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## **A comprehensive framework to evaluate hydraulic and water quality impacts of pipe breaks on water distribution systems**

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**Abstract:** Pipe breaks have significant impacts on the hydraulic and water quality performance of water distribution systems (WDSs). Therefore, it is important to evaluate these impacts for developing effective strategies to ultimately minimize the consequences of these events. However, there has been surprisingly limited research focusing on impact evaluation for pipe breaks so far. To address this gap, this paper proposes a framework to comprehensively evaluate hydraulic and water quality impacts of pipe breaks on a WDS using six quantitative metrics. These metrics primarily focus on identifying (i) break outflow volume, (ii) water shortage, (iii) nodes with reduced service quality, (iv) pipes with affected pressures, (v) pipes with reversed flow directions, and (vi) pipes with significantly increased velocities, for each breaking event within a WDS. Statistical behaviors, spatial properties and pipe rankings of metric results are analyzed to reveal the underlying characteristics of impacts induced by pipe breaks. We illustrate the proposed framework using three WDSs with different properties. Results show that impacts of pipe breaks not only vary with pipe diameters, but are also significantly influenced by pipe locations, when the break occurs, and the specific metric considered. The proposed framework greatly enhances the fundamental understanding of the underlying properties of breaking impacts on the hydraulic and water quality of WDSs, as well as the ranking of pipes based on the consequences of breaks. Such understanding offers important guidance

to develop effective pipe management, resource planning and break restoration strategies to minimize the impacts of breaking events on WDSs.

**Keywords:** water distribution systems; impacts of pipe breaks; hydraulics; water quality; quantitative metrics; disaster planning

## 1. Introduction

Water distribution systems (WDSs) can be defined as the facilities (e.g. pipes, pumps, valves, tanks) that are collectively used to supply water from their source to the points of usage, with desired quality, quantity and pressure [Berardi *et al.*, 2014; Housh and Ostfeld, 2015]. Pipe breaks are a common type of service failure for WDSs, with possible causes including sudden pressure variations [e.g. transient flow, Lechevallier *et al.*, 2003], pipe corrosion [Lee *et al.*, 2016], uneven ground settlement [Gheisi *et al.*, 2016], freezing and thawing cycles [Dineva and Nordlund, 2015], external loads [Gupta *et al.*, 2016], and natural disasters [e.g., earthquake, Yoo *et al.*, 2016].

Although the probability of pipe breaks can be lower than that of small leaks [Diao *et al.*, 2016; Qi *et al.*, 2018], such events have much more severe consequences as they can significantly impact the service level of WDSs [Jowitt and Xu, 1993; Besner *et al.*, 2011; Kanta *et al.*, 2013]. These impacts include significant water losses, intermittent supply, low pressure and a reduction in water quality [e.g. yellow water, Abraham *et al.*, 2018]. In addition to these hydraulic and water quality impacts, pipe breaks can also result in damage to surrounding infrastructure (e.g. ground collapse), posing severe threats to public security [Guo *et al.*, 2013]. For example, during 2016, there were more than 100 recorded pipe breaks in Guangzhou, China, which have significantly influenced the service quality of the WDSs for the city [Zhang *et al.*,

2016]. Moreover, one of the events flooded an underground garage, resulting in significant economic loss.

Due to the potentially large impacts of pipe breaks, it is important to prevent such extreme events before their occurrence and to reduce their consequences should they occur. Regarding the prevention of pipe breaks, many studies have been carried out to optimally manage the operational pressure and velocity of WDSs, thereby avoiding flow transients that are highly likely to cause pipe breaks [Araujo *et al.*, 2006; Kapelan *et al.*, 2017]. Alternative approaches have been developed to analyze the physical condition and deterioration status of pipes within WDSs in order to repair or replace pipes with high breaking likelihood in a timely fashion [Kleiner and Rajani, 2001]. Meanwhile, other studies have been undertaken to predict pipe breaks through statistical models based on available breaking records, which can be used to determine which actions can be taken to prevent their occurrence [Pelletier *et al.*, 2003; Yamijala *et al.*, 2009].

While the above research has made significant contributions to advance knowledge in the modelling and prediction of pipe breaks, their practical applications are not without difficulties [Francis *et al.*, 2014]. This is because pipe breaks are essentially, at least partly, random, in both their times and locations of occurrence. The possible

'random' causes for these events include transient pressures resulting from improper system operation (e.g. pumping switch or valve operation), external accidents (e.g. power off or inappropriate road construction) and natural disasters (e.g. floods or earthquakes) [Vítkovský *et al.*, 2000; Wang *et al.*, 2013; Islam *et al.*, 2013]. In recognition of this, there has been increasing interest in developing methods for reducing the impacts of pipe breaks on the performance of WDSs in recent years.

One typical way to reduce the impacts of pipe breaks is through improving response efficiency, which ensures that breaks can be isolated/repared in a timely manner [Wu *et al.*, 2016; Liu *et al.*, 2017]. Such improved efficiency is critical, as even a break of a short duration would cause large water losses and severe damage to the surrounding infrastructure [Kapelan *et al.*, 2017]. This has motivated the development of many approaches to efficiently detect and localize pipe breaks, which include real-time monitoring methods, transient-based methods and hydraulic-model-based methods [Hugenschmidt and Kalogeropoulos, 2009; Misiunas *et al.*, 2005; Wu and Sage, 2006; Sanz *et al.*, 2016].

In addition to the detection and localization methods mentioned above, impacts of pipe breaks can also be reduced through increasing the resilience of WDSs to pipe breaking events [Colombo and Karney, 2002]. This goal can be attained by improving

understanding of the impacts of breaking events on the hydraulics and water quality of WDSs, both in an overall sense, and the detailed spatial distribution of these impacts. This knowledge is valuable, as it can guide the allocation of emergency resources, the development of restoration schemes, the assignment of regular-checking routines, as well as the deployment of detection sensors. This is because the resources required for these practices are often limited, and hence they should be prioritized for pipes with relatively larger breaking impacts, in order to reduce the overall consequences of breaking events within WDSs.

For example, the 2018 water distribution system analysis (WDSA) conference has organized a special battle competition focusing on the restoration of a WDS with many pipes that were broken after an earthquake. The objective was to explore the best way to use available resources for restoration, as well as to identify the most effective strategy that a water utility can take to prepare for such a scenario [*Colombo and Karney, 2002*]. For such a disaster event, prior knowledge of the properties of impacts induced by each breaking event on the WDS is essential to facilitate decision-making regarding restoration schemes (e.g. which pipes should be repaired/replaced first).

Despite the importance of understanding the impacts of pipe breaks within WDSs, only a limited number of studies have focused on this particular area. Work so far has mainly focused on the assessment of undelivered demands [Creaco *et al.*, 2012; Kapelan *et al.*, 2017; Diao *et al.*, 2016; Ostfeld *et al.*, 2002, 2004] and the pressure drops caused by pipe breaks [Mahmoud *et al.*, 2017; Giustolisi and Walski, 2012]. While this information is important, it cannot fully indicate the underlying properties of the impacts associated with each pipe break. Specifically, how pipe breaks affect the hydraulics, and more importantly, the water quality of a WDS, has not been comprehensively explored. To address this gap, this study proposes a comprehensive framework to evaluate the impacts of pipe breaks on the hydraulics and water quality of WDSs.

The core component of the proposed framework includes six quantitative metrics, which primarily focus on identifying six aspects of impacts induced by each pipe break event within a WDS. These are: (i) break outflow volume, as a direct measure of water losses; (ii) total water shortage, which represent the overall immediate impacts on the supply service of the WDS; (iii) demand nodes with reduced service quality, as an indicator of the spatial distribution of the affected users; (iv) pipes with affected pressures, which are used to develop response plans to pipe breaking events; (v) pipes with reversed flow directions, which are likely to cause water quality issues

(e.g. yellow water); and (vi) pipes with significantly increased flow velocities, within which biofilms may be dislodged, thereby deteriorating water quality. The first three metrics focus on evaluating the hydraulic effects of pipe breaks on WDSs, whereas the last three metrics evaluate water quality impacts with the aid of indirect indicators. In addition to defining these quantitative metrics, we also propose analytical approaches for statistical behavior, spatial properties and pipe ranking analysis based on the values of these metrics, as part of the evaluation framework.

The proposed evaluation framework can significantly improve the understanding of impacts of pipe breaks on the hydraulic and water quality performance of WDSs. With this understanding, pipes within a WDS can be ranked based on the relative consequences associated with the breakage of each pipe. As pointed out in the WDSA 2018 battle competition, the preparation of emergency strategies should be a critical consideration for each water utility to minimize the impacts of pipe breaks caused by unforeseeable events (e.g. earthquakes) [Gheisi *et al.*, 2016]. This further highlights the need for the proposed framework for the evaluation of the consequences of pipe breaks. To our best knowledge, the current work represents the most comprehensive framework to quantitatively evaluate the underlying properties of impacts of pipe breaks on WDSs, considering both hydraulics and water quality perspectives.

The paper is organized as follows. Section 2 describes the proposed evaluation framework. Section 3 presents three WDSs on which the proposed framework is tested, as well as the computational experiments used for achieving this . The case study results are presented and discussed in Section 4, followed by summaries and conclusions of this study in Section 5.

## **2. Framework for evaluation of impacts of pipe breaks**

A schematic of the proposed framework for evaluating the impacts of pipe breaks on the hydraulics and water quality of WDSs is given in Figure 1. As can be seen, the first step of the proposed framework consists of the generation of a large number of different pipe break scenarios, the hydraulic performance of which is then assessed with the aid of a steady-state pressure-driven simulation model. This enables the calculation of the six evaluation metrics. Finally, the statistical behavior and spatial distribution of the metric values across all breaking scenarios, as well as the resulting pipe rankings, are analyzed. Through these analyses, the hydraulic and water quality impacts of pipe breaks are comprehensively evaluated, which thus achieves the aim of this study. Details of each step of the proposed evaluation framework are given in the subsequent sub-sections.

### ***2.1 Pipe break scenarios and simulations***

To evaluate the impact of a large number of possible pipe break events within a specific WDS with  $N$  pipes,  $N$  pipe-break scenarios should be generated, with each corresponding to a breaking event in one pipe. Although it is possible that multiple pipes can break simultaneously [Diao *et al.*, 2016], the probability of such an event is relatively low and hence it is not considered in the proposed framework.

The hydraulics of pipe breaks can be modelled in different ways, two of which are illustrated here with the aid of the small synthetic WDS shown in Fig. 2. It should be noted that the pipe breaks considered should be large, where the outflows are similar to those from the hydrants. As can be seen from Fig. 2, the WDS considered consists of four nodes and five pipes, where nodal demands are provided by a reservoir with a head of 20m and a break occurs in pipe [5]. The pressure at each node before the occurrence of the break is presented in Fig. 2(a). Details of the two alternatives for modeling the hydraulics of pipe breaks are given below, as part of which the hydraulics of the entire WDS are simulated using a steady-state pressure-driven model (see Section “2.2 Steady-state pressure-driven model”).

