Identifying critical elements in drinking water distribution networks using graph theory

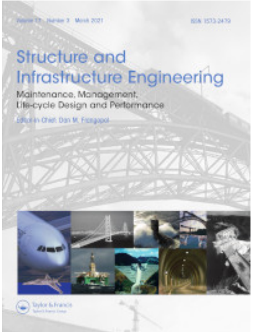
Meijer, Didrik; Post, Johan; Hoek, Jan Peter van der; Korving, Hans; Langeveld, Jeroen; Clemens, François

DOI
10.1080/15732479.2020.1751664

Publication date
2021

Document Version
Final published version

Published in
Structure and Infrastructure Engineering



Taylor & Francis
Taylor & Francis Group

Structure and Infrastructure Engineering

Maintenance, Management, Life-Cycle Design and Performance

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/nsie20

Identifying critical elements in drinking water distribution networks using graph theory

Didrik Meijer , Johan Post , Jan Peter van der Hoek , Hans Korving , Jeroen Langeveld & François Clemens

To cite this article: Didrik Meijer , Johan Post , Jan Peter van der Hoek , Hans Korving , Jeroen Langeveld & François Clemens (2021) Identifying critical elements in drinking water distribution networks using graph theory, Structure and Infrastructure Engineering, 17:3, 347-360, DOI: 10.1080/15732479.2020.1751664

To link to this article: https://doi.org/10.1080/15732479.2020.1751664

STRUCTURE AND INFRASTRUCTURE ENGINEERING
2021, VOL. 17, NO. 3, 347–360
https://doi.org/10.1080/15732479.2020.1751664

Identifying critical elements in drinking water distribution networks using graph theory

Didrik Meijer[a,b], Johan Post[c], Jan Peter van der Hoek[b,d], Hans Korving[a], Jeroen Langeveld[b,c] and François Clemens[a,b]

[a]Deltares, Delft, the Netherlands; [b]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands; [c]Partners4urbanwater, Nijmegen, The Netherlands; [d]Waternet, Amsterdam, the Netherlands

ABSTRACT

Drinking water distribution networks (WDNs) are a crucial infrastructure for life in cities. Deterioration of this ageing, and partly hidden from view, infrastructure can result in losses due to leakage and an increased contamination risk. To counteract this, maintenance strategies are required to maintain the service level. Information on the most critical elements of a WDN, with respect to the functioning of the system as a whole, is essential for prioritising maintenance or rehabilitation activities. In this study a Graph theory based method is developed and applied for efficiently identifying the most critical elements. The main advantage of this method is that it avoids the need to perform elaborate hydrodynamic model calculations. Instead, the structure of the network is the main starting point. The results show that the structure of the network is more decisive than the hydraulics with respect to the criticality of the system's performance as a whole. Results depict that the suggested approach is applicable not only to the main (primary) network, but also to the capillaries which are normally beyond the scope of the traditional methods applied so-far because of the complexity of the networks and the required calculation time.

ARTICLE HISTORY
Received 14 August 2019
Revised 20 January 2020
Accepted 27 January 2020

KEYWORDS
asset management; critical elements; deterioration; drinking water distribution networks; Graph theory; maintenance; leakages

1. Introduction

In 2006, an estimated 133 million m^3/day (90 million m^3/day, excluding non-revenue water) of treated drinking water leaked from water supply systems around the world (Kingdom, Liemberger, & Marin, 2006). Similar estimates for 2015 were reported by LaBrecque (2015); 126 million m^3/day (including non-revenue water). This is in the order of 16 litres per day per person, which is over three times the amount of water consumed by people categorised as people lacking access to clean water (UNDP, 2006). Kingdom et al. (2006) estimate the costs of physical drinking water losses at 14.6 billion US$/year. These figures illustrate the need for asset managers to take up the challenge of reducing these losses that are, at least in part, due to ageing of existing infrastructure.

To maintain or reclaim the desired level of service, proper maintenance and rehabilitation of the infrastructure are essential (see e.g. Le Gauffre et al., 2007; Wirahadikusumah, Abraham, & Iseley, 2001). Amongst others, the occurrence of pipe bursts causes a significant negative impact on the service level. In case of a Water Distribution Network (WDN), the required service in the Netherlands is defined as: '*a minimum water pressure at the delivery point of at least 150 kPa in relation to the ground level and a minimum capacity of 1000 liters per hour*' (Drinkwaterbesluit art. 45, 2015). Since maintenance and rehabilitation budgets are limited, prioritization of rehabilitation and maintenance activities is needed. Effective prioritization calls for information on where leakages have the strongest negative impact on the service level.

Prioritization of rehabilitation projects based on failure risks is applied in practice. Risk is often defined as a combination of the Likelihood of Failure (LoF) with the Consequence of Failure (CoF) (see e.g. Anbari, Tabesh, & Roozbahani, 2017; Arthur, Crow, Pedezert, & Karikas, 2008; Scott Arthur & Crow, 2007; Baah, Dubey, Harvey, & McBean, 2015; Laakso, Ahopelto, Lampola, Kokkonen, & Vahala, 2018; Lukas & Merrill, 2006; Mancuso, Compare, Salo, Zio, & Laakso, 2016; McDonald & Zhao, 2001; Pienaar, 2013; Ward & Savic, 2012). Approaches used to express the consequences of failure can be divided into three categories:

1. Consequences related to the pipe characteristics (e.g. pipe size, pipe depth).
2. The location of the pipes in the urban area (pipes under railways or roads, pipes close to subway entrances, pipes close to main gas transport lines).
3. The number of people left without water after a pipe break.

CONTACT Didrik Meijer didrik.meijer@deltares.nl

Supplemental data for this article is available online at https://doi.org/10.1080/15732479.2020.1751664.

A common way to assess failure consequences is hydrodynamic modelling and calculation of differences between water supply and demand (see e.g. Möderl & Rauch, 2011). Tscheikner-Gratl, Sitzenfrei, Rauch, and Kleidorfer (2016) present a method for prioritising sewer conduits and drinking water pipes as part of a larger framework. The priority of drinking water pipes is based on 'estimating the discharged water due to transmission mains failure for certain failure modes depending on the pipe material' (Friedl et al., 2012; Fuchs-Hanusch, Möderl, Sitzenfrei, Friedl, & Muschalla, 2014).

Meijer et al. (2018) present the Graph Theory Method (GTM), a methodology to rank elements of sewer systems based on the minimum distance from every manhole to an outflow structure. Graph theory is a mathematical theory and is widely used in, for example, vehicle route problems and optimization of flow problems. Networks such as water supply networks, sewer systems, electricity networks are typical examples of graphs consisting of links (pipes, cables) and nodes (connections or manholes). In hydrological models, graphs are used to represent the structure of the network.

Graph theory based methods have been used to analyse WDNs. Michaud and Apostolakis (2006) present a methodology to rank elements of WDNs based on water supply and demand. Instead of hydraulic calculations, their methodology is based on multi-attribute utility theory and Graph theory. For the so called high level drinking water network (the main distribution pipes only, leaving out the capillaries of the system), they used the Dijkstra algorithm (Dijkstra, 1959) to define the supply coverage at a given location defined as the ratio between the demand and the actual supply to this location. The optimization of supply occurs for each sink sequentially. The order of sinks influences the outcomes, because the capacity of sources and pipes that are used to deliver water to the sinks with a high priority can (partly) not be used for other sinks. As a result, the supply to sinks that are lower in the priority list becomes suboptimal in some cases. The method is based on a reduction of the pipe capacity. Diao et al. (2014) also applied Graph theory to identify the clusters with the strongest external connections and used the number of people deprived of water as criterion. Both Graph methods focus on the analysis of the main system and did not include the capillaries of the system.

Balekelayi and Tesfamariam (2019) compared the outcomes of two approaches to evaluate the reliability of WDNs: topological and hydraulic. Simulation-based hydraulic reliability was compared with four topological graph metrics (Betweenness, Topological information centrality, Eigenvector centrality and Principal Component Centrality) that utilise the location of a pipe inside a network to determine its importance. The authors showed that these topological graph metric approaches cannot individually capture the hydraulic reliability of complex drinking water networks. Each topological metric provides a hypothesis about the connection point's importance based on the network topology. These hypotheses are combined to produce an updated, joint probability for each connection point's importance. A Bayesian Belief Network (BBN)-based data fusion technique is used for combining the hypotheses. With the combined criticality it is possible to identify 12 out the 20 most critical components in the WDN of Richmond (Balekelayi & Tesfamariam, 2019).

Except for hydrodynamic modelling-based and Graph theory approaches, the discussed methodologies do not take into account the effect of a failure of an individual element in the network on the functioning of the network as a whole. The Graph theory techniques determine the criticality of an element based on the location of the pipe in the network and the (physical) characteristics of the pipe. The consequences of a failure of an individual element for the whole network can be quantified, for example the number of people (temporally) deprived of water supply or the number of households confronted with a water pressure <10 kPa. Methods that do include these effects generally focus on the main network, while neglecting the capillaries of the system. Apparently, this is mainly due to the prohibitive computational effort associated with the hydraulic calculations for large scale networks. To the knowledge of the authors, there are no other methods available, or published to date, to determine the criticality of elements of WDN in relation to the network performance. So, the common approaches do include either

1. the effects of failure on the functioning of the network, or
2. include the main and the capillaries of the system, but not both.

