al., 2018)		1				1		1						2
Pressure-dependent fire demand metric (Hernandez Hernandez and Ormsbee, 2021)		1				1		1						2
Graceful degradation (Pelz et al., 2021)		1			1			1			1			2
Pressure-dependent normal demand metric (Hernandez Hernandez and Ormsbee, 2021)		1				1		1			1			2
Pressure-dependent hydrant demand metric (Hernandez Hernandez and Ormsbee, 2021)		1				1		1						2
Leakage-related power dissipation (Creaco et al., 2016)				1	1			1				1		3

(continued on next page)

Table B.2 (*continued*).

Metric	M	R	L	A	TI	TD	GT	PB	SB	CM	BF	RD	RC	CL
Ratio for excess pressure beyond design pressure (Amarasinghe et al., 2016)				1	1			1			1			3
Shannon's entropy function (Tanyimboh and Templeman, 1993)				1	1			1						3
Network resilience deviation (Di Nardo et al., 2015)				1	1			1						3
System-wide hydraulic uniformity index (Jeong and Kang, 2020)				1	1			1						3
Criticality score (He and Yuan, 2019)				1	1			1		1			1	3
Ratio for service capacity at threshold pressure to full service capacity (Amarasinghe et al., 2016)				1	1			1			1			3
Integrative resilience framework (Gonzales and Ajami, 2017)				1	1			1		1				3
Degree of service capacity reduction with increased pressure (Amarasinghe et al., 2016)				1	1			1			1			3
Topology-based resilience metric (seismic) (Farahmandfar and Piratla, 2018)				1	1			1						3
Reserve capacity (Wright et al., 2015)				1	1			1						3
Potentially recoverable energy index (PREI) (Cubides-Castro et al., 2021)				1		1		1			1			3
Combined network entropy-resiliency index (Sirsant and Reddy, 2020)				1	1			1		1				3
Combined entropy-resiliency index (Sirsant and Reddy, 2020)				1	1			1		1				3
Seismic resilience metric (Farahmandfar et al., 2017)				1	1			1				1		3
Buffering capacity (Altherr et al., 2018)				1	1			1			1	1		3
Diameter-sensitive flow entropy (Liu et al., 2014)				1	1			1				1		3
Resilience index (Todini, 2000)				1	1			1			1	1		3
Criticality-demand concentration (Ottenburger et al., 2019)				1	1			1						3
Maintainability (Huizar et al., 2018)				1	1			1					1	3
Probabilistic resilience index (PRI) (Bin Mahmoud and Piratla, 2018)				1	1			1			1			3
Topological metric (Hernandez Hernandez and Ormsbee, 2021)				1	1			1						3
Water supply system seismic resilience indicator (Balaei et al., 2018)				1	1				1	1		1		4
Resilience index (Herrera et al., 2016)				1	1		1					1		4
Relative number of connected node pairs (Dwivedi, 2014)				1	1		1					1		4
Demand-adjusted entropic degree (Yazdani and Jeffrey, 2012)				1	1		1							4
Resilience metric (Assad et al., 2019)				1	1		1			1		1		4
Bridge ratio index (Di Nardo et al., 2018)				1	1		1					1		4
Water flow edge betweenness centrality (Ulusoy et al., 2018)				1	1		1					1		4
Composite resilience metric (Ottenburger et al., 2019)				1	1		1			1		1		4
Overall system resilience (Sweya et al., 2020)			1	1	1		1		1	1		1		4
Resilience indicator (Rak and Żywiec, 2020)				1	1				1					4
Weighted average path length (Di Nardo et al., 2018)				1	1		1					1		4
Water provision resilience (Milman and Short, 2008)	1	1		1		1			1	1	1	1	1	5

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