Probably a common way to model the hydraulics of a serious pipe break is to add a dummy reservoir that is connected to the broken pipe through a dummy pipe (large diameter and small length) and a dummy node (no demand is applied) [Ang and Jowitt,

2006; Babu and Mohan, 2011], as illustrated in Fig. 2(b). It is noted that the elevations of the dummy node and reservoir are identical to those of the breaking point and the check valves are used to prevent inflows from the dummy reservoir. The inflows to the reservoir can be considered as the break outflow volume. As stated previously, the hydraulics of all nodes are simulated using a steady-state pressure-driven model as described in Section 2.2. Consequently, actual nodal flows of many nodes (Fig. 2(b)) are lower than their corresponding specified demands (Fig. 2(a)).

An alternative approach to modelling the hydraulic impact of a pipe break is to separate the broken pipe into two segments and to add a node at the end of each of these segments, both of which have the same elevation as the broken pipe [Qi *et al.*, 2018], as illustrated in Fig. 2(c). A large demand is then applied at each of these nodes as an initial guess of break outflow (e.g. we used 10,000L/s for the simple example shown here) to trigger the simulation of the pressure-driven model. Next, the actual nodal flows at the two nodes are determined by iteratively reducing the pressure at the break location based on Equation 1 (see Section “2.2 Steady-state pressure-driven model”). The final flows at the two nodes resulting from the iterative process are then summed to obtain the actual break outflow induced by the pipe break (Fig. 2(d)). The hydraulics of the other nodes are also simulated using this steady-state pressure-driven model.

As shown in Fig. 2(b) and Fig.2(d), the hydraulic results of all pipes and nodes from both approaches are identical for the example considered, where the total outflow caused by the break of pipe [5] is 248L/s, with contributions of 218 L/s and 30L/s from the left and right pipes, respectively. These results indicate that this break causes substantial changes in hydraulic conditions within the WDS compared with conditions prior to the event, which can be visualized by comparing the pressures, pipe flow directions and flow velocities between Figs. 2(a) and 2(b)/2(d).

## **2.2 Steady-state pressure-driven model**

A pressure deficit may occur in a WDS under some operating scenarios, such as pipe breaks [Sivakumar and Prasad, 2015]. Within traditional demand-driven analysis, the assigned demands are fully satisfied, irrespective of the available pressure values, implying that the demands can be delivered under negative pressure values [Mahmoud *et al.*, 2017]. However, this does not conform to reality, as outflow (or demands) under such extreme scenarios would depend on the remaining pressure at the nodes, and no demands would be delivered when the pressure approaches zero (no negative pressure exists under steady-state hydraulic conditions [Wu *et al.*, 2009]). Therefore, to better model realistic hydraulic conditions in WDSs after pipe breaks, a pressure-driven model is used in the proposed framework to overcome the limitations of demand-driven models outlined above [Giustolisi and Walski, 2012]. It should be

noted that the pressure-driven model adopted in this study is based on steady-state hydraulic condition (i.e., steady-state pressure-driven model), which describes the hydraulic status after the transient period induced by pipe breaks. Such a pressure-driven analysis approach has been widely used in the WDS research domain [Wu *et al.*, 2009; Piller *et al.*, 2016; Mahmoud *et al.*, 2017]. Since this framework focuses on complete pipe breaks, which result in significant drops in nodal pressures, the relationship between pipe break outflow and pressure is represented using the model of Wagner *et al.* [1988], due to its simplicity and broad application in practice. This model is given in Eq. 1.

$$Q_i = Q_i^{req} \left( \frac{H_i - H_i^{\min}}{H_i^{req} - H_i^{\min}} \right)^\gamma \quad H_i^{\min} \leq H_i \leq H_i^{req} \quad (1)$$

where  $Q_i$  is the actual water delivered to node  $i$ , which is the outflow during the breaking event.  $Q_i^{req}$  and  $H_i^{req}$  are the required nodal demand and pressure, respectively. Both requirements have to be satisfied to meet the desired service level.  $H_i$  is the actual nodal pressure and  $H_i^{\min}$  is the minimum pressure below which no water can be supplied to the node (usually  $H_i^{\min}=0$ ).  $\gamma$  is the pressure exponent, which often takes a constant of 0.5, as recommended in previous studies [Lambert 2002; Zyl and Cassa 2014].

### 2.3 Evaluation metrics

To provide insight into different aspects of pipe break impacts on the hydraulics and water quality aspects of WDSs, we propose six quantitative metrics, with each emphasizing a particular aspect of impact, as summarized in Table 1. The hydraulic impacts are represented by the metrics of break outflow volume, water shortage and affected nodes, whereas water quality impacts are reflected by the metrics of affected pipes, affected flow directions and affected velocities.

In addition to the starting time of the pipe break ( $t$ ), the values of both the break outflow volume and the water shortage also depend on the breaking duration  $T$ , i.e. from the time of break occurrence to the time the break is isolated. Therefore, these two metrics are defined as a function of breaking start time  $t$  and break duration  $T$ . The values of the other four metrics are calculated using outputs from the hydraulic simulation model and are therefore affected by the temporal variation of hydraulic conditions within the WDS (e.g. demand patterns and pumping switches). Therefore, these four metrics are defined as a function of break start time  $t$ . Details of each metric are presented in the subsequent paragraphs.

### **Break outflow volume**

The metric  $BO_j(T)$  is used to estimate the break outflow volume when a break occurs at time  $T_0$  and ends (e.g. is isolated) at time  $T_B$  (with  $T=T_B-T_0$ ) at pipe  $j$  and is

calculated for each pipe within the WDS. This metric can be mathematically expressed as:

$$BO_j(t,T) = \int_{t=T_0}^{t=T_b} d_j(t), \quad j = 1, \dots, N \quad (2)$$

where  $d_j(t)$  is the outflow rate of a break occurring at pipe  $j=1, 2, \dots, N$  at time  $t$ , which is determined by the pressure-driven model (Eq.1 in Section 2.1). This metric is meaningful, as it can estimate water losses associated with a pipe break, thus assessing its hydraulic impact in an easy-to-understand manner. From a practical perspective, this enables more emergency response resources to be allocated to pipes with larger values of  $BO_j(T)$ . Furthermore, pipes with larger values of  $BO_j(T)$  are also likely to warrant more frequent inspection (e.g. with crews or sensors) and maintenance. It should be noted that this metric considers the importance of the users based on their associated demands. However, this is not always the case. For example, the demands / break outflow volumes of some important users such as schools and hospitals might be low [He et al., 2018]. Consequently, the demand nodes corresponding to such users must be considered separately (i.e., they should be given particular importance).

### **Water shortage**

The metric of water shortage,  $WS_j(T)$ , measures the amount of water deficit over the breaking period  $T$  (from  $T_0$  to  $T_B$ ) at pipe  $j$ . This metric can be estimated as:

$$WS_j(t, T) = \int_{t=T_0}^{t=T_B} \left\{ \sum_{i=1}^M G_i^j(t) [Q_i^{req}(t) - Q_i^j(t)] \right\} \quad (3)$$

where  $G_i(t)$  is an indicator function representing whether the break of pipe  $j$  leads to a water shortage at node  $i$  at time step  $t$ . This indicator function is mathematically defined as:

$$G_i^j(t) = \begin{cases} 1, & \text{if } H_i^j(t) < H_i^{req}(t) \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where  $Q_i^{req}(t)$  and  $H_i^{req}(t)$  are the required nodal demand and pressure (as defined for Eq. 1 in Section 2.1), respectively, at node  $i=1, 2, \dots, M$  (total number of nodes) at time  $t$ .  $Q_i^j(t)$  and  $H_i^j(t)$  are the actual demand supplied and pressure provided at node  $i$  when a break occurs at pipe  $j$  at time  $t$ , which are determined by the pressure-driven model (Eq. 1). A value of  $WS_j(T)$  is estimated for each pipe within the WDS.

A larger value of  $WS_j(T)$  suggests greater water shortage of the WDS under the circumstances of pipe breaks and hence represents larger impacts. This metric is an important indicator of the impacts of pipe breaks on the overall service level of a

WDS. The insight obtained from this metric can offer guidance for the preparation of emergency response resources for future pipe breaks, for example, determining the amount of emergency water supply needed in case of a break.

### **Affected nodes**

The metrics of break outflow volume and water shortage represent the total water losses and demand shortfall resulting from pipe breaks within the WDS, but they cannot indicate the spatial distribution of the users that experience service disruption or reduced service quality (i.e.  $Q_i^j(t) < Q_i^{rep}(t)$ ). Therefore, it is meaningful to identify all affected nodes,  $\Omega_j^{AN}(t)$ , for each pipe breaking event  $j$  at time  $t$ . This metric can be expressed as:

$$\Omega_j^{AN}(t) = \{i \mid Q_i^j(t) < Q_i^{rep}(t), i = 1, 2, \dots, M\} \quad (5)$$

The metric of affected nodes indicates the spatial distribution of the users that are experiencing service disruption or reduced service quality during pipe breaks. For the example network in Fig. 2, if the required pressure for each node is 15m, a break at pipe [5] causes the pressures at Nodes 2, 3 and 4 to drop below 15 m (i.e. unsatisfied demands), resulting in  $\Omega_5^{AN}(t) = \{2, 3, 4\}$  and  $\|\Omega_5^{AN}(t)\| = 3$  (the number of values in the set). The information obtained from this metric is particularly useful for

identifying the users influenced by pipe breaks, and hence a prompt response (e.g. prior notice of water shortages) can be provided before complaints are received from customers.

### **Affected pipes**

In addition to affected nodes, it is also important to identify pipes where supply pressures are affected by breaking events. This is because a sudden pipe break is highly likely to induce a transient within the WDS, and hence may cause significant pressure drops or even negative pressures for some pipes [Walski and Lutes, 1994]. Such negative pressures can result in water quality issues, as they may suck contaminated water from the surrounding environment towards the areas in the system where the leaks are occurring [Buchberger and Nadimpalli, 2004]. Therefore, it is meaningful to identify pipes with affected pressures, as this can inform effective emergency management plans in relation to potential water quality issues after pipe breaks, such as pipe flushing and isolation of valve operation.

The metric of affected pipes,  $\Omega_j^{AP}(t)$ , for a break occurring at pipe  $j$  at time  $t$ , can be described as:

$$\Omega_j^{AP}(t) = \{k \mid (k_u, k_D) \in \Omega_j^{AN}(t), k = 1, 2, \dots, N\} \quad (6)$$

where  $(k_u, k_D)$  are the upstream and downstream nodes of pipe  $k=1, 2, \dots, N$ . As indicated in this equation,  $\Omega_j^{AP}(t)$  actually consists of pipes with connected nodes at both sides that are all affected by the break at pipe  $j$  (see Eq. 5). For the example in Fig. 2,  $\Omega_j^{AP}(t) = \{[4], [5]\}$  and  $\|\Omega_j^{AP}(t)\| = 2$ . For practical purposes, the total length of the affected pipes can also be calculated to provide an indication of the overall impacts of pipe breaks on the water quality security of a WDS.