In this article, a Graph theory-based method is proposed for ranking elements (pipe and valves) of a WDN using the functioning of the WDN as a metric. This method takes the effects of failure on the functioning of the system into account and is applicable on the whole (main and capillaries) of the network. This method is an extension of the GTM, developed to determine the criticality of elements in sewer systems (Meijer et al., 2018). In the GTM, the structure of the network is taken as a starting point instead of the results of a multitude of hydraulic calculations. When the elements of a WDN are ranked based on the impact of their individual failure with respect to the performance of the complete network, the system managers obtain information that can be utilised (1) to prioritise maintenance or rehabilitation activities, or (2) to identify monitoring locations, or (3) to differentiate the required quality levels for more and less important elements in the network as input for asset management, (4) design and implement adaptations to the system's structure to reduce vulnerability.

Based on their criticality, elements are divided into groups with, e.g. the 10% elements where a leak has the biggest impact on the service level. WDN managers may prioritise maintenance on the most critical elements to maximise the service level given the limited available resources. Conditions in WDN's are dynamic, e.g. when a pipe break is detected valves are closed to isolate the section with the

Table 1. Main characteristics of the WDNs Cavlar, Tuindorp and Leimuiden.

Characteristics	Cavlar	Tuindorp	Leimuiden
Drinking water utility	Does not apply	Vitens	Oasen
Area (km^2)	5.7	1.7	1.5
Nr. Water pumping stations	1	2	1
Nr. Households	5817	1922	1835
Network length (km)	34.9	37.2	26
Nr. pipes + valves	1054	1701	3243
Nr. connection points	1040	1611	3218
Nr. connection points with water users	747	503	1438
Min. diameter (mm)	22	25	32
Max. diameter (mm)	600	710	315
Loops[a]	15	92	25
Branches	118	174	79

[a]A loop is defined as a path with the same start and end of more than 2 nodes with the least number of nodes with a minimum degree of 3.

break in order to prevent losses and to allow for repairs to be effectuated. Ideally the network, apart from the isolated section, achieves the minimum required service level. In this sense, two operational modes conditions are distinguished (1) complete system is operational, (2) one or more sections are isolated from the rest of the system. A distinction for both modes has to be made when applying the GTM. This study focuses on the situation directly after a pipe break when all valves are open.

This article is organised as follows: The Section 2 presents the case studies applied and the outline of the GTM. In the section 3, a comparison between the GTM and the outcomes of hydrodynamic models is presented. In the section 4, application and its limitations of the GTM are discussed. In the section 5, the key findings are summarised along with an outlook and recommendations for future research.

2. Materials and methods

2.1. Studied water distribution networks

To validate the GTM, three WDNs acted as case studies for a comparative analysis using the GTM compared to a hydrodynamic reference model. The first case study is the Cavlar WDN. This is a benchmark WDN that is used as test model of the Dutch Watercycle Research Institute (Mesman, 2018). The second network is the WDN of the village of Leimuiden (the Netherlands). This network was chosen because it has been used as a case study in previous research (e.g. Moors et al., 2018), as a result detailed, validated models are available. The third model is the WDN of Tuindorp in Utrecht (the Netherlands).

The Tuindorp WDN is part of the larger WDN of the city of Utrecht and was used as since detailed and validated WDN and the drainage network information is available. Thus, allowing for combined analysis of the criticality of both networks in future research. Table 1 presents the most important characteristics of the WDN and Figure 1 shows the layout of the networks (for more details see supplementary material).

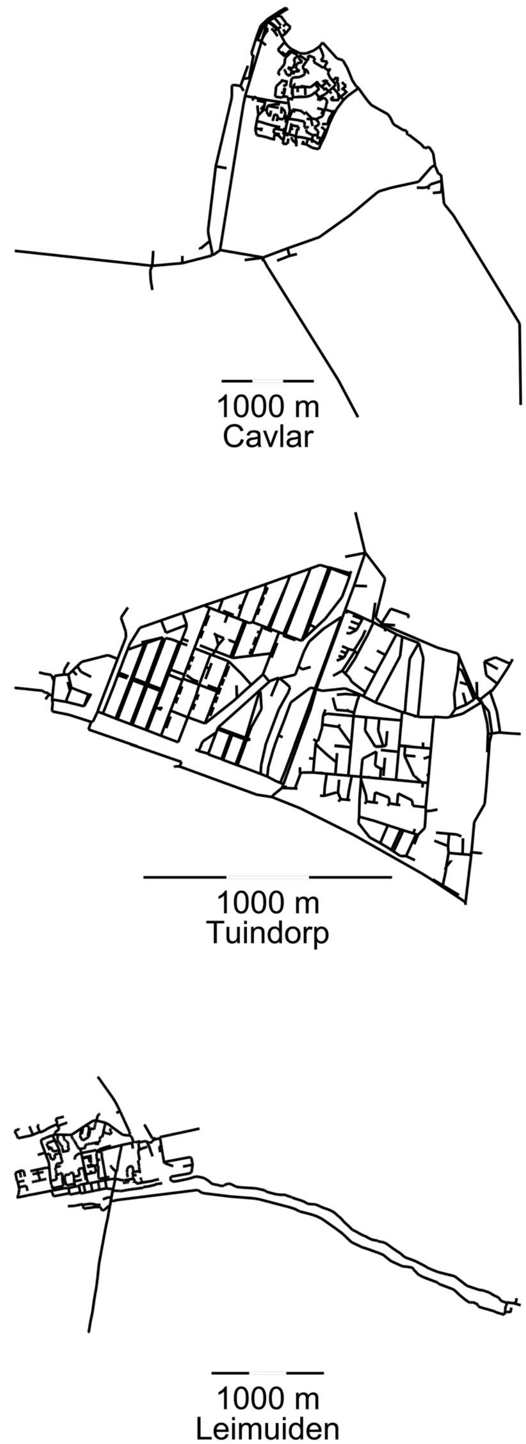


Figure 1. The structure of the WDNs.

2.2. Hydrodynamic reference model

As previously stated, various methods exist to quantify the impact of a leakage or pipe blockage using hydrodynamic models (e.g. the Achilles Approach (Mair, Sitzenfrei, Kleidorfer, Möderl, & Rauch, 2012; Möderl, Kleidorfer, Sitzenfrei, & Rauch, 2009) and the method described by Fuchs-Hanusch et al. (2014)). A generally applicable method to determine the criticality of an element in a WDN is shown in Figure 2. This method is used as a reference for the three case studies.

The software tool Wanda (Deltares, Delft, the Netherlands) was used for the hydraulic calculations. The first step is a simulation with the complete original WDN model (run 0). The calculated head (pressure) at every

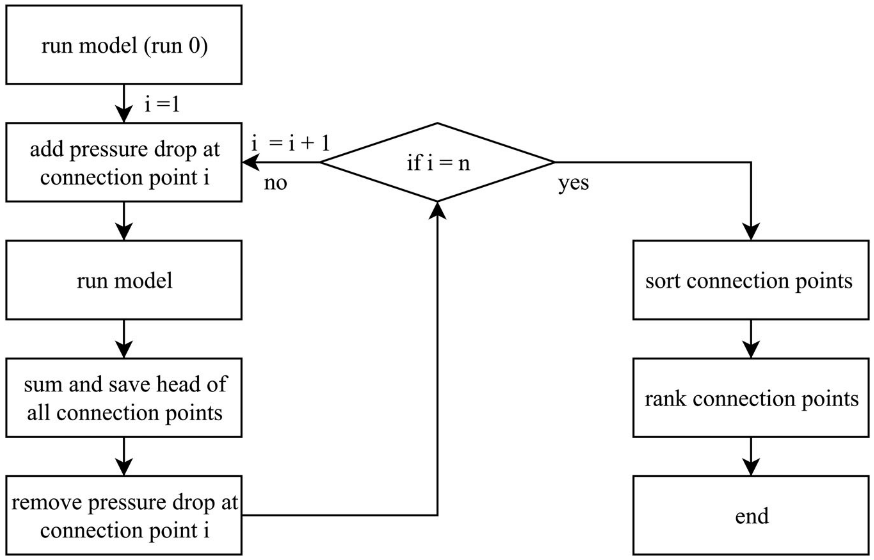


Figure 2. General process to determine the degree of criticality with a hydrodynamic model.

connection point was stored. Thereafter, a pipe and reservoir are added to the network. The new pipe is connected to one of the connection points of the original network. This represents a leak where the water can flow out of the WDN. Then a new simulation is performed. The new head in the network is saved. Subsequently, the new pipe is connected to another connection point just as often until as many calculations have been made as connection points in the WDN are present.