### **Affected flow directions**

It has been well demonstrated that a reversal of water flow direction caused by pipe breaks is highly likely to induce water quality issues (e.g. yellow water), as the biofilms located inside the pipe walls can be dislodged easily under such circumstances [LeChevallier, 1990; Kowalski et al., 2010; Abraham et al., 2018]. In recognition of this, we propose a metric to identify pipes for which flow directions are reversed after the breaking event. It is noted that only pipes with fixed flow directions are considered for this metric (pipes with flow directions that change frequently due to diurnal demands or boundary condition variation are not included). The set of these pipes,  $\Omega_j^{AFD}(t)$ , for breaking event  $j$  occurring at time  $t$ , can be described as:

$$\Omega_j^{AFD}(t) = \{k \mid \text{sgn}(F_k^B(j, t)) \times \text{sgn}(F_k^A(j, t)) < 0, k = 1, 2, \dots, N\} \quad (7)$$

where  $F_k^B(j,t)$  and  $F_k^A(j,t)$  are, respectively, the flow vector of pipe  $k$  before and after the breaking event occurring at pipe  $j$  at time  $t$ .  $\text{sgn}()$  returns the sign of the flow vector, with  $\text{sgn}()=1$  if the flow is positive and  $\text{sgn}()=-1$  if the flow is negative.

This metric explicitly indicates the spatial distribution of the pipes with reversed flow direction caused by the breaking event. For the WDS in Fig. 2,  $\Omega_j^{AFD}(t) = \{[4]\}$  as the flow direction of pipe [4] reverses after pipe [5] breaks. In addition, the total length of all pipes in  $\Omega_j^{AFD}(t)$  can be computed to represent the overall impact of pipe breaks on the water quality security of a WDS, with larger values implying higher water quality risks.

### **Affected velocities**

In addition to the reversed flow directions, a significant increase in pipe flow velocity induced by pipe breaks is also likely to cause water quality issues within a WDS [Lehtola *et al.*, 2006]. This is because a large increase in flow velocity can re-suspend particulate matter that has settled during low velocity periods (e.g. due to pipe wall corrosion) and can also significantly increase the scour strength within pipes, potentially dislodging biofilms that have formed on pipe walls [Donlan and Pipes, 1988; Colombo and Karney, 2002]. Therefore, it is important to consider the affected velocities,  $\Omega_j^{AV}(t)$ , to evaluate the impacts of pipe breaks on the water quality

security of the WDS [Shamsaei et al., 2013]. This metric aims to identify pipes with large increases in velocity when a break occurs at pipe  $j$  at time  $t$ , which can be expressed as:

$$\Omega_j^{AV}(t) = \{k \mid V_k^A(j,t) \geq \lambda(MV_k^B), k = 1, 2, \dots, N\} \quad (8)$$

where  $V_k^A(j,t)$  is the resultant velocity at pipe  $k$  after the breaking event  $j$  at time  $t$ .  $MV_k^B$  is the maximum velocity of pipe  $k$  over different demand patterns before the breaking event.  $\lambda > 1$  is a user-specified multiplier, which sets a threshold to identify pipes with potential water quality issues. We used  $\lambda = 1.2$  in the present study, which indicates that pipe  $k$  is considered to have water quality issues if the resultant velocity after the breaking event  $j$  is more than 20% of its maximum velocity i.e.  $k \in \Omega_j^{AV}(t)$ . It is noted that the choice of  $\lambda$  does not affect the application of this metric, but will affect the elements in  $\Omega_j^{AV}(t)$ .

As is the case for the metric of affected flow directions (Eq. 7), the total length of the pipes in  $\Omega_j^{AV}(t)$  can be computed to indicate the overall consequences of pipe breaks on the water quality security of a WDS. For the example WDS in Fig. 2,  $\Omega_j^{AV}(t) = \{[1],[2],[3],[4]\}$  when  $\lambda = 1.2$  is used, indicating that the velocities of all of these pipes significantly increase as a result of the breaking event at pipe [5].

It should be noted that while pipes may be designed to allow for high velocities (say 3m/s) under emergency conditions (e.g., fires), they deliver water at much lower velocities during the majority of system operation. Consequently, particulate matter can settle and biofilms can become stable, which are then re-suspended / dislodged when a sudden increase in velocity beyond the range of normal operating conditions occurs, resulting in water quality issues. Consequently, the proposed metric can be used to assess the potential water quality impacts of a range of high-flow events, such as serious pipe breaks and fire flows.

However, it should also be noted that the degree to which particulate matter can settle and biofilms can form depends on the way WDSs are operated. For example, in many developed countries, flow velocities are maintained above certain minimum levels (e.g. >0.3 m/s), and regular flushing operations are conducted, to prevent biofilm formation / build-up and the settling of particulate matter. In contrast, this is often not the case in developing countries as systems are designed to cater to rapid population growth, resulting in much lower flow velocities until these conditions are met [*Wang et al.*, 2012].

#### ***2.4 Result analysis methods***

As shown in Fig. 1, a statistical analysis of all metric values is conducted in order to provide an overall evaluation of the impacts of pipe breaks on the hydraulics and water quality security of a WDS, across all breaking scenarios. Furthermore, the spatial distribution of each metric value is analyzed, in order to offer a straightforward visualization on the spatial extent of the impacts of pipe breaking events.

Pipe ranking based on associated breaking consequences is also important, as it can provide guidance for developing effective strategies for pipe management and maintenance, emergency planning and event recovery. This is because the available resources (finance or crew) to manage or deal with pipe breaks are often limited, and hence a larger proportion of these limited resources should be assigned to pipes for which the impacts are more severe. Therefore, the proposed evaluation framework also includes a pipe ranking analysis based on the values of each of the six metrics at all pipes. More specifically, metrics of break outflow volume and water shortage are numeric values and hence can be directly used for pipe ranking analysis. The number of the values in the set of the metric of affected nodes can also be directly included in the ranking analysis. For the other three water quality metrics (i.e. affected pipes, affected flow directions and affected velocities), the total lengths of pipes within their corresponding metric sets are used for the ranking. In addition to applying the ranking

analysis to individual metrics, we also rank the pipes by considering all six metrics simultaneously.

To better visualize the ranking results, we categorize the values of each metric at different pipes into five groups from R1 to R5, which represent increasing impacts on the performance of the WDS. In other words, for a particular metric, pipes with the lowest 20% percentile values are grouped into R1, while R5 includes pipes with the highest 20% percentile values. Similarly, R2, R3 and R4 correspond to pipes with metric values falling into (60%, 80%], (40%, 60%], (20%, 40%] percentile of values of the metric, respectively.

### **3. Computational Experiments**

#### ***3.1 Case studies***

The proposed evaluation framework was applied to two types of WDSs, where the first type corresponds to gravity-fed systems and the other type corresponds to the systems with pumps and tanks. For the first type, two real-world WDS case studies in China were considered: the Jiayou network (JYN) and the Zhuohao network (ZHN). These networks represent two typical WDS topologies: the JYN mainly has a highly looped structure, while the ZHN consists of many branched structures. The JYN includes two fixed-head reservoirs, 349 demand nodes and 509 pipes (Fig. 3(a)). The ZHN consists of one reservoir with variable heads, 3,439 demand nodes, 3,512 pipes and 16 valves

(Fig. 3(b)). We considered two operational scenarios for both networks, representing: (1) a peak hour demand (PHD) scenario, for the hour with the largest demands in a day, and (2) a minimum hour demand (MHD) scenario, for the hour with the lowest demands in a day. Both scenarios are commonly used to analyze pipe breaking and leaking events [Tabesh *et al.*, 2004; Liu *et al.*, 2016].

The second type of WDS considered was a complex system with two reservoirs, two pump stations, three tanks, 92 nodes and 117 pipes (Fig. 3(c)). This WDS is an example used in the EPANET2.0 package [Rossman, 2000]. The two pump stations and the three tanks are jointly used to supply water during the peak hour demand (PHD) period, and during the minimum hour demand (MHD) scenario, the pumps not only assist with meeting end-user demands, but also with filling the three tanks. As is the case for the two gravity-fed WDSs, two demand scenarios are considered including PHD and MHD periods. It should be noted that while the proposed method is applied to serious breaking events in this paper, it could also be applied to cases where small leaks/pipe breaks are of interest. However, in such cases, the outflow simulation method should be slightly changed [Ang and Jowitt, 2006; Wu *et al.*, 2009; Babu and Mohan, 2011; Giustolisi and Walski, 2012], as the method adopted in this paper focuses on serious pipe breaks.

### **3.2 Parameterization**

The hydraulic models used for the case studies have already been calibrated by engineers from the relevant water utilities. For all case studies, the required pressure used to deliver the specified demands ( $H_j^{req}$ ) for each demand node is 18 m, and the minimum pressure allowed ( $H_i^{min}$ ) below which no water can be supplied to the node is 0 m. To estimate the metrics of break outflow volume ( $BO_j(T)$ ) and water shortage ( $WS_j(T)$ ),  $T=1$  hour is used based on the assumption that a break can be typically isolated or repaired within 1 hour since its occurrence [Qi *et al.*, 2018].

The method of Qi *et al.* [2018] was used for modeling the hydraulics of the pipe breaks (see Section 2.1) for ease of implementation. As was the case for the simple hypothetical example in Section 2.1, an initial value of 10,000 L/s was applied to the breaking pipes to trigger the pressure driven model, with the actual outflow values determined using the iterative procedure outlined in Section 2.1. Comparisons of the resulting values with those obtained using the method of adding a dummy reservoir and pipe (see Section 2.1) for a range of the pipe break scenarios considered indicated that the value of 10,000 L/s was sufficient, as the hydraulic outputs resulting from the pipe breaks obtained using both methods were identical for all scenarios tested.

The proposed evaluation framework was coded in C++ on the freely available platform MinGW Developer Studio 2.05. The hydraulic simulations were carried out

using a steady state model, the EPANET 2.0-EMITTER solver, which is a pressure-driven simulation package based on EPANET2.0, following a previous study on the same WDSs [Qi *et al.*, 2018].

## **4. Results and Discussions**

### ***4.1 Results for the gravity-fed WDSs***

#### ***4.1.1 Statistical properties of results***

To evaluate the overall impacts of pipe breaks on the hydraulics and water quality security of the two gravity-fed WDSs considered, we present and discuss the statistical properties of the values of the proposed metrics in this section. Fig. 4 presents the probability density function of each metric for each of the two case studies. As shown in this figure, the mean values of the one-hour break for the JYN and ZHN are approximately 2,000 and 300 m<sup>3</sup>, respectively, regardless of the demand scenario. Water shortages caused by pipe breaks are highly likely to be lower than 100 m<sup>3</sup> for the two WDSs, except for the JYN during the PHD period, which has relatively higher values of water shortages. Such relatively large water shortages are associated with the relatively higher ratio of affected nodes caused by breaking events within the JYN under the PHD scenario, as illustrated in Fig. 4(c).

Regarding water quality impacts, it is observed that the lengths of affected pipes and pipes with affected flow directions caused by pipe breaks are more likely to be less

than 30 km, with substantial variation with case studies and demand patterns (Figs. 4(d) and (e)). For example, the majority of the breaking events for the ZHN during the PHD period would result in approximately 3 km length of pipes with reversed flow directions, but this value can be up to 10 km for the JYN case study.

Interestingly, the lengths of pipes with significantly increased velocities are generally larger than those of pipes with reversed flows (Figs. 4 (e) and (f), respectively). This is evidenced by the fact that the mean of the length of pipes affected by velocities is approximately 40 km, which is substantially greater than that of the pipes with reversed flow directions (approximately 16 km). This is as expected, as a breaking event is highly likely to induce large outflows, as shown in Fig. 4(a), and hence flow velocities at many pipes are significantly increased to deliver such large outflows. This indicates that water quality deterioration after a breaking event is more likely to be caused by pipe-wall scouring due to significant velocity increases.

One common pattern across all six metrics in Fig. 4 is that the impacts of pipe breaks are generally larger during the PHD period compared with the MHD period. One exception is that the MHD period is more likely to induce more serious consequences when measured by the metric of affected flow directions (Fig. 4(e)). This is because in the gravity-fed system without tanks, water flows within the MHD scenario are

overall significantly smaller than those within the PHD scenario, and hence they are more likely to be reversed due to pipe breaks.

In comparing the distribution of metric values between the two WDSs, the ZHN exhibits a better overall performance, as for this network, pipe breaks generally result in lower hydraulic and water quality impacts (Fig. 4). This is due to the fact that (i) the nodal demands and pipe diameters within the JYN are generally larger than those within the ZHN, as the former is a transmission network (larger diameters and nodal demands), while the latter is a distribution network; and (ii) the network topology of the JYN is significantly more complex than that of the ZHN, with a large number of loops. Therefore, we can deduce that the consequences of pipe breaks tend to be much larger for WDSs with relatively larger pipe diameters and nodal demands, as well as greater complexity in network topology. This knowledge can provide guidance for the design of WDSs in terms of both network scale and topology if pipe breaking impacts are to be taken into account.

#### ***4.1.2 Spatial properties of results***

In this section, the spatial properties of the evaluation metrics are discussed to gain insight into the spatial extent of impacts caused by breaking events. Note that we have analyzed the spatial distributions of the metrics for each breaking event occurring at

each pipe within each of the WDSs and have observed high similarities across different pipe breaking scenarios. Therefore, in this section we only focus on results that are typical and representative.

Fig. 5 shows the results for the affected nodes and pipes induced by two typical breaking events at two pipes with a 300 mm diameter within the JYN, during both PHD and MHD scenarios. Two events with identical pipe diameters were selected to investigate how location can affect the consequence of pipe breaks. As clearly illustrated in Fig. 5, even though the diameters of the two breaking pipes are identical, their overall severity of impact, as represented by the number of affected nodes and pipes and the spatial extent of these impacts, are noticeably different, especially during the MHD period (Figs. 5(a) and (b)). In addition, the spatial extent of impacts during the PHD period is substantially larger compared with that during the MHD period for the gravity-fed WDS, which is consistent with the statistical results in Fig. 4. For example, when comparing impacts of the same breaking pipe in Figs. 5(b) and (d), only four demand nodes and three pipes are affected during the MHD period; however, 86 nodes and 83 pipes can be affected if this event occurs during the PHD period.

Figs. 6 and 7 present the spatial distributions of the metrics of affected flow directions and velocities for the two breaking events during the PHD and MHD periods, respectively. Similar to the observations from Fig. 5, these two breaking events exhibit large differences in the spatial distributions of impacts when measured by affected flow directions and velocities, even though their diameters are identical (300 mm).

Interestingly, it is observed that the nodes and pipes that are affected by pipe breaks are not necessarily distributed in the surrounding regions of these broken pipes, which is especially the case for the water quality metrics (Figs. 6 and 7). For instance, as illustrated in Fig. 6(a) and Fig. 7(a), some nodes and pipes located in the surrounding region of the broken pipe (blue line) are not actually significantly affected by the break in terms of hydraulics and water quality, but some nodes and pipes that are far away from this broken pipe are appreciably influenced by this event. Another interesting observation is that the spatial properties of the affected nodes and pipes identified to have hydraulic impacts (Fig. 5) are significantly different from those identified to have water quality impacts (Figs. 6 and 7). Furthermore, even among the water quality impacts, the spatial distributions of the affected pipes can appreciably vary with different water quality metrics.

It is also observed that the number of pipes with affected velocities is significantly greater than that with affected flow directions for both the PHD and MHD scenarios, as shown in Figs. 6 and 7, which is consistent with the statistical results in Fig. 4. We also find that while pipe breaks for the MHD scenario may have limited hydraulic impacts (Figs. 5c and d), their influences on water quality are substantial, as illustrated in Fig. 7. This is because the demands required by users are appreciably reduced during the MHD period (which is often around midnight) compared with the PHD period in the gravity-fed system without tanks, and hence the number of affected nodes and pipes that display hydraulic impacts is lower during such time periods. This implies that water quality security should be of primary concern for breaks that occur during minimum hour demand periods for gravity-fed WDSs, rather than hydraulic impacts.

Fig. 8 outlines the spatial distributions of the four metrics for a breaking event applied to a 600mm diameter pipe in the ZHN during the PHD period. Similar to previous findings from the JYN (Figures 5 to 7), this breaking event significantly affects the hydraulics and water quality for not only nodes and pipes in the surrounding region of the broken pipe, but also nodes and pipes that are far away.

As observed in this section, within a WDS, the spatial distributions of affected nodes and pipes caused by different breaking events can vary substantially, even for breaking events occurring at pipes with the same diameter. This is due to the fact that all pipes and nodes within a WDS are highly interdependent in both hydraulics and water quality, so that the impacts of breaking events are largely dependent on their spatial locations. Furthermore, for breaks occurring at the same pipe, the spatial distributions of affected nodes and pipes are also highly variable with time of occurrence and specific evaluation metrics. This implies that the identification of the spatial extent of the nodes and pipes affected by pipe breaks is highly complex. These challenges highlight the importance and necessity of developing a framework to comprehensively evaluate the impacts associated with each breaking event on the hydraulics and water quality security of WDSs, as is done in this paper.

#### ***4.1.3 Ranking results***

In this section, we present the results of the pipe rankings based on their breaking impacts. It is worth noting that although we have shown in Sections 4.1.1 and 4.1.2 that pipes breaks during the PHD period generally have greater overall impact on the performance of gravity-fed WDSs, we found very similar pipe ranking results during the PHD and MHD periods. Therefore, only the ranking results during the PHD periods are presented for the JYN and ZHN case studies in Fig. 9. As shown in this

figure, pipes on the periphery of the WDS generally have relatively low ranking levels (i.e. low impacts), and vice versa. This is expected, as pipes with relatively large diameters generally deliver a large amount of water, and hence their breaks are more likely to have more severe consequences. However, this is not always the case, as many pipes with smaller diameters can result in larger impacts (high ranking levels) than pipes with larger diameters. This can be seen in Fig. 10, which plots the distribution of the values of two metrics, break outflow volume and affected flow directions, against pipe diameters, for the JYN and ZHN case studies.

As shown in Fig. 10, while breaks in pipes with larger diameters generally have more severe consequences, some pipes with smaller diameters can result in larger impacts in terms of break outflow volume and affected flow directions. For example, as illustrated in Fig. 10(b), while the mean break outflow volume for the 150mm pipes is larger than that of the 100mm pipes, some 100mm pipes can result in larger break outflow volumes than the 150mm pipes. In addition, Fig. 10 also shows that pipes with the identical diameter can also have significant variations in their breaking impacts, which is consistent with the findings in Fig. 5. Consistent patterns are also observed for the other four evaluation metrics, which are not presented here.

In addition to the above observations that pipe rankings can vary with diameters, the ranking results can also significantly change as a function of evaluation metrics. The radar graph in Fig. 11 shows the rankings of a 400mm pipe within the JYN based on six evaluation metrics, for both the peak and minimum hour demand periods. The specific ranking of this pipe can vary significantly when different metrics are considered. For example, during the peak hour demand period, this pipe is ranked 22 based on the metric of affected velocities (M6), which drops to 167 when using the metric of affected nodes (M3). This, again, highlights the importance of evaluating impacts of pipe breaks comprehensively with multiple metrics, as they may suggest quite different ranks when different aspects of breaking impacts are considered.

To account for the ranking variability across different metrics, we then rank the pipes by assigning equal weight to each of the six metrics considered, which results in a final ranking level map, as shown in Fig. 12. These ranking levels differ from any of those based on a single metric in Fig. 9. Note that to produce the results in Fig. 12, we assumed that each metric is equally important. However, in practice, the weights of the metrics are adjustable to reflect their relative importance in a particular decision context, which would result in different overall rankings to those presented in Fig. 12. For example, if the amounts of water shortage are considered to be more important

than other metrics during breaking events, this metric can be assigned a relatively high weight and the ranking map can be updated accordingly.

#### ***4.2 Results for the WDS with pumps and tanks***

Fig. 13 shows the statistical results of the break outflow volume and ratio of affected nodes for the WDS with pumps and tanks. It is found that the density distributions of these two metrics are overall similar to those from the two gravity-fed systems (Fig. 4). However, some breaking events during the minimum hour demand (MHD) can have similar or even larger impacts than those occur during the peak hour demand (PHD) period in terms of the metrics of break outflow volume and ratio of affected nodes, as illustrated in Fig. 13(a,b), which significantly differs from the observations for the gravity-fed systems. This is because these pipes deliver large flows to fill the tanks during the MHD period and hence their breaks can induce significant impacts.

For an identical breaking event (300 mm, highlighted in Fig. 13 (c,d)), the affected nodes and pipes during the MHD period are overall similar to those during the MHD scenario. The break outflow volume for this event during the MHD period is  $46.54 \text{ m}^3$ , which is higher than that during the PHD scenario ( $36.55 \text{ m}^3$ ). This is because this pipe is used to deliver user demands during the PHD period, and is employed to fill the tanks with large flows during the MHD period, and hence a pipe breaking event during this low demand period could also induce large hydraulic impacts.

The ranks based on the metric of the break outflow volume for the WDS with pumps and tanks are given in Fig. 14 (a,b). It is observed that the pipes that are used to fill tanks during the MHD period have overall relatively high ranks during both the PHD and MHD scenarios, such as pipe 2 (P2) and pipe 3 (P3) as illustrated in Fig. 14 (a,b), even though these pipes might be located far from the reservoirs (e.g., P3). It is noted that while pipe 1 (P1) connects to a pump and a reservoir, this pipe delivers small flows during the PHD period and is closed during the MHD period, leading to low breaking impacts.

Interestingly, when the six metrics are jointly considered, the relative ranks of the pipes that are used to fill tanks during the MHD period become lower compared to those when only the break outflow volume is considered, such as P3 in Fig. 14(c,d). This is because that the impacts of pipe breaks during the MHD period can be low when assessed by other metrics, such as the metric of water shortage. The statistical results, spatial distribution properties and ranking results of the other metrics (water quality metrics) are overall similar to those of the gravity-fed WDSs in section 4.1, and hence are not presented.