The head in the reservoir of the leak is an indication of the size of the leak. A relatively low head is a result of a relatively large leak and a high head a small leak. In order to apply similar leaks at the different connection points, the head in the leak reservoir must be adjusted to the operational pressure in a connection point minus the pressure drop. The effect of various pressure drops was tested. The head for connection point n is set at

$$H_{\text{leak } n} = H_{\text{connection point } n} - \text{pd} \tag{1}$$

in which $H_{\text{leak } n}$ is head of the reservoir connected to connection points n (m), $H_{\text{connection points } n}$ is calculated head in run 0 for connection points n (m), pd is the pressure drop (m) and run-0 is run complete network.

Two methods were tested to rank the elements based on the criticality. In the first method, the connection points are ranked based on total head. The simulation with the lowest total head indicates that the ‘leak’ is connected to the most critical element. When the sum of the head is low the impact is large and vice versa.

$$H_{\text{total } j} = \sum_{i=0}^{n} head_i \tag{2}$$

in which $H_{\text{total } j}$ is summed head of all connection points for run j (m), $Head_i$ is calculated head in connection point i (m) and n is number of connection points.

In the second method the number of users confronted with a water pressure below a certain threshold are counted for each run ($Users_{p<t}$). The impact increases with an increasing value of $Users_{p<t}$

$$Users_{p<t\ j} = \sum_{i=0}^{n} Users_i \text{ if } H_{node\ i} < H_{\text{threshold}} \tag{3}$$

in which $Users_{p<t\ j}$ is users with a water pressure < threshold pressure for run j (-), $Users_i$ is users connected to connection point i (-), $H_{\text{connection point } i}$ is head in connection point i (m), $H_{\text{threshold}}$ is threshold pressure (m) and n = number of connection points (-).

2.3. The graph theory method (GTM)

Meijer et al. (2018) presented the GTM to identify critical elements in sewer networks. The GTM, as applied for sewer networks, cannot directly be transferred to WDNs as there are some fundamental differences between WDN and sewer networks:

- A WDN is driven by the water demand, while a urban drainage network is supply driven (storm water runoff and/or wastewater). This implies that water in a WDN flows from a limited number of points to many connection points. In an urban drainage system, this is exactly the opposite.
- A WDN is a pressurised system. Normally the drinking water pumping stations maintain an overpressure to prevent the risk of contamination by e.g. groundwater. Urban drainage systems (in our case combined sewer systems) comprise subsystems with gravity driven flow and pressurised subsystems. It is common that water is collected in gravity systems and transported by gravity to pumping stations or CSOs, on a regional scale pumping stations transport the wastewater in pressurised systems to Wastewater Treatment Plants.
- For determining the criticality of conduits of urban drainage systems, 100% loss of transport capacity (blockage or complete structural collapse) was used as failure mechanism conduits. In WDN a pressure-drop as a

result of a leakage or pipe burst is considered as the dominant failure mechanism.

2.4. The GTM for water distribution networks

Figure 3 presents the GTM used for determining the criticality of elements (pipe/valve) in WDN. The criticality is based on a combination of: (1) the location of the leak relative to Water Pumping Station (WPS) and (2) the position of the leak in the network relative to other connection points in the system. The location relative to the WPS is based on the shortest path from the leak location to the WPS. The 'shortest path' is interpreted as the 'cheapest path' or the path with the 'least resistance'. The term most often used is the cheapest path and is therefore adopted here as well. The shortest path algorithm of Dijkstra (1959) has been used to calculate the costs between the leakage and the WPS.

In Graph theory 'costs' are expressed by a set of weights such as e.g. real costs or distance or, in this case, a head loss. Costs are assigned to each link between 2 connection points. Based on the costs of each link the shortest (cheapest) path between a source (connection point) and target connection point (water pumping stations, WPS) is determined. In case of multiple WPS the costs of all nodes to all WPS are determined and for each node the costs to the closest WPS is used as shortest path.

In the GTM, the costs per link are derived from the dynamic head loss in a link. Energy is needed to transport water from A to B. The amount of energy that is lost due to the flow resistance between A and B is expressed as the head loss. The head loss in a WDN is the amount of energy needed to transport water from the WPS to a customer. The head loss depends on the characteristics of the liquid and the element dimension and hydraulic characteristics. The head loss in an element is described with the following formulas:

$$\Delta H = \frac{L(q/A)^2}{C^2 R} \tag{4}$$

$$C = 18\log\left(\frac{12R}{k}\right) \tag{5}$$

in which A is area of element (m^2), C is Chézy coefficient (m$^{1/2}$/s), ΔH is head loss (m), k is wall roughness (m), L is length (m), q is discharge (m^3/s) and R is hydraulic radius (m).

The head loss of the elements depends on the applied discharge (q). However, in the GTM the discharge functions as the scaling factor. The scaling factor is the same for all elements. The applied discharge does not influence the outcome of the GTM as long as $q > 0$.

In the GTM, the number of runs is equal to the number of connection points plus one (see Figure 3). The first run is the original graph. The costs for each path from a connection point to the WPS (target) are computed. If the costs are low the connection point is situated close to the target and if the costs are high the connection point is situated far from the target. In the following runs, a leak is added to one of the connection points. The leak is used as an extra target connection point apart from the WPS. Two evaluation methods are tested

1. The number of connection points whereof the costs of the shortest path to leakage are lower than the costs of the connection points to a WPS are counted. Thus, the number of connection points where the head loss to the leak < the head loss to the WPS is counted. This is an indication of the area of influence of a leak.
2. Instead of counting the number of nodes where the costs of connection points to the leak are lower than the costs to the WPS, the sum of 1/(costs connection points to the WPS) for these connection points is used. As a result, the connection points close to the WPS are ranked as more important than the connection points far from the WPS. So the number of the connecting points where the head loss to the leak < the head loss to the WPS is counted and a weight is used for each node.

The connection points are ranked from the highest counted number of connection points (most important) to the lowest number of connection points (less important). The criticality of the elements of the WDN is compared for first all connection points and second for only the connection points with water users.

2.5. Comparison of criticality between hydrodynamic model method (HMM) and graph theory method (GTM)

The Kendall rank correlation coefficient (Kendall, 1945), commonly referred to as Kendall's tau-b coefficient (τ_b), is used to determine the overlap between the outcomes of the HMM and the GTM (see Formula (6)). τ_b is a non-parametric measure of association based on the number of concordances and discordances in paired observations. τ_b is used to compare the relationship of datasets and not of individual elements. Minus one (-1) implies a 100% negative association, one (1) is a 100% positive association:

$$\tau_b = \frac{(P-Q)}{(\sqrt{(P+Q+X_0)*(P+Q+Y_0)})} \tag{6}$$

in which τ_b is Kendall's tau b coefficient (-), P is the number of concordant pairs (-), Q is the number of discordant pairs (-), X_0 is the number of pairs tied only on the X variable (-) and Y_0 is the number of pairs tied only on the Y variable (-).

The F1-measure (or F1 score) is a measure of the accuracy of a test. It combines the recall and precision in a single measure which falls between recall and precisions. The recall is a measure of the critical elements that were correctly identified as such and the precision represents the proportion of critically identified elements that were critical according to the reference model. If recall and precision are of equal weight the formula is (Chinchor, 1992):

$$P = \frac{TP}{TP + FP} \tag{7}$$

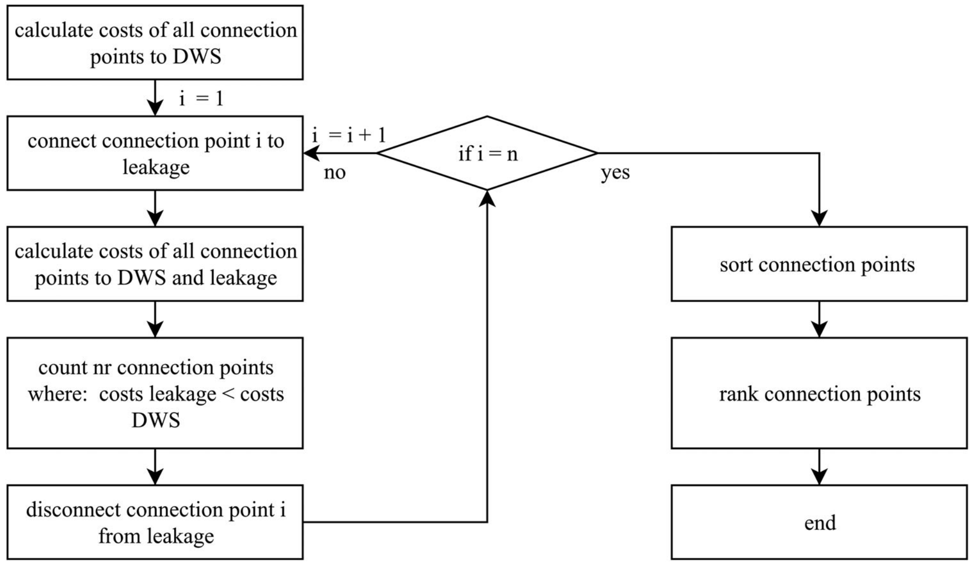


Figure 3. Process to determine degree of criticality with GTM for WDN.