## **5. Conclusions**

While the probability of pipe breaks is relatively low, especially compared with that of small leaks, such breaks are likely to result in serious threats to water distribution

systems (WDSs) in terms of both hydraulic and water quality security. This, therefore, provides the motivation for developing strategies to prevent the occurrence of pipe breaks, as well as the preparation of emergency response resources for dealing with pipe breaks to minimize their associated impact. To ensure the effectiveness of these strategies, it is critical to understand the underlying properties of impacts caused by pipe breaks on the hydraulic and water quality security of WDSs.

The present study attempts to address the above need by introducing a comprehensive framework for evaluating the hydraulic and water quality impact of pipe breaks on WDSs with the aid of six proposed metrics. These metrics focus on identifying different aspects of the impact of each pipe break event within a WDS, namely: (i) break outflow volume; (ii) water shortage; (iii) nodes with significant pressure drops; (iv) pipes with significantly decreased pressures; (v) pipes with reversed flow directions; and (vi) pipes with significant increases in flow velocity.

Two types of WDS case studies with varying attributes, scales and topologies are used to demonstrate the utility of the proposed evaluation framework. The proposed metrics are calculated with the aid of a steady-state pressure-driven model, which can represent a realistic relationship between outflows and pressures at the breaking pipe.

We then investigated the statistical behaviors, spatial properties and pipe rankings of metric values. The key findings from this study are outlined below.

- (i) The degree of impact caused by a breaking event is not only dependent on the diameter of the breaking pipe, but is also heavily influenced by the location of the breaking pipe within the WDS. This implies that two pipes with identical diameters may result in significantly different levels of consequences when they break.
- (ii) The severity of a pipe breaking event can vary as a function of the time of occurrence of the event. Breaking events during peak hour demand (PHD) periods have relatively higher consequences compared with those during minimum hour demand (MHD) periods for gravity-fed WDSs, especially with regard to the hydraulic aspects of WDSs. For WDSs with pumps and tanks, pipes that are used to fill the tanks have overall large hydraulic impacts induced by their breaks during the MHD period, which could result in even more serious hydraulic consequences (break outflow volume or affected nodes) than those experienced during the PHD period.
- (iii) The nodes and pipes that are affected by breaking events in terms of hydraulics and water quality are not necessarily located in the surrounding regions of the broken pipes and can sometimes be a significant distance away.

- (iv) The spatial distribution of affected pipes can be significantly different when different evaluation metrics are considered. This difference is especially prominent when comparing the spatial distributions of the metrics based on hydraulics (e.g. affected pipes in terms of pressures) with those based on water quality (e.g. affected pipes with reversed flow directions). This highlights the merit of the proposed framework in terms of its consideration of the impact of pipe breaks on a range of aspects of the performance of WDSs.
- (v) The pipe rankings in terms of breaking impacts vary with the specific evaluation metric considered. This, again, highlights that pipe ranking should account for the impacts from multiple aspects (e.g. hydraulics and water quality) in order to obtain a comprehensive understanding on the relative impacts of breaking events at different pipes within a WDS.

The aforementioned findings can provide valuable recommendations for water engineers and practitioners from water utilities, in relation to the development of strategies for pipe management and maintenance, as well as the planning for emergency response and event recovery. Furthermore, the comprehensive evaluation framework proposed in this study will also benefit relevant government departments, as it can be a particularly useful tool for evaluating the impacts of pipes breaks when designing effective management schemes for natural disasters (e.g. earthquakes).

It is noted that the break probabilities of pipes (pipe break history) and pipe material are not yet considered in the proposed framework, which can also be important to enable pipe management (e.g., prioritizing interventions) for water utilities, in addition to the improved understanding of the impact of pipe breaks as demonstrated in the present study. However, it should be straightforward to add such metrics to the proposed framework without significant changes to its workflow. For example, if information on the break probability of pipes is available, this can be directly added to the current framework with a given weight. Consequently, the evaluation framework can not only show the impacts of pipe breaks, but also indicate the breaking probability of each pipe, which is one important future direction along this research line. In addition, it should be noted that negative pressures may be observed if transient dynamics caused by pipe breaks are considered [Fernandes and Karney, 2004; Colombo *et al.*, 2009]. However, this goes beyond the scope of the current study, as it mainly focuses on the hydraulic and water quality impacts induced by pipe breaks under steady-state conditions, but future studies should incorporate metrics that account for the transient impacts caused by breaking events into the proposed evaluation framework.

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**Table 1. Summary of the six quantitative metrics proposed for evaluating the impact of pipe breaks on WDSs**

<b>Metric</b>	<b>Equation</b>	<b>Purpose of metric</b>	<b>Interpretation of metric</b>
Break outflow volume, $BO_j(t,T)$	Eq. (2)	To estimate outflows of a breaking event.	$(0, +\infty ]$ , with a higher value indicating larger water losses.
Water shortage, $WS_j(t,T)$	Eq. (3)	To calculate water shortages induced by a pipe break.	$(0, +\infty ]$ , with a higher value representing greater shortages.
Affected nodes, $\Omega_j^{AN}(t)$	Eq. (5)	To identify nodes at which water supply is affected by a breaking event in terms of water supply.	This is a set with a range between $(0, M]$ , where $M$ is the total number of nodes in the network. A larger range indicates a larger number of affected nodes.
Affected pipes, $\Omega_j^{AP}(t)$	Eq. (6)	To identify pipes in which pressures are affected by a breaking event.	This is a set, with a range between $(0, N]$ , where $N$ is the total number of pipes in the WDS. A larger range represents a larger number of affected pipes.
Affected flow directions, $\Omega_j^{AFD}(t)$	Eq. (7)	To identify pipes with reversed flow directions after a breaking event.	This is a set, with a range between $(0, N]$ . A larger range represents a larger number of pipes with water quality issues.
Affected velocities, $\Omega_j^{AV}(t)$	Eq. (8)	To identify pipes with significantly increased velocities due to a breaking event.	This is a set with a range between $(0, N]$ . A larger range represents a larger number of pipes with water quality issues.

## **Figure captions**

**Figure 1. Outline of the proposed framework for evaluating the impacts of pipe breaks within WDSs**

**Figure 2. Procedure used to simulate the hydraulic effects of a pipe break within a WDS: (a) before the pipe break, (b) simulation of the hydraulic effects of a break at pipe [5] by adding a series of artificial hydraulic components, (c) trigger a pipe break at pipe [5], and (d) simulation of the hydraulic effects of a break at pipe [5], where  $P$ ,  $D$  and  $V$  represent pressure, demand and velocity, respectively.**

**Figure 3. Network layouts of the (a) the JYN, (b) the ZHN and (c) a WDS with pumps and tanks**

**Figure 4. Distribution of the six metric values for the two WDSs**

**Figure 5. Spatial distributions of the affected nodes and pipes under the PHD and MHD scenarios (top and bottom rows, respectively). Left and right columns show breaking events at two different pipes within the JYN, both with 300 mm diameter.**

**Figure 6. Spatial distributions of the affected flow directions and velocities (red lines) during the PHD period. Left and right columns show breaking events at two different pipes within the JYN, both with 300 mm diameter.**

**Figure 7. Spatial distributions of the affected flow directions and velocities (red lines) during the MHD period. Left and right columns show breaking events at two different pipes within the JYN, both with 300 mm diameter.**

**Figure 8. Spatial distributions of the four metrics (red node and lines) for a breaking pipe with 600 mm (blue line) of the ZHN during the PHD period.**

**Figure 9. Pipe ranking results for the two case studies during the PHD periods, with rank level 1 (R1) and rank level 5 (R5) indicating the pipes with lowest and largest impacts, respectively.**

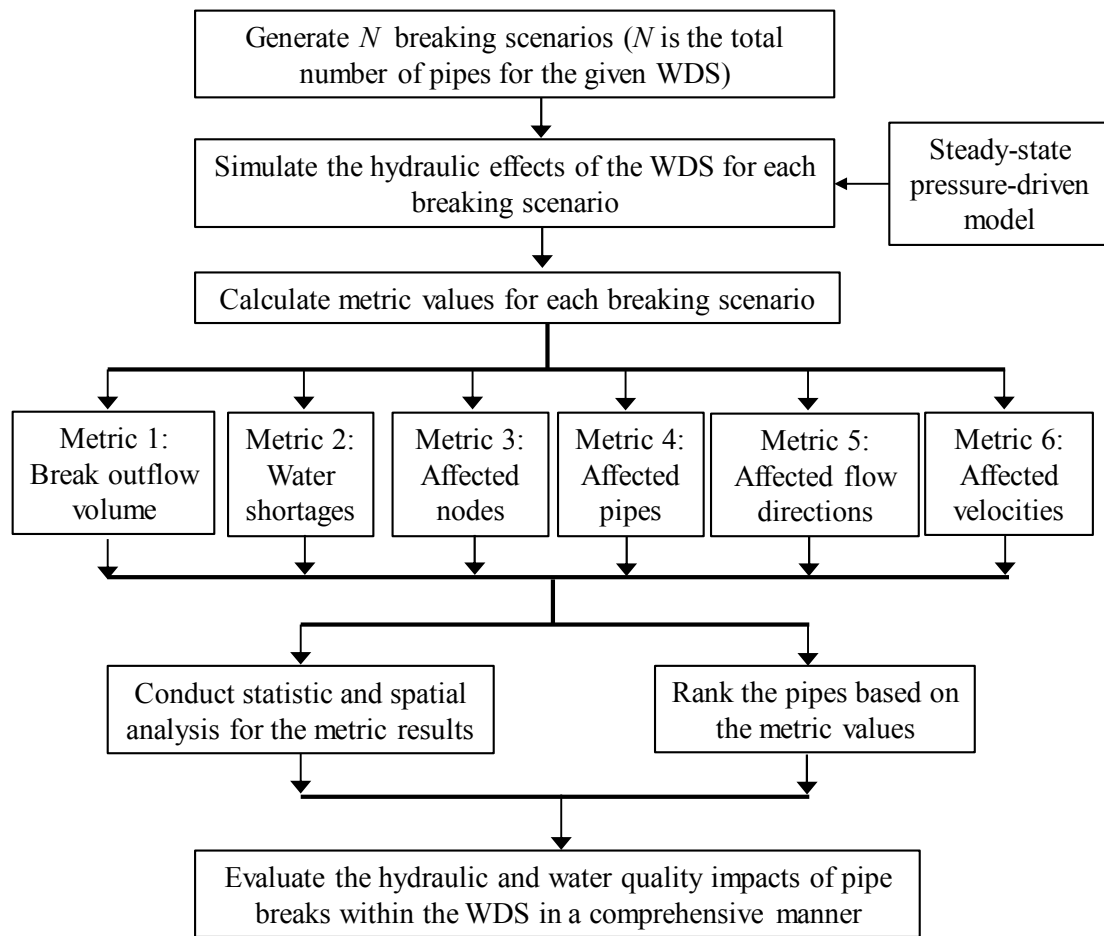
**Figure. 10. Values of two evaluation metrics, break outflow volume and affected flow directions, versus the corresponding pipe diameters, during the PHD periods for the JYN and ZHN case studies**

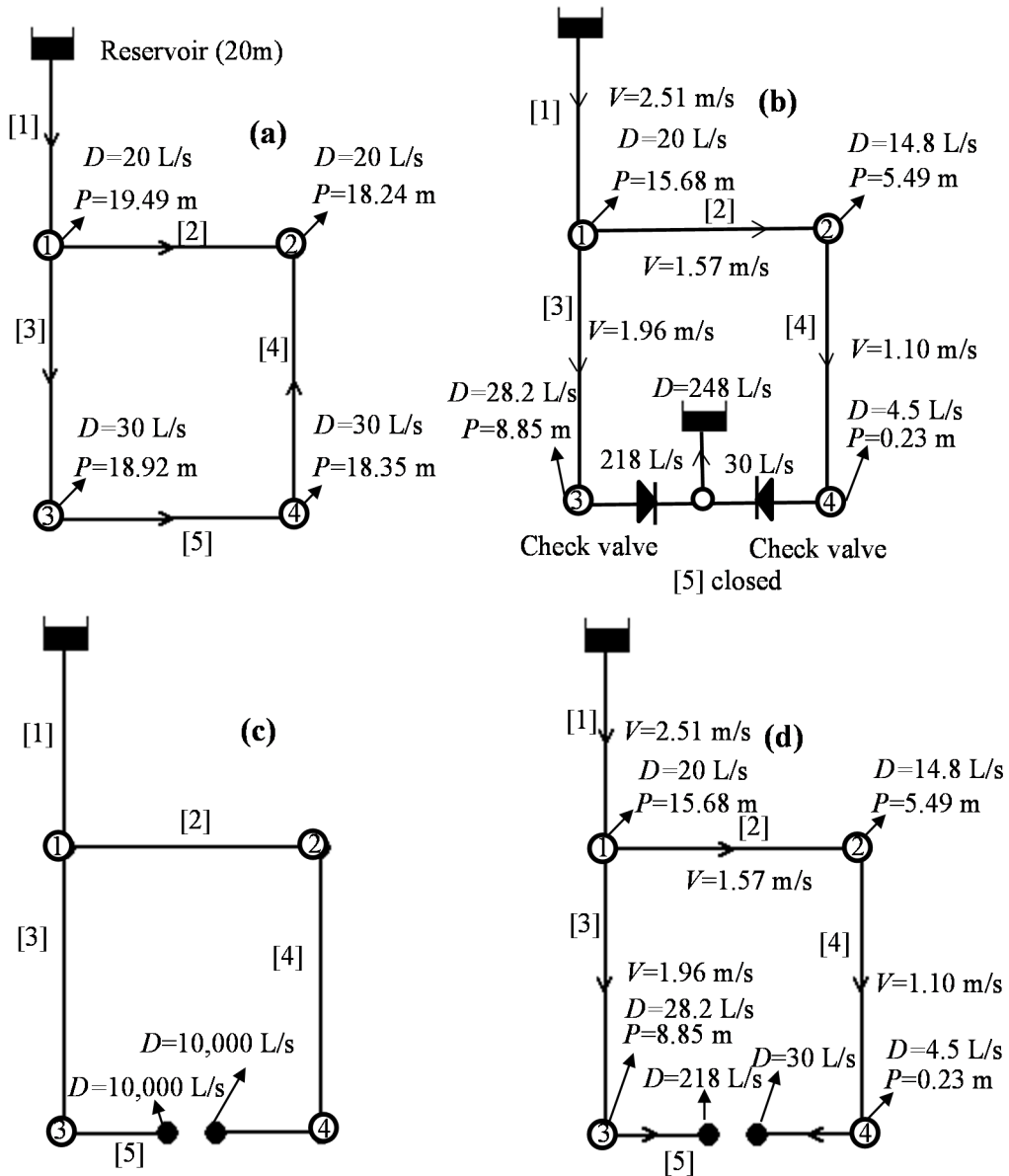
**Figure 11. Rank of a single pipe (400 mm) within the JYN based on different metrics. The rank can range between 1 and  $N$  (the total number of pipes) based on the value of each metric (M1 and M6 are the first and last metrics in Table 1, respectively), with a smaller ranking value indicating a larger impact.**

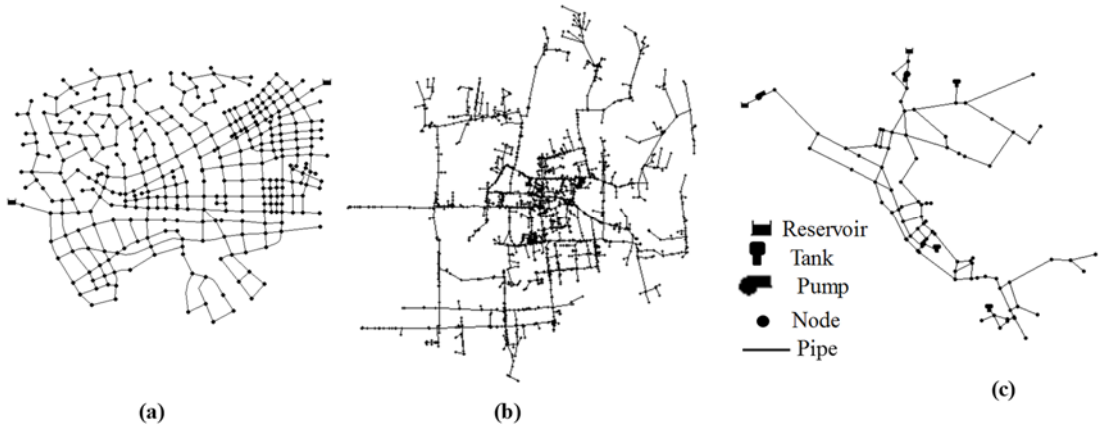
**Figure 12. Ranking levels of the JYN and ZHN during PHD periods obtained by assigning equal weight to each metric. Rank level 1 (R1) and rank level 5 (R5) indicating the groups of pipes with the lowest and largest impacts, respectively.**

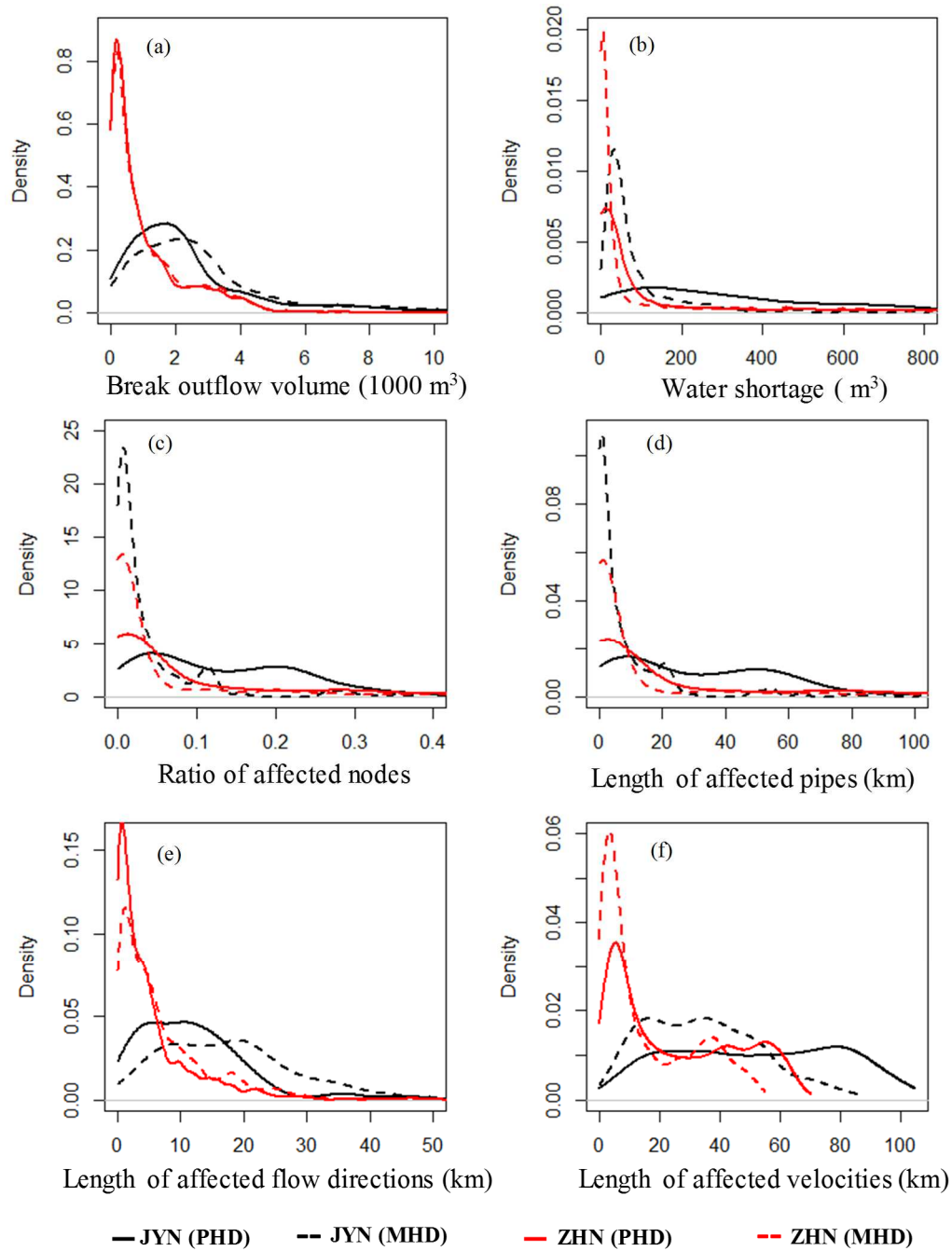
**Figure 13. Statistical results and distribution of affected nodes and pipes for the breaking events of the WDS with pumps and tanks.**

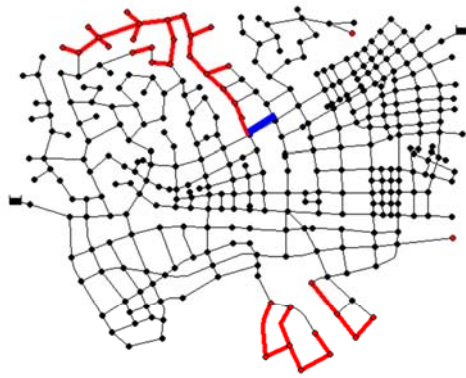
**Figure 14. Ranks based on the metric of break outflow volume and six metrics for the WDS with pumps and tanks. Rank level 1 (R1) and rank level 5 (R5) indicating the groups of pipes with the lowest and largest impacts, respectively.**