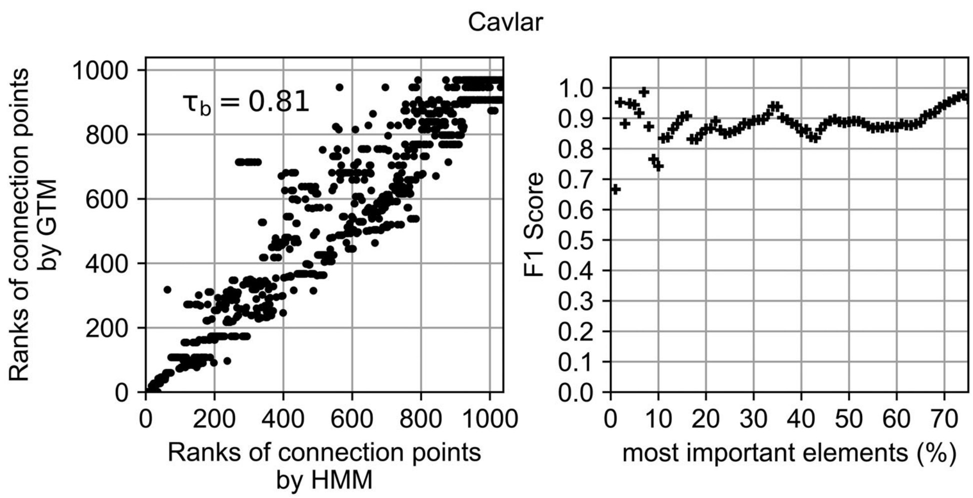


Figure 4. Overview of the correlation between the outcomes and the F1-score of the HMM and the GTM for the Cavlar WDN, with a pressure drop of 20 m for all connection points.

$$R = \frac{TP}{TP + FN} \tag{8}$$

$$F_1 = \frac{2*P*R}{P+R} = \frac{2*TP}{2*TP + FP + FN} \tag{9}$$

where P is Precision (-), R is Recall (-), TP is True positive (-), FP is False positive (-), FN is False negative (-) and F^1 is F1 score (-).

The F1-score is used as follows: for the studied WDN a percentage of the most critical elements, identified with the hydraulic model method, is selected. The same percentage of most critical elements identified with the GTM is selected. A comparison is made of the true positive, false positive and false negative items. Because the group size is predefined, the number of false positive and false negative elements are the same (unless there are equal rank numbers), and therefore the precision and recall and F1-score are also the same. For maintenance and rehabilitation strategies the elements of a WDN can be divided into groups. The exact ranking within each group is less important as long as the overlap between the HMM and the GTM is sufficient. The F1-score is a measure of the overlap.

3. Results

3.1. The Cavlar WDN

Figure 4 presents the comparison between the criticality based on the hydrodynamic model method (HMM) and the GTM. Figure 4 depicts the case in which all connection points are ranked, the supplementary material presents the case in which only the connection points with water users are considered. Taking all connection points into account allows for a detailed analysis, since more connections points are used. When only the connection points with drinking water users are ranked, the ranking is focused on the affected number of users.

On the left side of Figure 4 the correlation between the HMM and the GTM is plotted. The rank number 1 is the most critical element and the highest rank number (1040)

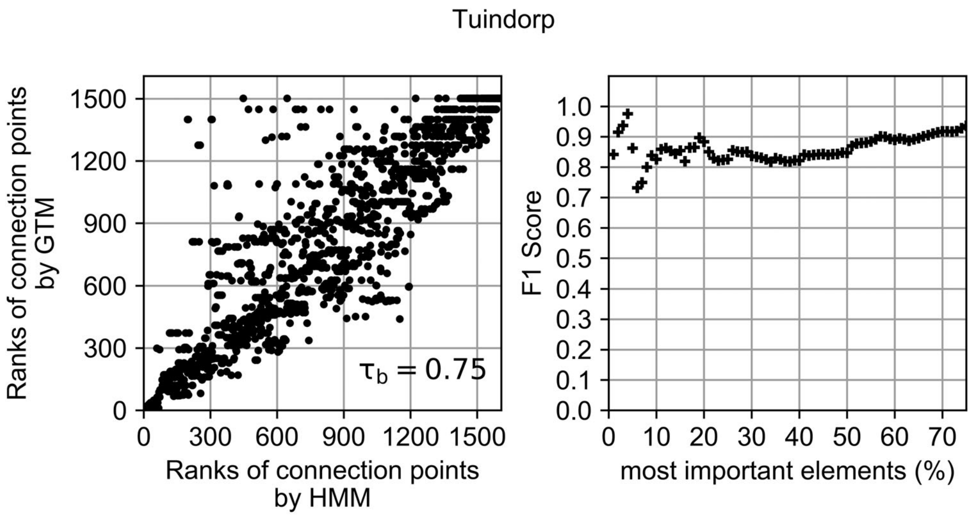


Figure 5. Overview of the correlation between the outcomes and the F1-score of the HMM and the GTM for the Tuindorp WDN, with a pressure drop of 20 m for all connection points.

the least important. Figure 4 depicts a correlation between the outcomes for all connection points ($\tau_b = 0.81$). The results for the case with the connection points with water consumers are similar ($\tau_b = 0.79$). The right side of Figure 4 presents the F1-score. Figure shows an overlap of more than 70% between the critical elements based on the GTM and the HMM, except when only the 1% of the most important connection points are selected.

In order to calculate the F1-score for the 1% most import elements, the 10 most important elements (1% of 1040) according to the HMM were selected. A similar approach was attempted for the GTM. However, the GTM ranked the first 18 elements as equally important (GTM rank =1, HMM rank = 1–16, 22 and 35) and therefore it was not possible to select exactly 1% of the elements. By calculating the F1 score for the first 1% of the most critical elements the recall is 1 (the selected elements by the GTM included the elements with the rank 1–10 of the HMM) but the precision is relatively low because 18 elements were selected instead of the requested 10 elements.

The GTM allows the quick identification of the most important elements. For this purpose, the exact ranking within the group is less important as long as the overlap between the HMM and the GTM is sufficient. In the Cavlar case, in the top 10% critical connection points as identified by the GTM, 78 elements are in the selection as obtained by application of the HMM. The points in the left graph of Figure 4 shows that the 71 most important connection points according to the GTM includes the 50 most important elements according to the HMM. In comparison to the HMM, the GTM has a tendency to overestimate the importance of the branches (for more details see supplementary material).

3.2. The tuindorp WDN

For the WDN of Tuindorp, the results of the GTM are compared with the outcomes of a hydrodynamic model for a pressure drop of 20 m. Figure 5 depicts a correlation ($\tau_b = 0.75$) between the criticality based on the GTM and the HMM. The F1-score depicts that for the percentages 1–10% of the most critical elements, the GTM and the HMM are in agreement on 73–97% of the selected elements. The other F1-scores are > 0.8. The results for the case with the connection points with water consumers are similar. An analysis of the differences between the criticality based on the HMM and the GTM for the WDN of Tuindorp indicates that, as is the case for the WDN of Cavlar, an overestimation of the criticality of the branches by the GTM.

3.3. Leimuiden WDN

For the Leimuiden case Figure 6 shows a correlation of $\tau_b = 0.65$ for a pressure drop of 20 m. Giving a correlation between the HMM and the GTM for the connection points with a rank < 600 (20% most important elements) and > 2700, (80% most important elements) but the point cloud is more dispersed than for the Cavlar and Tuindorp case. For the connection points with a rank between 600 and 2700 the differences between the results of the HMM and GTM are large.

The same pattern is visible in the F1-scores, because at the start the point line is relatively wide the F1-score is relatively low. For the case that all connections points are used to determine the criticality, the F1-score shows that, if the 1–10% most critical elements are selected, the 48–86% of the elements selected by the GTM match with the elements identified with the HMM. The F1-score for percentages between 42 and 53 varies between 0.6 and 0.7. This corresponds with the graph at the left side of Figure 6 where the differences between the HMM and GTM are larger. The other F1-scores are > 0.7. The results for the case with the connection points with water consumers are similar.

An analysis of the difference between the outcomes of the HMM and the GTM depicts that of the WDN of Leimuiden, the importance of the connection points in the loop at the right side of Leimuiden (see Figure 1) and the branches are overestimated. An underestimation of the criticality is visible in the centre of the WDN of Leimuiden (for more details see supplementary material).

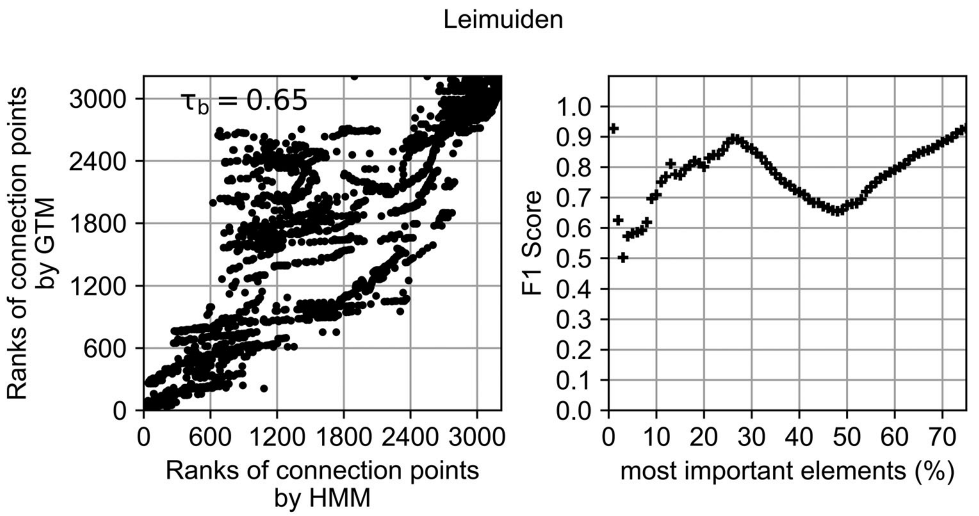


Figure 6. Overview of the correlation between the outcomes and the F1-score of the HMM and the GTM for the Leimuiden WDN, with a pressure drop of 20 m for all connection points.

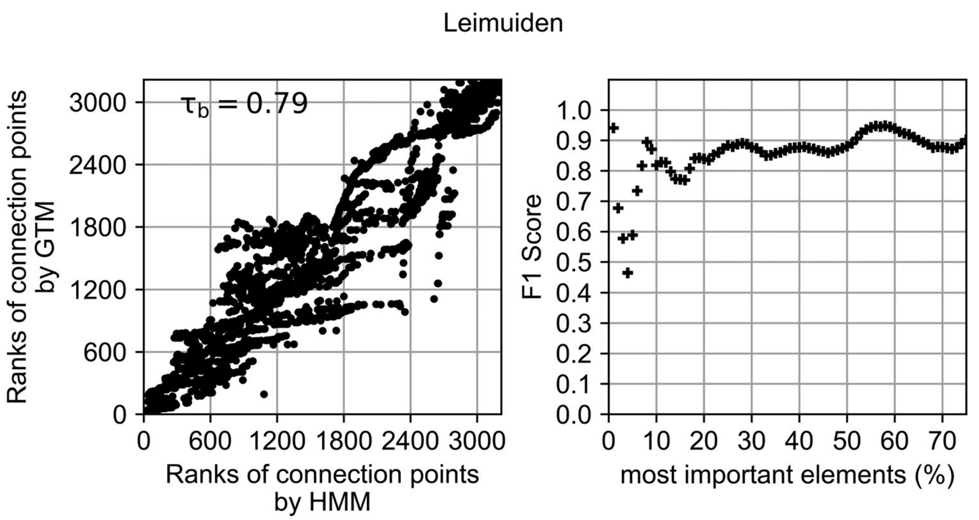


Figure 7. Overview of the correlation between the outcomes and the F1-score of the HMM and the GTM for the Leimuiden WDN with a pressure drop of 20 m for all connection points. The criticality is based on sum of (costs to WPS)$^{-1}$ for the connection points where the costs to the leak is less than to the WPS.

3.4. Leimuiden, second evaluation method

The criticality of the connection points of the WDN of Leimuiden was also determined with the second evaluation method (counting 1/(costs connection points to the WPS) of the nodes that are closer situated to a leak than to a WPS). The results are presented in Figure 7. The points are less dispersed than in Figure 6, and the τ_b is 0.14 higher (0.79). Figure 7 shows that the F1-score is the lowest when the 4% most important items are selected (F1 = 0.48), but all other F1-scores are > 0.57 and for a percentage of 7% and higher the F1-score is > 0.75.

3.5. The impact of the head loss on the criticality in a hydrodynamic model

With the HMM, the criticality of the connection points is determined for various pressure drops. The degree of criticality of the connection points for different pressures drops was computed and plotted against each other together with the corresponding values. If the degree of criticality is independent of the pressure drop, $\tau_b = 1$. Figure 8 presents the results for the Cavlar WDN. The Figure shows that the criticality depends on the size of the pressure drop. However, the differences are limited and the τ_b is for all combinations >0.92. Because the correlation between the different pressure drops is high and the size of the pressure drop has almost no influence on the 40–50% most critical connection points, the GTM can be used for different pressure drops and the pressure drop does not influence the applicability of the GTM.

3.6. Ranking based on the number of connections with a pressure below threshold

A different approach to rank the outcomes of the HMM, is counting the connection points with a pressure below a certain threshold pressure. Table 2 presents an overview of the results for the Leimuiden case in which only the connection points with water users are included.

The maintained operational pressure head in the WDN is 30 m. A leak is added to the network with a pressure head of 20 m below the operational pressure, so the pressure on the leak location is 10 m. The criticality of the elements is determined four times for four different thresholds. When the criticality of the HMM is based on connection points with a pressure < operational pressure −19 m (pressure < 11 m) the GTM does not identify the same critical elements. Too many connection points get attributed the same ranking in the HMM. When the elements in the HMM are ranked on the number of connection points with a threshold pressure of 5 or 10 m below the operational pressure, $\tau_b > 0.7$ and the F1 score > 0.6 is for the 10% most critical elements. The larger the differences between the pressure on the location of the leak location and the threshold the higher the τ_b and the F1 score.

Figure 9 presents the result of ranking the connection points on a threshold value with the HMM. It shows that the correlation between the rank based on the various thresholds is low. This implies that the result of the method is very sensitive to the criteria applied to the ranking of the elements.

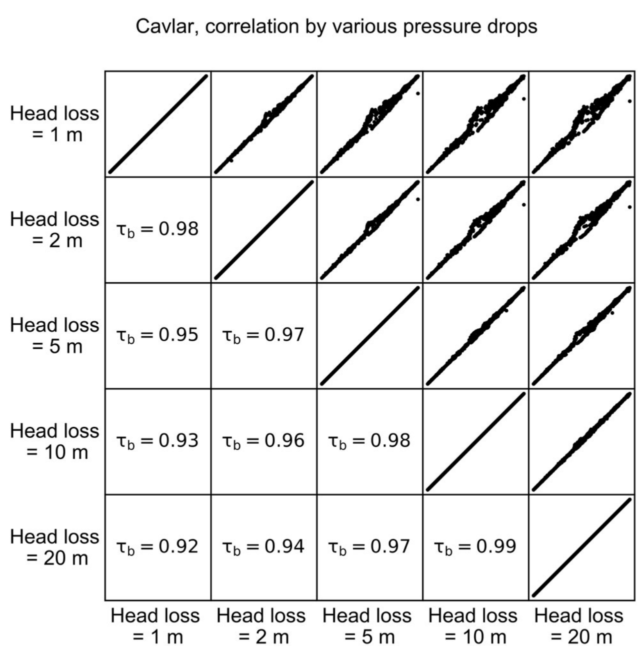


Figure 8. Overview of the correlation of criticality of elements based on the HMM by various pressure drops for the Cavlar WDN. E.g. $\tau_b = 0.96$ in cell Head loss = 2 m, Head loss = 10 m (0.96), corresponds with the scatter plot in cell Head loss = 10 m, Head loss = 2 m.

4. Discussion

4.1. Ranking criteria in the hydrodynamic modelling method

The outcomes of the GTM and the HMM are compared. Two methods are used to determine the criticality with the HMM:

1. Criticality based on the sum of the pressure in the connection points.
2. Criticality based on the number of nodes with a pressure below a threshold.

With the first method, the criticality is comparable for various pressure drops. The outcomes of the second method are highly dependent on the chosen threshold and the occurring pressure drop (see Table 2 and Figure 9). An advantage of the first method is that no threshold is needed, resulting in an objective method. An advantage of the second method is that it provides more information about the number of water users with a pressure below the required service level.

For the described WDN, the F1-score of the GTM is > 0.7 for 10% most important elements when the first method is used. The F1-score of the GTM is > 0.6 for 10% most important elements when the threshold value is: threshold < operational pressure −15 m. Balekelayi and Tesfamariam (2019) were able to identify 12 out of 20 most critical components of the Richmond WDN (836 connection points, 1 reservoir, 6 cascading tanks, 948 pipes, 7 pumps, and 1 valve). This corresponds with a F1-score of 0.6. For the WDNs analysed with the GTM, the F1-score is > 0.6. Since the test network used by Balekelayi and Tesfamariam is different from the network in this research, an exact comparison of the results is not possible. However, for the tested networks the F1 score is in same order of magnitude as the method of Balekelayi and Tesfamariam applied on the Richmond WDN.

4.2. Hydraulics versus network geometry

In the GTM the criticality depends completely on the geometry of the WDN. In the HMM the combination of hydraulics and the geometry determines the criticality of the elements. To obtain stable results from a hydraulic model, various iterations are needed due to the non-linear nature of the equations involved. In each iteration, the discharge in the elements is adjusted until the required precision is met or the maximum number of iterations is reached. The Wanda software can control the number of iterations.