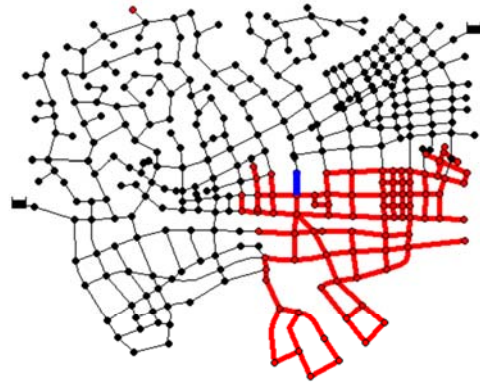




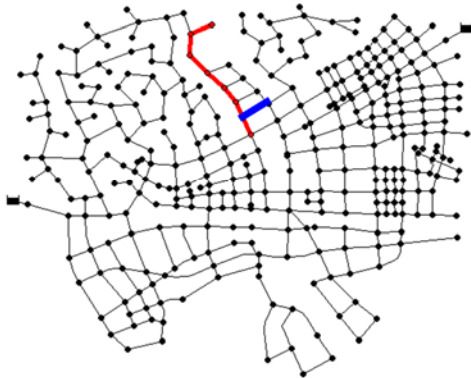




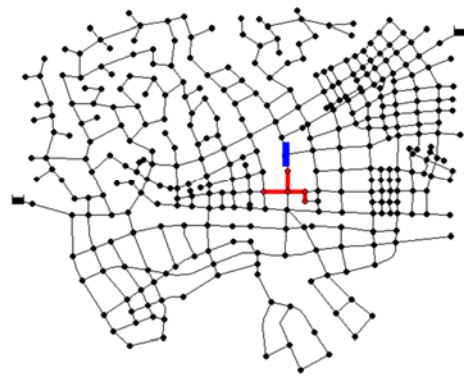
(a) Break scenario 1 (PHD)



(b) Break scenario 2 (PHD)



(c) Break scenario 1 (MHD)

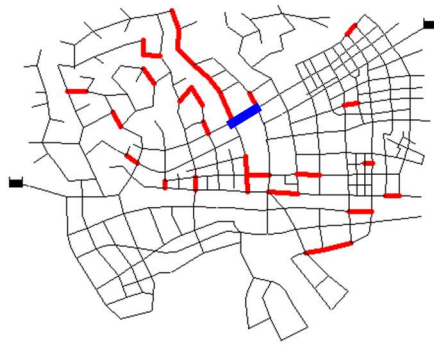


(d) Break scenario 2 (MHD)

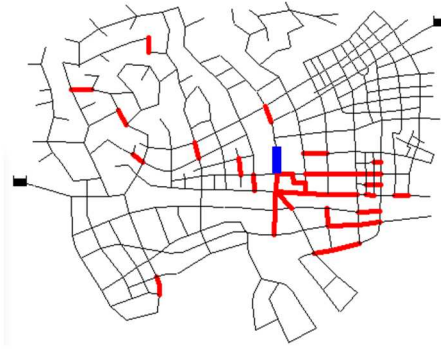
— Breaking pipes (300mm)

• Affected nodes

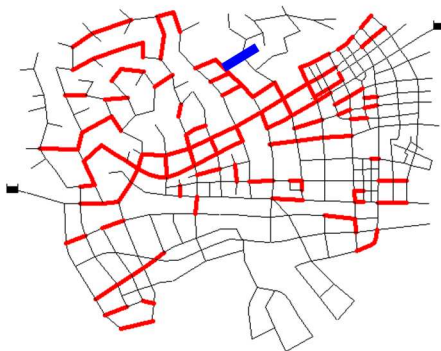
— Affected pipes



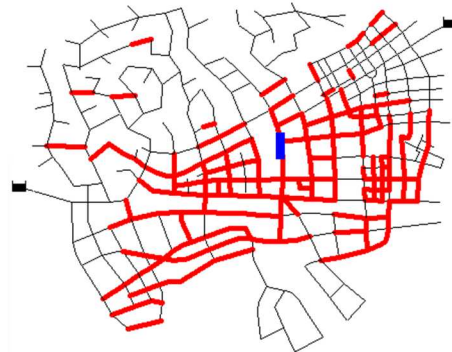
(a) Affected flow directions  
(break scenario 1)



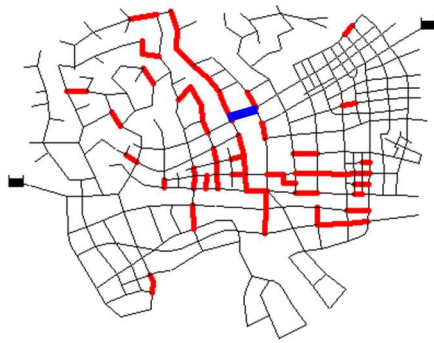
(b) Affected flow directions  
(break scenario 2)



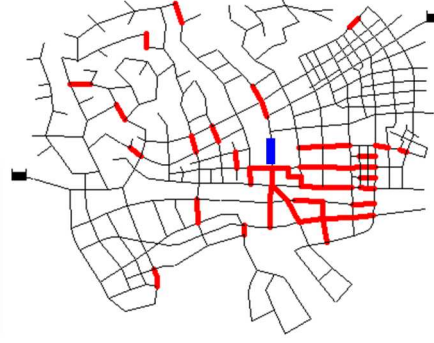
(c) Affected velocities  
(break scenario 1)



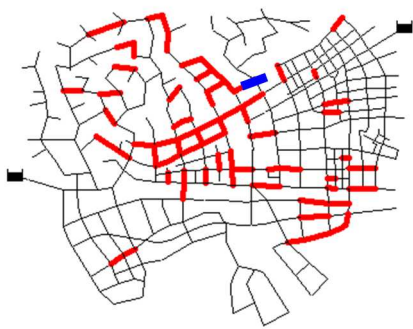
(d) Affected velocities  
(break scenario 2)



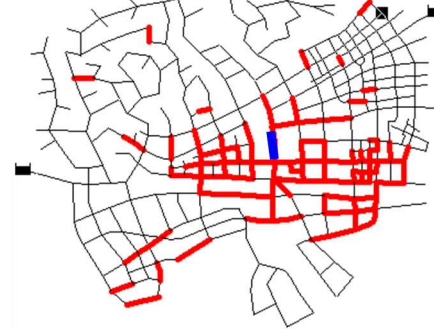
(a) Affected flow directions  
(break scenario 1)



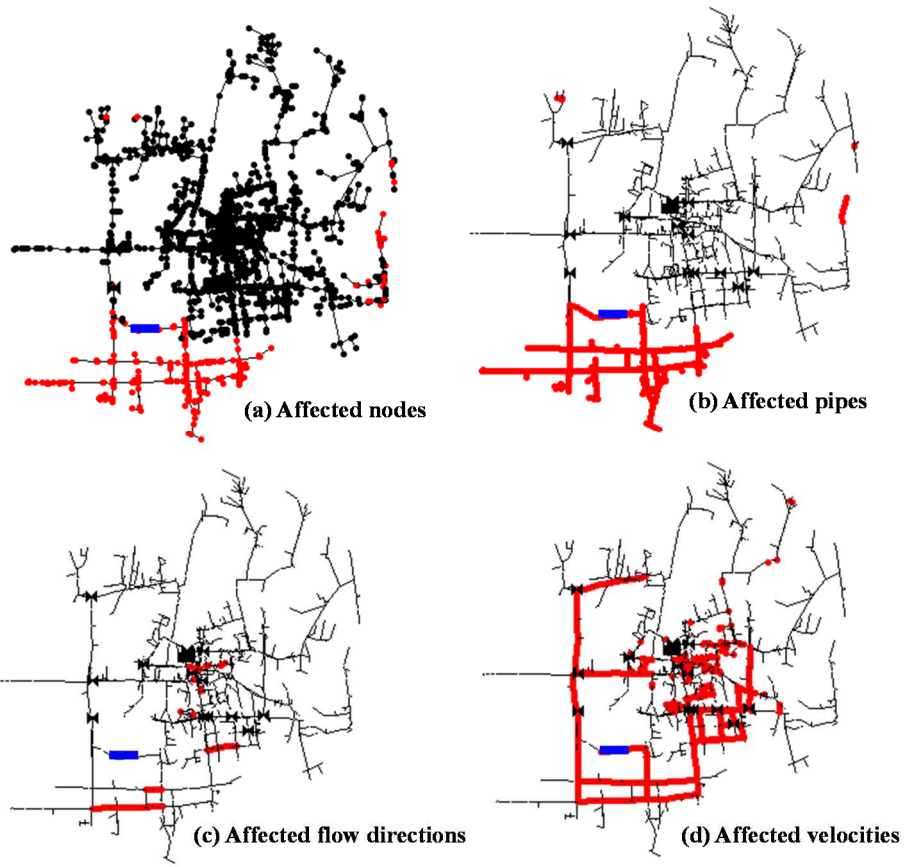
(b) Affected flow directions  
(break scenario 2)