Table 2. Overview of the τb of the comparison of the results of the HMM ranked on the number of connection points with a pressure below a threshold and the GTM.

	Pressure at connection points < operational pressure -19 m	Pressure at connection points < operational pressure -15 m	Pressure at connection points < operational pressure -10 m	Pressure at connection points < operational pressure -5 m
Cavlar	0.45	0.69	0.84	0.82
Tuindorp	0.29	0.57	0.78	0.82
Leimuiden	0.23	0.58	0.73	0.75

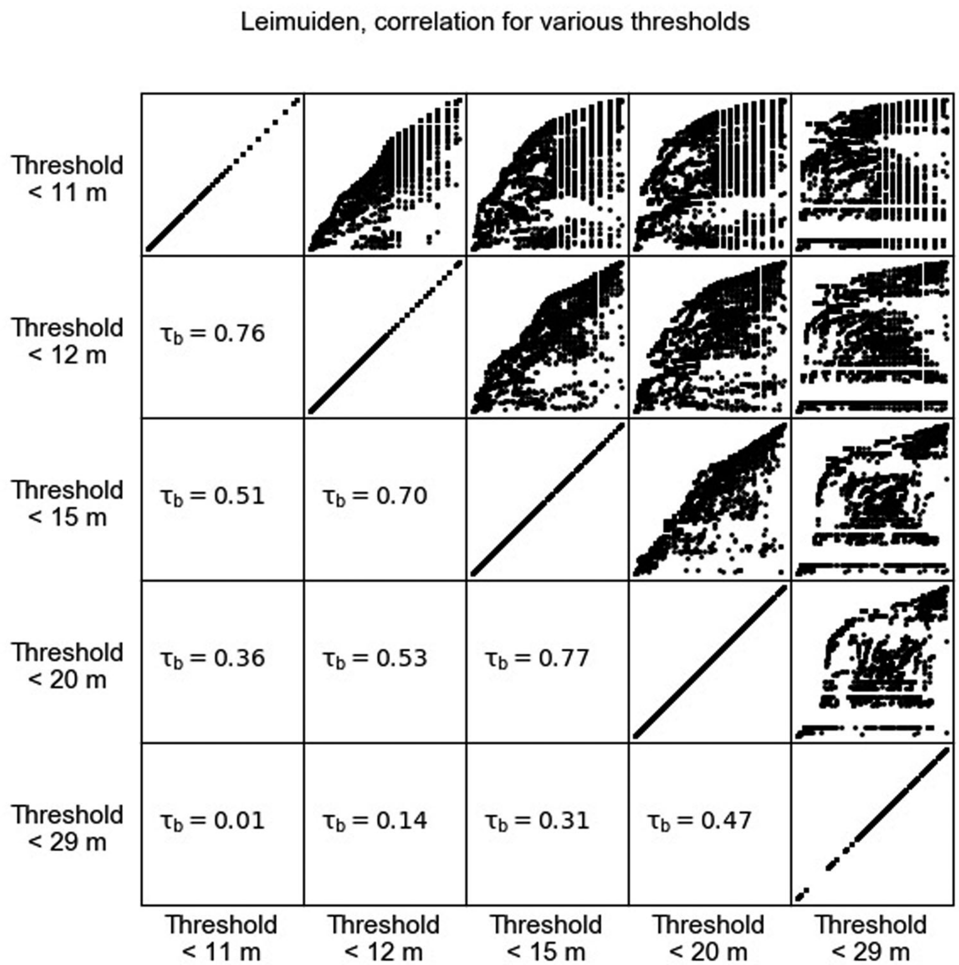


Figure 9. Overview of the correlation of criticality of elements based on the HMM by various pressure thresholds for the Leimuiden WDN.

Figure 10 presents a comparison of simulations with 2, 5, 10 and 25 iterations with a model run of 100 iterations for the WDN of Tuindorp. Figure 10 shows that with 2 iterations $\tau_b = 0.76$ (comparable with τ_b of the GTM and the HMM) and with 10 iterations increases $\tau_b = 0.97$. The $\tau_b = 0.76$ for two iterations implies that in a hydraulic model as well, the outcomes depend strongly on the structure of the network. The correlation increases fast between the 5 and 10 iterations.

In the GTM, the costs of the links are based on a uniform discharge through all elements. It is possible to use differentiated discharges in the elements to determine the costs of the elements in the GTM. In this way, one hydraulic aspect is taken into account more precisely in the GTM. Other hydraulic aspects as redistribution of flows after a break are still not considered. The effect of a differentiated discharge is tested with the GTM. The discharge influences the costs of the elements and therefore the shortest paths. The discharge of each element is determined iteratively. In the first run (1) the costs of the elements are based on the same discharge for all elements. The calculated discharge (see formula 10) of run n is used to calculate the costs of the elements for run n + 1:

$$Q_{\text{tot element i}} = Q_{\text{con}} + (Q_{\text{var}} * NSP_{\text{element i}}) \qquad (10)$$

in which $Q_{\text{tot element i}}$ is Total discharge in conduit i for run n + 1 (m^3/s), Q_{con} is Constant discharge (m^3/s), Q_{var} is Variable discharge (m^3/s), $NSP_{\text{element i}}$ is No. times element i in shortest path from all connection points to the closest WPS in run n (-).

For the first iteration, the constant and variable discharge are the same for all elements. After the first iteration, the new discharges are used to determine new costs of the elements and this process is repeated. The GTM results did not match better with the outcomes of the HMM and therefore this method has not been applied further in the GTM. For the Cavlar network the bests results (comparable with only a constant discharge) were obtained with a constant discharge 10,000 larger than the variable discharge and with only one iteration.

The simplification of hydraulics in the GTM to only the cost of an element leads to differences between the outcomes of the HMM and the GTM. In a hydraulic model the discharge increases for some of the elements in case of a leakage. This effect is not included in the GTM: if leakage occurs in or close to an element with a large diameter or high pressure the impact according to the HMM is visible in a large part of the system. The GTM assumes that the impact is limited to the part of the network where the connection points of the costs to the leak are lower than the costs to the WPS. Consequently, the GTM underestimates the importance of these elements.

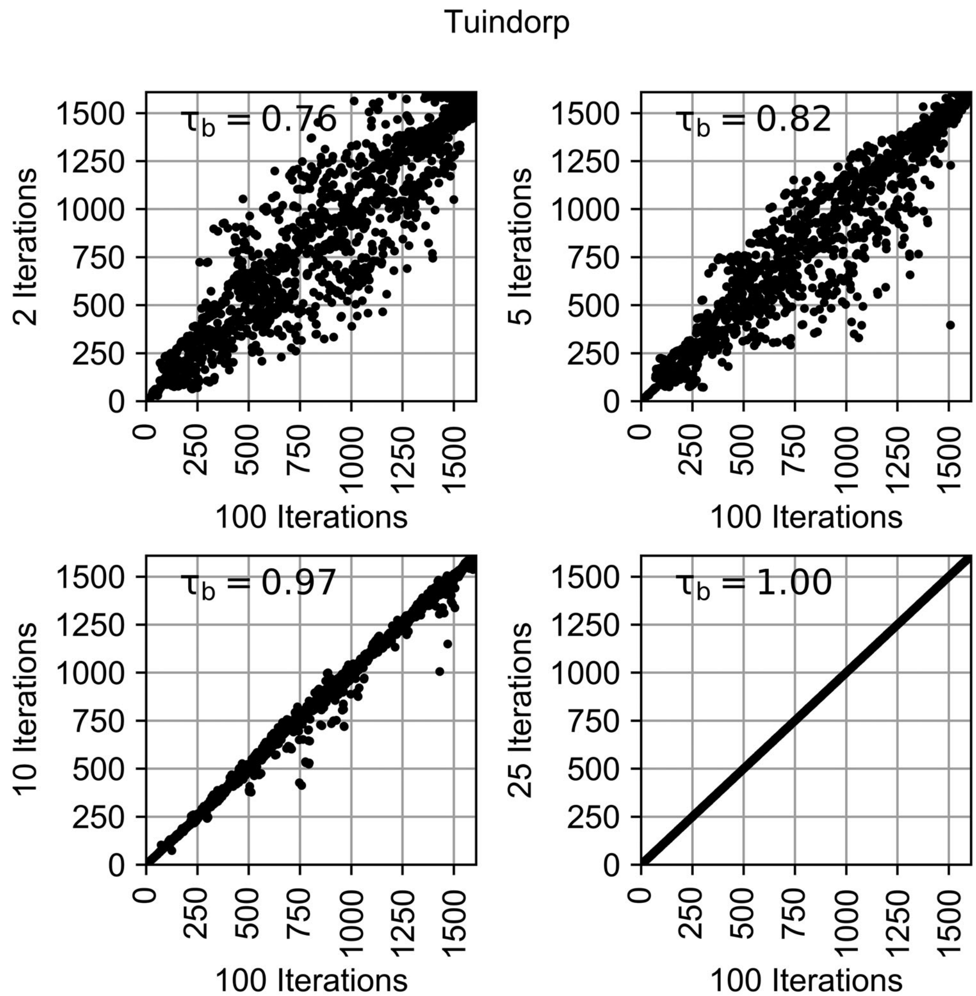


Figure 10. Overview of the criticality of the elements of the WDN of Tuindorp based on, respectively, 2, 5, 10 and 25 iterations compared with the reference scenario of 100 iterations.