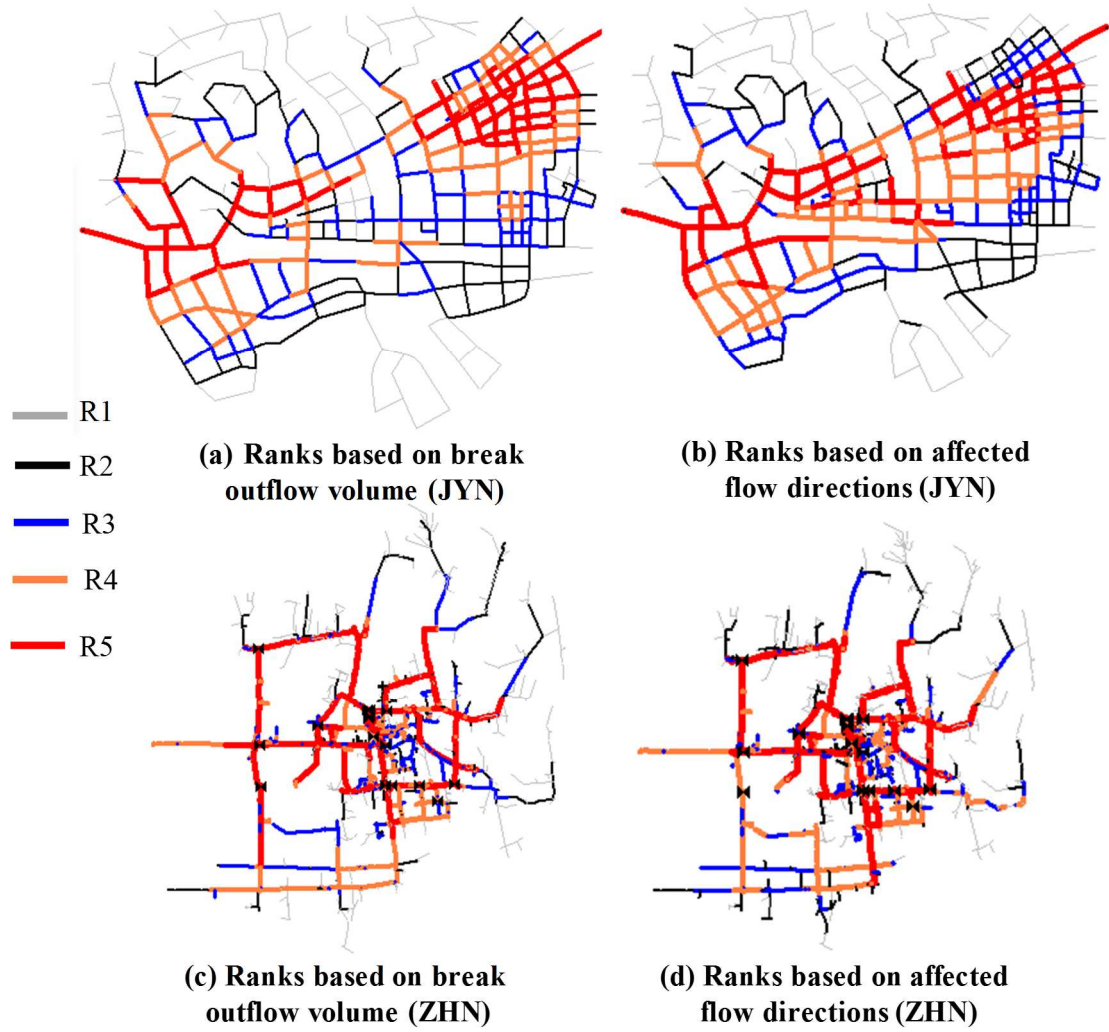


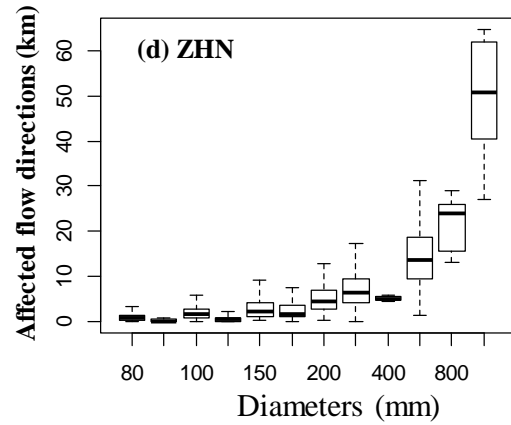
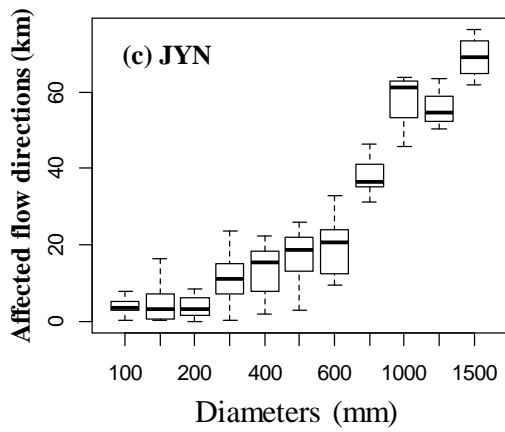
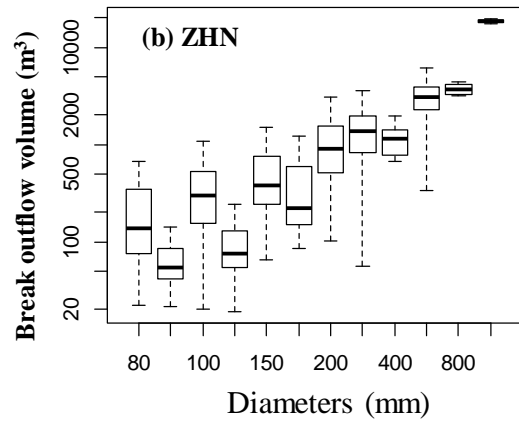
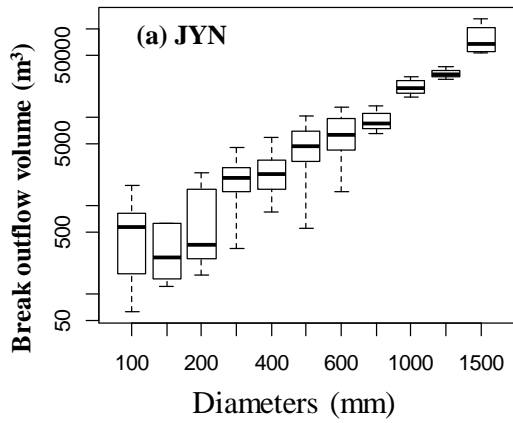
(c):Affected velocities  
(break scenario 1)

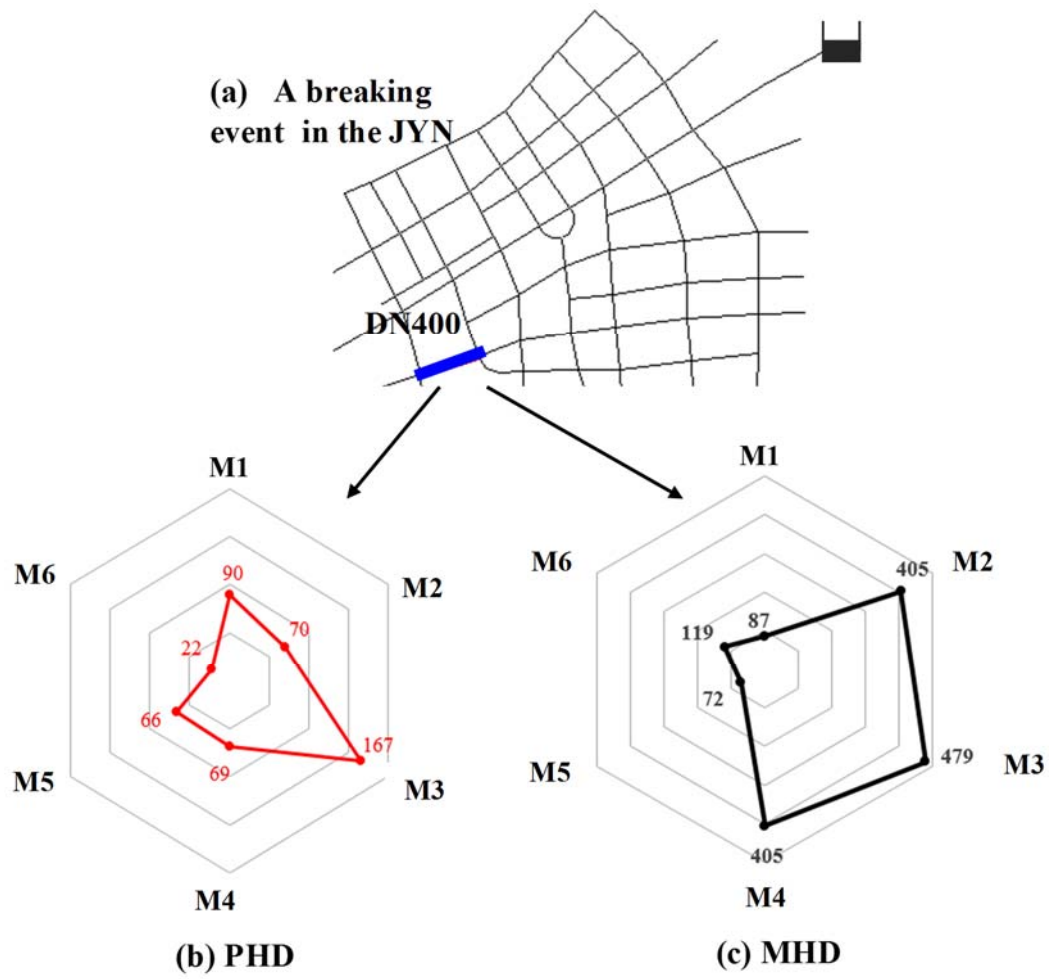


(d):Affected velocities  
(break scenario 2)

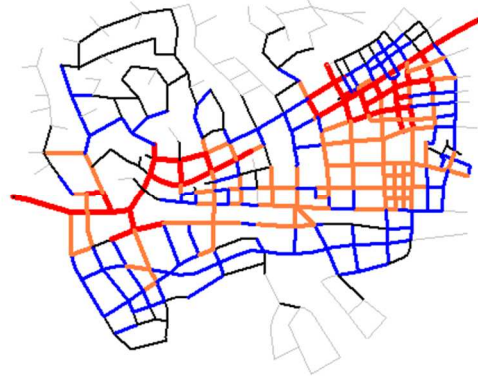








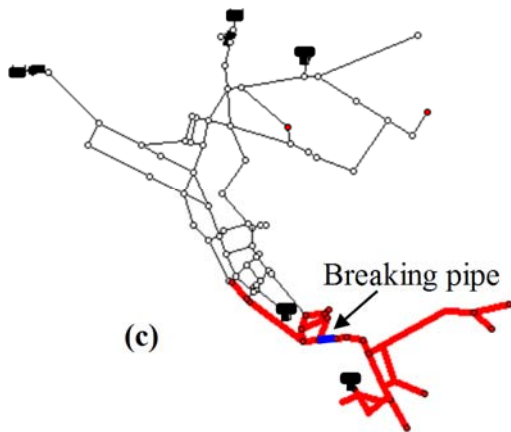
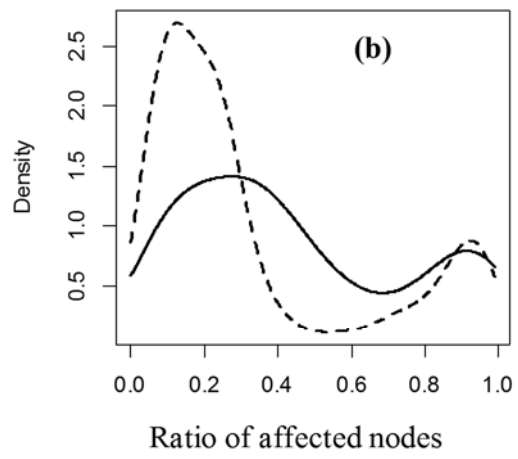
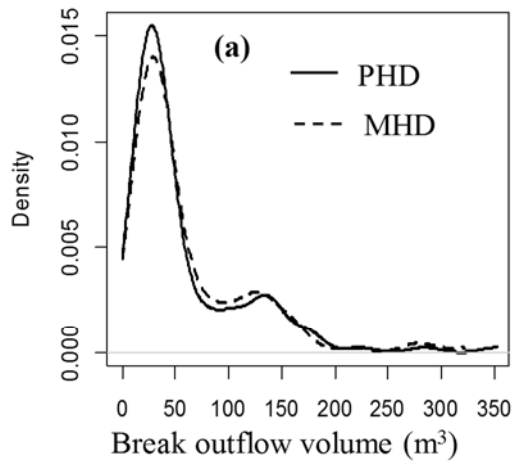
- R1
- R2
- R3
- R4
- R5



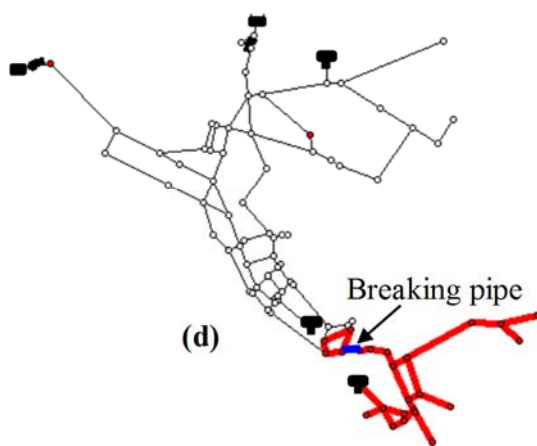
(a): JYN



(b): ZHN



(c) Affected nodes and pipes (PHD)



(d) Affected nodes and pipes (MHD)