As stated in section 3, analysis of the differences between the criticality based on the HMM and the GTM shows that the GTM overestimates the criticality of the branches (for more details see supplementary material). The HMM classifies these elements as less important because they are dead-end parts of the WDN. In case of a leakage, the WDN has enough capacity to compensate for the loss in pressure in the other parts of the network, so the effect of leakage is only locally visible.

4.3. Use of the GTM with the two evaluation methods

The F1-score for the Leimuiden's WDN is relatively small (0.6–0.8) for the 35–60% most important elements. With evaluation method 1, the GTM counts the number of connection points with lower costs to the leakage than to a WPS. If instead the sum is used of (costs from connection point to WPS)$^{-1}$ of these connection points the F1-score increases.

This can be explained by the fact that in Leimuidens' WDN there are some clusters of connection points relatively far from the WPS. The GTM overestimates the importance of these connection points. By summing (costs from connection point to WPS)$^{-1}$ the position of the leakage relative to the WPS becomes more important, and that results in a higher F1-score for Leimuidens' WDN. If the distance from the connection points to the WPS is evenly distributed summing the connection points results in a higher F1-score. With both evaluation methods, it is possible to determine the 10% most important elements with an F1 score > 0.7. However, the first evaluation method is less accurate for the Leimuiden case if a small ($<$10%) percentage of the most important elements is selected.

4.4. Classification of water distribution networks

As explained in section 2.4, the GTM uses the position of the leakage relative to the WPS and the position in the network to determine the criticality. Section 4.2 describes that the F1-score for the WDN of Leimuiden is less for the 35–60% most important elements because of the distribution of the connection points in the network. Therefore, it should be helpful to objectively classify WDN's. Ormsbee & Bryson, 2017 derived a classification method to distinguish grid, looped and branched networks but the differences between the WDNs in three case studies are very small when applying these criteria. The criteria are:

- Branch configuration: No. of branch pipes/Total no. pipes > 0.5.

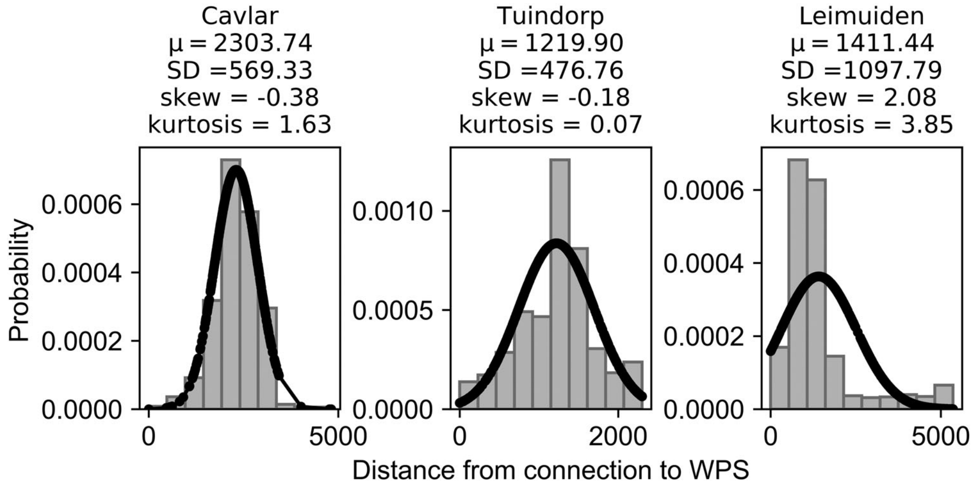


Figure 11. Statistical description of the distribution of the distance from the connections to the closest WPS of the three analysed water distribution networks.

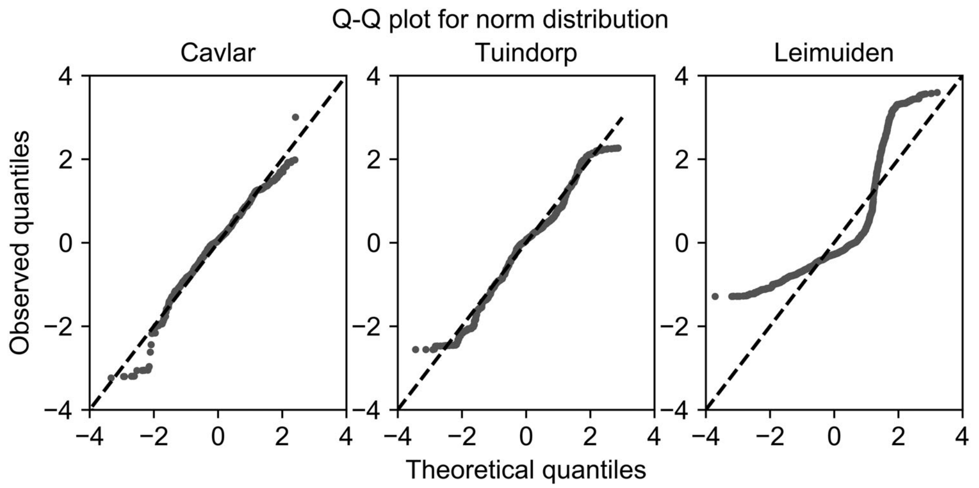


Figure 12. Distribution of the distance from the connection points to the WPSs.

- Grid configuration: No. 3-pipe loops + No. 5- pipe loops < No. 4-pipe loops.
- Loop configuration: No. 3-pipe loops + No. 5- pipe loops > No. 4-pipe loops.

The structure of Cavlar and Tuindorp is such that the central parts of these networks receive water from two sources (pumping stations). In the Leimuiden network, the central part receives water from one source only. Apart from this, there are clusters of connection points in the loop at the east side of Leimuiden and some branches. This is also apparent in the distribution of the distance from the connection points to the WPS. Figure 11 shows the distribution of the distance of the connection points to the WPS. It depicts a skew distance distribution of the Leimuidens' network.

To compare the distance from the connection points to the WPS Q–Q plots (quantile–quantile) are used. A Q–Q plot is a graphical method for comparing two probability distributions. Quantiles are plotted against each other. The distribution of the Cavlar and Tuindorp network closely resemble the normal distribution (see Figure 12), in contrast to the distribution of Leimuidens' WDN, which clearly deviates from a normal distribution. To the authors' knowledge, this criterium is not often applied for the classification of WDNs. However, the criterion is objective and easy to apply and therefore suitable for choosing the counting method in GTM. More research is needed to determine the robustness of the criterium 'normal distribution' for which option of the GTM should be used, or that the skewness is the dominant discriminating factor.

4.5. Connection points vs elements

The elements of the WDN that are ranked with the GTM are the connection points. For the maintenance of the system, the elements are more important than the connection points. However, the connection points give a clear pattern (for more details see supplementary material) in the network that can be used to select the most important elements of the network.

5. Conclusions

The GTM is a network geometry based method used to identify the most critical elements in a WDN with respect to malfunctioning of the entire system. The degree of criticality based on the GTM is compared with the degree of criticality obtained using the HMM. Results show that the outcomes of the GTM correspond with the outcomes of the HMM, since the F1-score (the F1-score is a measure of the overlap between the HMM and the GTM) for the results is > 0.7 for 10% of the most important elements. Thus, the GTM is able to classify the most critical elements correctly, for the cases used in this research where the distance from connection points to the WPS follow a normal distribution.

Because the GTM can be used to classify the critical elements, and the GTM is based on the structure, it is likely that for the studied WDNs the geometrical structure has more influence on the functioning of the WDN than the hydraulics. The comparison of the degree of hydraulic correctness of a hydrodynamic model supports this conclusion because after only two iterations a clear ($\tau_b > 0.76$) correlation between the outcomes of 2 and 100 iterations was found.

With the GTM it is possible, from the perspective of the functioning of the entire system, to divide the elements of a WDN into groups of important and less important elements. Managers of WDNs can use these groups to prioritise maintenance or rehabilitation activities or differentiate quality requirements to the network. Combining the results of the GTM with the failure probability, managers of WDNs could use the outcomes in a risk-based maintenance approach.

The GTM was originally developed for sewer networks (Meijer et al., 2018). This study illustrates that the GTM is also applicable to WDNs. Because the characteristics of district heating networks are comparable to WDNs, the expectation is that the GTM can be used for these systems without or with only minor adjustments. Future research should focus on the validity of the characterisation of other networks based on the distance of the connection points to the pumping station. More research is recommended on whether a normal distribution of the distance from the connection points to the WPS is a robust indicator or that the skewness is a dominant factor for selecting the evaluation method of the GTM.

Acknowledgments

The research is part of the TKI-project Risk Framework for Urban Infrastructure and is performed within the program Topsector Water & Maritiem of the ministry of economic affairs. The involved parties are: Deltares and Partners4UrbanWater. The authors thank water company Oasen for providing the information about the WDN of Leimuiden and water company Vitens for providing the information about the WDN of Tuindorp. Furthermore, the research is supported by the Dutch 'Kennisprogramma Urban Drainage' (Knowledge Programme Urban Drainage). The involved parties are: ARCADIS, Brabant Water, Deltares, Evides, Gemeente Almere, Gemeente Arnhem, Gemeente Breda, Gemeente Ede, Gemeente Utrecht, Gemeentewerken Rotterdam, Oasen, Royal HaskoningDHV, Samenwerking (Afval)waterketen Zeeland, Sweco, Vitens, Waterboard Brabantse Delta, Waterboard De Dommel and Waternet.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Anbari, M. J., Tabesh, M., & Roozbahani, A. (2017). Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks. *Journal of Environmental Management*, *190*, 91–101. doi: 10.1016/j.jenvman.2016.12.052

Arthur, S., & Crow, H. (2007). Prioritising sewerage maintenance using serviceability criteria. *Proceedings of the Institution of Civil Engineers - Water Management*, *160*(3), 189–194. doi:10.1680/wama.2007.160.3.189

Arthur, S., Crow, H., Pedezert, L., & Karikas, N. (2008). Using serviceability to prioritise proactive sewer maintenance. In Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, UK, 2008 (pp. 1–11). doi:10.2166/wst.2009.134.

Baah, K., Dubey, B., Harvey, R., & McBean, E. (2015). A risk-based approach to sanitary sewer pipe asset management. *Science of the Total Environment*, *505*, 1011–1017. doi:10.1016/j.scitotenv.2014.10.040

Balekelayi, N., & Tesfamariam, S. M. (2019). Graph theoretic surrogate measure to analyze reliability of water distribution system using Bayesian belief network-based data fusion technique. *Journal of Water Resources Planning and Management*, *145*(8), 04019028. doi: 10.1061/(ASCE)WR.1943-5452.0001087

Chinchor, N. (1992). *MUC-4 evaluation metrics*. In MUC4 '92 Proceedings of the 4th conference on Message understanding (pp. 22–29). Retrieved from https://dl.acm.org/citation.cfm?id=1072067. doi:10.3115/1072064.1072067

Diao, K., Farmani, R., Fu, G., Astaraie-Imani, M., Ward, S., & Butler, D. (2014). Clustering analysis of water distribution systems : identifying critical components and community impacts. *Water Science and Technology*, *70*(11), 1764–1773. doi:10.2166/wst.2014.268

Dijkstra, E. W. D. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, *1*(1), 269–271. doi:10.1007/BF01386390

Drinkwaterbesluit art. 45. (2015). Drinkwaterbesluit (Drinking water decree (in Dutch). Retrieved February 7, 2018, from http://wetten.overheid.nl/BWBR0030111/2015-11-28#Hoofdstuk5.

Friedl, F., Möderl, M., Rauch, W., Liu, Q., Schrotter, S., & Fuchs-Hanusch, D. (2012). *Failure propagation for large-diameter transmission water mains using dynamic failure risk index*. In World Environmental and Water Resources Congress (pp. 3082–3095). doi: 10.1061/9780784412312.310

Fuchs-Hanusch, D., Möderl, M., Sitzenfrei, R., Friedl, F., & Muschalla, D. (2014). Systematic estimation of discharge water due to transmission mains failure by the means of EPANET2. Retrieved February 8, 2018, from https://pure.tugraz.at/portal/files/2799374/75.pdf.

Kendall, M. G. (1945). Biometrika trust the treatment of ties in ranking problems. *Biometrika*, *33*(3), 239–251. doi:10.1093/biomet/33.3.239

Kingdom, B., Liemberger, R., & Marin, P. (2006). *The challenge of reducing non-revenue water (NRW) in developing countries how the private sector can help : A Look at performance-based service contracting*. Retrieved from http://documents.worldbank.org/curated/en/385761468330326484/pdf/394050Reducing1e0water0WSS81PUBLIC1.pdf.

Laakso, T., Ahopelto, S., Lampola, T., Kokkonen, T., & Vahala, R. (2018). Estimating water and wastewater pipe failure consequences and the most detrimental failure modes. *Water Science and Technology* and Water Supply, *18*(3), 901–909. doi:10.2166/ws.2017.164

LaBrecque, S. (2015). Water loss: seven things you need to know about an invisible global problem. Retrieved February 7, 2018, from https://www.theguardian.com/sustainable-business/2015/mar/02/water-loss-eight-things-you-need-to-know-about-an-invisible-global-problem.

Le Gauffre, P., Joannis, C., Vasconcelos, E., Breysse, D., Gibello, C., & Desmulliez, J. (2007). Performance indicators and multicriteria decision support for sewer asset management. *Journal of Infrastructure Systems*, *13*(2), 105–114.(ASCE)1076-0342(2007)13:2(105) doi:10.1061/(ASCE)1076-0342(2007)13:2(105)

Lukas, A., & Merrill, M. (2006). Scraps: an expert system for prioritizing sewer inspections. In North American Society for Trenchless Technology (NASTT), 1–10.

Mair, M., Sitzenfrei, R., Kleidorfer, M., Möderl, M., & Rauch, W. (2012). GIS-based applications of sensitivity analysis for sewer models. *Water Science and Technology*, *65*(7), 1215–1222. doi:10.2166/wst.2012.954

Mancuso, A., Compare, M., Salo, A., Zio, E., & Laakso, T. (2016). Risk-based optimization of pipe inspections in large underground networks with imprecise information. *Reliability Engineering & System Safety*, *152*, 228–238. doi:10.1016/j.ress.2016.03.011

McDonald, S., & Zhao, J. (2001). Condition assessment and rehabilitation of large sewers. In *International Conference on Underground Infrastructure Research,* Waterloo, ON, Canada, *10–12 June 2001* (pp. 361–369). Retrieved from http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc44696/nrcc44696.pdf.

Meijer, D., Bijnen, M., Langeveld, J., Korving, H., Post, J., & Clemens, F. (2018). Identifying critical elements in sewer networks using graph-theory. *Water (Switzerland)*, *10*(2), 136. doi:10.3390/w10020136

Mesman, G. (2018). KWR, Cavlar. Retrieved February 7, 2018, from http://waterware.kwrwater.nl/Cavlar/Testmodels/.

Michaud, D., & Apostolakis, G. E. (2006). Methodology for Ranking the Elements of Water-Supply Networks. *Journal of Infrastructure Systems*, *12*(4), 230–242.. (ASCE)1076-0342(2006)12:4(230) doi:10.1061/(ASCE)1076-0342(2006)12:4(230)

Möderl, M., Kleidorfer, M., Sitzenfrei, R., & Rauch, W. (2009). Identifying weak points of urban drainage systems by means of VulNetUD. *Water Science and Technology*, *60*(10), 2507–2513. doi:10.2166/wst.2009.664

Möderl, M., & Rauch, W. (2011). Spatial risk assessment for critical network infrastructure using sensitivity analysis. *Frontiers of Earth Science*, *5*(4), 414–420. doi:10.1007/s11707-011-0202-1

Moors, J., Scholten, L., Hoek, J. P., Van Der Besten, J. & Den, (2018). Automated leak localization performance without detailed demand distribution data. *Urban Water Journal*, *15*(2), 116–123. doi:10.1080/1573062X.2017.1414272

Ormsbee, L. E., & Bryson, L. S. (2017). *Classification of water distribution systems for research applications*. In World Environmental and Water Resources Congress 2015. doi:10.1061/9780784479162.064

Pienaar, M. (2013). Outcomes from a sewer maintenance backlog investigation. In *Institute of Municipal Engineering of South Africa (IMESA) Conference* 2013*, Port Elizabeth, South Africa,* 21–*25 October 2013* (p. 11). Retrieved from https://www.imesa.org.za/wp-content/uploads/2015/08/Paper-19-Outcomes-from-a-Sewer-Backlog-Study-Morne-Pienaar.pdf.

Tscheikner-Gratl, F., Sitzenfrei, R., Rauch, W., & Kleidorfer, M. (2016). Integrated rehabilitation planning of urban infrastructure systems using a street section priority model. *Urban Water Journal*, *13*(1), 28–40. doi:10.1080/1573062X.2015.1057174

UNDP. (2006). *Human Development Report* 2006. Retrieved from http://hdr.undp.org/sites/default/files/reports/267/hdr06-complete.pdf.

Ward, B., & Savic, D. A. (2012). A multi-objective optimisation model for sewer rehabilitation considering critical risk of failure. *Water Science and Technology*, *66*(11), 2410–2417. doi:10.2166/wst.2012.393

Wirahadikusumah, R., Abraham, D., & Iseley, T. (2001). Challenging issues in modeling deterioration of combined sewers. *Journal of Infrastructure Systems*, *7*(2), 77–84.(ASCE)1076-0342(2001)7:2(77) doi:10.1061/(ASCE)1076-0342(2001)7:2(77)